Management of Multi-Provider Internet Services with Software Agents

Inauguraldissertation
der Philosophisch-naturwissenschaftlichen Fakultät
der Universität Bern

vorgelegt von

Manuel Günter

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Leiter der Arbeit:

Prof. Dr. T. Braun

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Prof. Dr. P. Bochsler

Preface

The following work was performed during my employment as research and lecture assistant at the Institute for Computer Science and Applied Mathematics (IAM) of the University of Berne. I would like to thank Prof. Dr. Torsten Braun, head of the Computer Network and Distributed Systems group (RVS), for supervising this work and for his insightful advises. Prof. Dr. Braun encouraged and motivated me to publish my research results and he provided me the opportunity to present the work on various conferences, for which I thank him.

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Contents

Chapter 1

Introduction

The Internet service providers are eager to create new and enhanced Internet Protocol (IP) services in order to support advanced network applications and to create new revenues. IP services may for example be enhanced by traffic prioritization and security guarantees. Yet, for Internet-wide service coverage IP services depend on the collaboration of several providers. Such multi-provider services profit from the economy of scale and attract more potential users. Ideally, such services span the whole Internet so that they can support a broader range of applications. Yet, today there is no service management platform for advanced multi-provider IP services available.

The Internet is a heterogeneous network and the providers use different management platforms for their IP networks. Today, coordination of management is a tedious process involving manually established business contracts. The first part of this thesis proposes a scalable architecture to manage new Internet services that involve the collaboration of multiple providers. The architecture is service independent and designed to fit into the autonomous domain structure of the Internet. The architecture introduces intelligent software agents and refers to them as *service brokers*. Service brokers act on behalf of the service providers and establish enhanced IP services on customer demand. This thesis studies how these service brokers communicate to establish a multi-provider service. It proposes a dynamic and flexible broker signaling protocol. Care must be taken that the automated collaboration of the brokers does not introduce scalability problems.

An important aspect of the service management is the *monitoring* of the service. Today, the providers try to hinder external insight into their network management because of security considerations. The customer of an enhanced network service is also denied of insight. Yet, the customer should be able to verify the enhancement of the service. For example, customers will not buy a secure network service if they cannot verify that the providers are really securing the service. The customer needs a way to verify that the IP service is indeed enhanced. Otherwise the customer will not pay the additional service charges. In case the service is provided through collaboration of multiple providers, they themselves may want to monitor if all partners collaborate as negotiated. The second part of the thesis presents a non-intrusive and generic customer-based service monitoring infrastructure (CSM) to address the latter problem. The proposed infrastructure exploits the unique ability of mobile software agents. The agents can roam to the network devices where the IP service is being delivered and thus monitor the service efficiently. The thesis also shows that service monitoring nicely fits into the service broker architecture.

The rest of this chapter introduces terminology and presents the state of the art of relevant technology. Section 1.1 describes the overall scenario. Section 1.2 presents two prominent examples of enhanced IP services: Differentiated services and virtual private IP networks. Throughout this thesis these services are used as motivating examples. This thesis proposes to deploy agent technology to solve multi-provider service management problems. The state of the art in agent technology is described in section 1.3. Section 1.4 gives an overview of a widely used management reference model which is relevant to IP services, too. Given that introductory information, we will be able to restate the problems addressed in this thesis in more detail (see section 1.5). Section 1.6 outlines the thesis.

1.1 Overall Scenario

This thesis refers to an Internet model with actors, roles, and relations as depicted in figure 1.1. There are business entities called Internet service providers (ISP) that sell IP services to customers. The business relation between customer and provider concerning this service is specified in a Service Level Agreement (SLA). This is a contract that describes the scope of delivery of the service in question. The SLA may be a traditional paper contract or an electronic contract. ISPs control an IP infrastructure in order to be able to provide Internet services. They may own network infrastructure or buy network services from other providers. Some Internet services such as priority traffic services require the collaboration of the involved ISPs. Throughout this thesis this is the case of most interest, because multi-provider collaboration is an open issue in many areas of Internet research.

The collaboration between providers is also regulated by service level agreements. Sometimes, one provider plays the role of the customer and sometimes both contracting parties play a symmetric provider role (peering agreements). Nevertheless, the SLAs between providers also describe what actions each party takes and what resources the parties devote to the deployment of the service. Thus, in many cases it is not necessary to distinguish between these different types of SLAs.

1.2 Advanced IP Network Services

The Internet technology introduced a new philosophy into the telecommunication world: the philosophy of the ‘stupid’ best-effort network [Ise97]. Such a network implements only a simple packet forwarding service without additional intel-

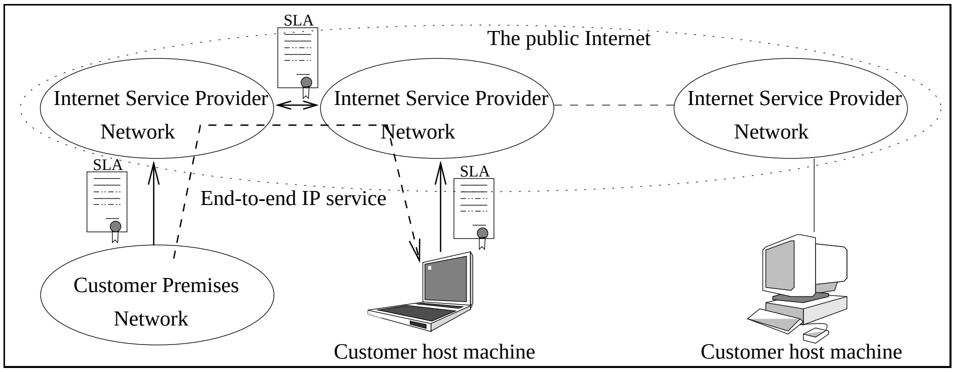

Figure 1.1: Overall scenario.

ligence. Advanced services must be implemented in the end devices (computers). Furthermore, the network capacity is shared. All packets are forwarded equally and as quickly as possible (best-effort). The rapid growth of the Internet reflects the success of this philosophy. Now the Internet is globally present and commercialized. Internet end-users try to handle as many telecommunication tasks as possible with the inexpensive Internet. However, some networking applications demand for service quality. For example IP telephony applications impose upper limits on network delays and delay jitter. Financial applications require communication privacy and real-time video transmission requires bandwidth guarantees. The deployment of service quality in the Internet requires control mechanisms in the network. The Internet must therefore become smarter. Service providers can deploy such intelligent mechanisms and use them to offer quality enhanced Internet services. This section describes two new and emerging Internet services: a virtual private network service and a quality-of-service related service differentiation. Throughout the thesis these two enhanced services serve as motivating examples.

1.2.1 Internet-based Virtual Private Network (VPN)

Large corporations used to interconnect local headquarters and branch offices with leases lines provided by telecommunication companies. They ran private networks, so called corporate networks. With the rise of the Internet technology more and more corporate networks switched from various networking protocols (such as Novell) to the TCP/IP protocol suite. Such private networks based on the Internet technology are also referred to as Intranets. Since leased lines are expensive and the corporations often already have Internet connectivity there is an economic pressure to replace the expensive leased lines and use the wide area interconnectivity of the global Internet instead. However, there are two problems that must be addressed: (1) The Intranet may use private addresses that are not unique in the global Internet and thus not routable [RMK+96]. (2) The Internet protocol does not assure privacy of the transmission. While the IP packets travel through the public Internet they may be eavesdropped or even altered. Virtual private networks

[FH98a, FH98b, GHAM00] encapsulate the packets with private addresses into packets with public addresses. This process is referred to as *tunneling*. If privacy and authenticity of the encapsulated packet is desired then this can be ensured with cryptographic means. Internet based VPNs encapsulate IP packets in IP packets.

Figure 1.2 shows the two most prominent VPN types: subnet-to-subnet VPNs and access VPNs.

- The subnet-to-subnet VPN interconnects geographically distributed private IP subnets. All traffic leaving one subnet destined for another one is tunneled through the public Internet.

- The access VPN allows roaming users to dial into the virtual network from their home machines or from arbitrary Internet points-of-presence.

Figure 1.2 also illustrates the tunneling mechanism. It shows the structure of a tunneled IP packet originating from an application that runs within the private subnet X. The packet's destination is a machine in a remotely located part of the VPN (the private subnet Y). The subnets X and Y use private IP addresses. These are not routed in the public Internet. The address structure of the VPN is invisible from the outside. The access routers of subnets X and Y incorporate VPN functionality. They have an interior network interface with a private IP address and an exterior network interface with a public IP address. The access router at X recognizes that the packet in question must be tunneled. It knows the public interface of the access router of subnet Y. It uses that address as destination address and its own public address as source address. The access router (also referred to as tunnel endpoint) creates a new IP packet with this new addresses and puts the original packet in the payload of the new packet. The payload is then encrypted. The new packet is sent to the tunnel endpoint at Y. The router there extracts the payload of the packet and decrypts the contents. So, the original packet is restored and can be routed on the private subnet Y towards the originally intended destination. The access VPN case also use tunnels. However there are two distinct possibilities. Either the home PC acts as a tunnel endpoint or the point-of-presence (POP) of an ISP acts as tunnel endpoint.

The address translation between private and public networks and the involved routing and cryptographic mechanisms make virtual private networks hard to manage. While a VPN may be useful for a small-to-medium sized company, the management of the VPN would require additional equipment and personnel. Therefore, there is a market for VPN services that let the customers outsource the management of their VPN. The Internet service provider can deploy VPN capable border routers and use them to introduce a VPN on-demand service [KBG00]. So several VPNs can be managed on the same infrastructure by the same personnel (of the ISP) thus both the customer and the provider can profit from the economy of scale.

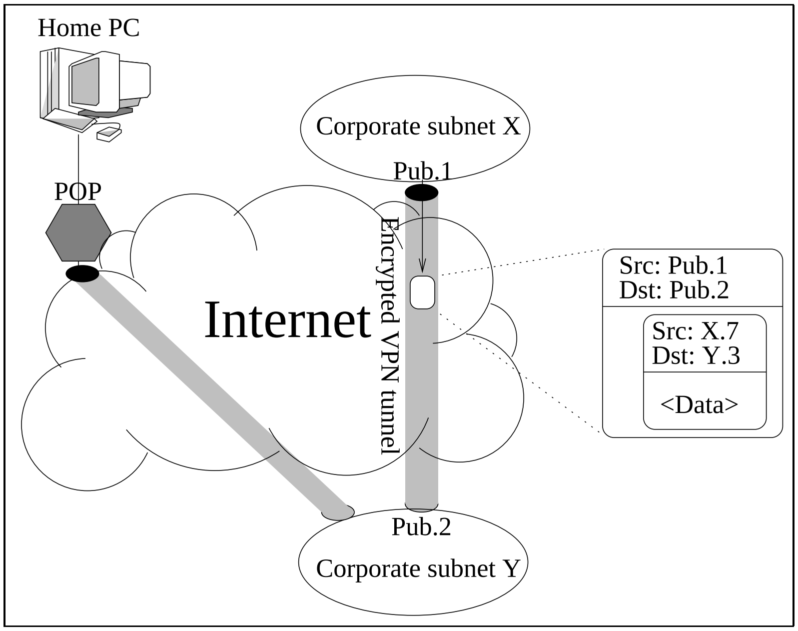

Figure 1.2: Virtual private network types.

1.2.2 The Security Architecture for the Internet Protocol

The Internet Engineering Task Force (IETF) standardized IP version 6 (IPv6) [DH98] to solve pending problems (such as address shortage) of current version of the IP protocol (IPv4). A spin-off development of this process was the IP security architecture (IPSec) which introduces per-packet security features. While the IP version 6 deployment has been delayed the security architecture has been adopted in the current IP version (IPv4). A key motivation for this was that IPSec includes all mechanisms needed to implement VPNs.

The Internet security architecture comprises of a family of protocols. IPSec describes IP packet header extensions and packet trailers that provide security features. The per-packet security features come from two protocols: The Authentication Header (AH) [KA98a] that provides packet integrity and authenticity and the Encapsulating Security Payload (ESP) [KA98b] that provides privacy through encryption. AH and ESP are independent protocols that can be used separately and that can be concatenated. One reason for the separation was that there are countries that have restrictive regulations on encrypted communication. There, IPSec can be deployed solely using AH because authentication mechanisms are not regulated. Both ESP and AH have two modi: the transport mode and the tunnel mode. The transport mode extends the IP headers by adding new fields. The tunnel mode adds a complete new IP header (plus extension fields). The transport mode allows the user to run IPSec end-to-end. The tunnel mode is ideal for implementing a VPN tunnel at Internet access routers (see figure 1.2). In tunnel mode both AH and ESP can be used to implement IP-VPN tunnels. AH and ESP dispose of a small standardized set of cryptographic algorithms to ensure authenticity and privacy. This set is required in order to guarantee interoperability between different IPSec implementations. Beside of that both protocols are specified independent of cryptographic algorithms. A new encryption algorithm for example can easily be added to IPSec. Both AH and ESP assume the presence of a secret key. This key material may be installed manually. A better and more scalable approach is to use the third protocol of the IPSec family: the Internet Key Exchange protocol (IKE) [HC98].

At some point in the network both AH and ESP perform a transformation to IP packets. The IPSec compliant machines always form sender-receiver pairs where the sender performs the transformation and the receiver reverses it. The relation between sender and receiver is describes as a *security association*. Note that the security association describes just one transformation (and its inverse). Concatenated AH and ESP transformations are described by concatenated security associations. Security associations can be seen as descriptions of ’open’ IPSec connections. Both IPSec peering machines store representations of security associations. The representation include information about what kind of protocol is used (AH or ESP) in what mode, the cryptographic algorithms used and the secret key. Each IPSec compliant machine may be involved in an arbitrary number of security associations. The security associations are identified by a 32-bit number, the so-called *Security Parameter Index* (SPI). The sending party writes the SPI into the appropriate field of the IP protocol extension. The receiver uses this information to identify the correct security association. In that way the receiver is able to invert the transformation and to restore the original packet. Let us have a closer look at the IPSec protocols and their security features.

The Encapsulation Security Payload

The Internet Assigned Numbers Authority (IANA) has assigned the protocol number 50 for the IPSec encapsulation security payload. ESP ensures privacy of the IP payload. For that purpose an ESP header and an ESP trailer clamp the IP payload between them. The payload and the trailer is encrypted. The ESP also provides optional authentication. Figure 1.3 depicts an IP packet transformed by ESP in transport mode. The ESP header is located after the IP header. It contains the security parameter index to identify the security association. Furthermore, there is a sequence number that increases by one for each consecutive packet. This helps to detect replay attacks, where the attacker records a packet and re-sends it later. After the payload the ESP trailer is added. The trailer includes a padding. The padding is necessary because the encryption algorithms often require the payload to come in blocks of fixed length (e.g. 8 bytes). The pad length field encodes the length of the padding in bits. The next header field contains the protocol number of the next (eventually higher layer) protocol in the payload (e.g. IP or a concatenated IPSec protocol). Note that the trailer up to here is also encrypted. So, an attacker can for example not read what protocol is in the payload data. The ESP trailer may end with optional authentication data. The data is a message authentication code (MAC) computed by a secure hash function. The input of the hash is a secret key, the ESP header, the ESP payload, and the rest of the ESP trailer. The MAC does not protect the initial IP header.

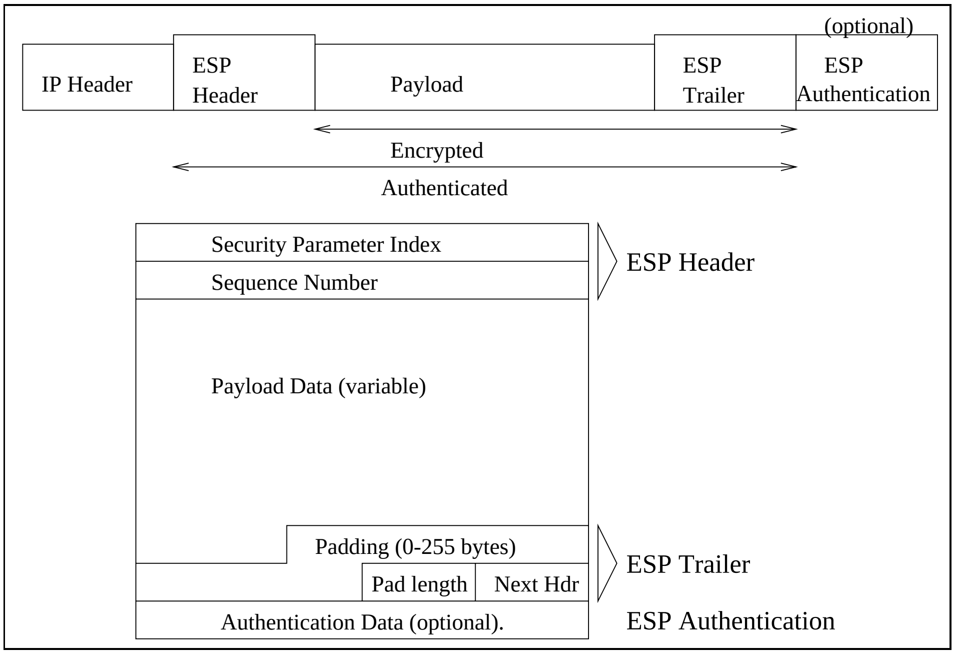

Figure 1.3: The encapsulation security payload.

The Authentication Header

The IANA has assigned the protocol number 51 for the IPSec authentication header. AH authenticates the packet so a receiving IPSec peer can know for sure that the packet originates from the sending peer. Furthermore, the packet integrity is guaranteed. The receiver can verify that nobody has changed the packet while it was in transit between the peers. AH ensures this by calculating authentication data with a secure one-way hash function. The calculation also includes the secret key. An attacker that does not know this key is neither able to forge a valid packet nor to authenticate the packet. Figure 1.4 depicts an IP packet transformed by AH in transport mode. The AH header includes the next header field and encodes the payload length. The length is necessary because the authentication data is variable in length. The AH header, just like the ESP header, contains a security parameter index and a sequence number. Finally, there is the authentication data (the secure hash value). In contrast to the optional authentication of ESP the authentication of AH covers also the original IP header. However, some fields of the IP header are excluded from the authentication, because their values may change during the forwarding of the packet. These exceptions are the time-to-live field that is decremented by each router and the Differentiated Services Code Point (DSCP) (see section 1.2.3).

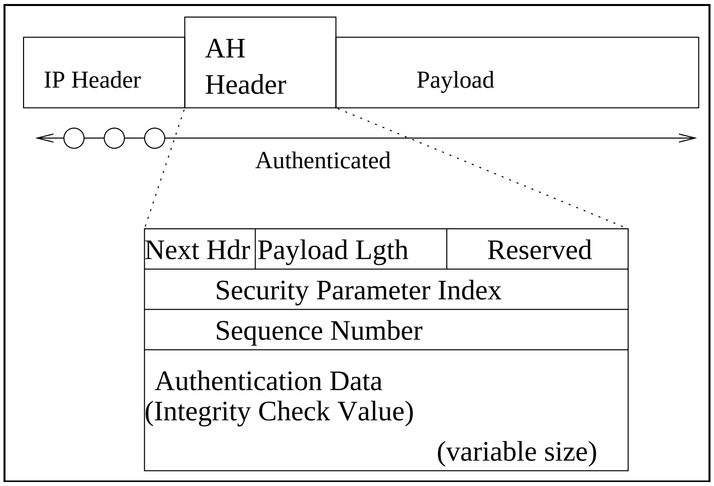

Figure 1.4: The authentication header.

The Internet Key Exchange Protocol

As mentioned before, a Security Association (SA) describes an open IPSec connection including the involved secret keys. The Internet key exchange protocol allows two machines to securely set up a security association. IKE allows these peers to negotiate the protocol (AH or ESP), the protocol mode, and the cryptographic algorithms to be used. Furthermore, IKE allows the peers to renew an established security association.

IKE uses the Internet Security Association and Key Management Protocol (ISAKMP) [MSST98] to exchange messages. ISAKMP provides a framework for authentication and key exchange but does not define a particular key exchange scheme. IKE uses parts of the key exchange schemes Oakley [Orm98] and SKEME [Kra96].

IKE operates in two phases. In phase 1 the two peers establish a secure authenticated communication channel (also called ISAKMP security association). In phase 2 security associations can be established on behalf of other services (most prominently IPSec security associations). Phase 2 exchanges require an existing ISAKMP SA. Several phase 2 exchanges can be protected by one ISAKMP SA and a phase 2 exchange can negotiate several SAs in behalf of other services.

ISAKMP SAs are bidirectional. The following attributes are used by IKE and are negotiated as part of the ISAKMP SA: encryption algorithm, hash algorithm, authentication method, and initial parameters for the Diffie-Hellman algorithm [Sch96].

Phase 1 Exchange. IKE defines two modes for phase 1 exchanges: main mode and aggressive mode. The main mode consists of three request-response message pairs. The first two messages negotiate policy (e.g. authentication method), the next two messages exchange Diffie-Hellman public values and ancillary data necessary for the key exchange. The last two messages authenticate the Diffie-Hellman exchange. The last two messages are encrypted and conceal the identity of the two peers.

The aggressive mode of phase 1 consists of only three messages. The first message and its reply negotiate policy, exchange Diffie-Hellman public values, ancillary data necessary for the key exchange, and identities. In addition the second message authenticates the responder. The third message authenticates the initiator and provides a proof of participation in the exchange. The final message may be encrypted. Aggressive mode securely exchanges authenticated key material and sets up a ISAKMP SA, but it reveals the identities of the ISAKMP SA peers to eavesdroppers.

Note, that the choice of the authentication method influences the specific composition of the payload of this exchange. Note also, that IKE assumes security policies that describe what options can be offered during the IKE negotiation.

Phase 2 Exchange. A phase 2 exchange negotiates security associations for other services and is protected (encrypted and authenticated) based on an existing ISAKMP security association. The payloads of all phase 2 messages are encrypted. A phase 2 exchange consists of three messages. The initiator sends a message containing a hash value, the proposed security association parameters and a nonce. The hash value is calculated over ISAKMP SA key material an proves authenticity. The nonce prevents replay attacks. Optionally, the initial message can also contain key exchange material. Such optional phase 2 key exchange generates key material which is independent of the key material of the ISAKMP SA. If the new SA should be broken, the ISAKMP SA is thus not compromised. The initial message may also contain identifiers in case the new SA is to be established between different peers than the ISAKMP SA peers.

The responder replies with a message of the same structure as the initial message: an authenticating hash value, the selected SA parameters and a nonce. If the initial message contained optional parameters, then these are also part of the reply. Finally, the initiator acknowledges the exchange with a third and final message containing yet another hash value.

Authentication. IKE establishes authenticated keying material. IKE supports four authentication methods to be used in phase 1: pre-shared secret keys, two forms of authentication with public key encryption, and digital signatures. Today's IKE implementations support X.509 certificates. So, two machines that do not know each other can initialize a security association through the help of the commonly trusted third party that verified the certificates.

1.2.3 Differentiated Services (DiffServ)

The best-effort nature of IP forwarding hinders for example the deployment of real-time applications. The most recent approach to bring Quality-of-Service (QoS) features such as small traffic latency or jitter, guaranteed bandwidth, and low loss rates to the Internet is called Differentiated Services (DiffServ).

Differentiated Services [BBC$^+$98] is a scalable technique that provides QoS in IP networks by traffic aggregation based on Differentiated Services Code Points (DSCP) [NBBB98]. The DSCP is a one-byte field in the IP header. The routers use the DSCP to map each packet to a per hop behavior. Inside of a DiffServ network, all IP traffic using the same code point is called a DiffServ behavior aggregate and is treated the same way. Since there are only a handful of PHBs, the DiffServ architecture scales also to large core networks.

The IP packets are classified and processed by traffic conditioners at the edge of a DiffServ domain. Thus, most DiffServ related processing is done at the edges of the domains. DiffServ domains are typically equivalent to administrative domains, i.e. a customer premises network or the network of an Internet Service Provider (ISP). A DiffServ service is specified in so-called Service Level Specifications (SLSs). These SLS must be established among the various DiffServ domains. Theses SLSs form the basis for traffic conditioning actions such as shaping, policing, and remarking at the edge routers.

For providing QoS guarantees similar to what customers have been used from leased line services, the Expedited Forwarding (EF) Per-Hop Behavior (PHB) is the appropriate choice [JNP99]. The EF PHB can be used to build a low latency assured bandwidth end-to-end service through DiffServ domains. Such a service appears to the endpoints like a point-to-point connection or a virtual leased line. A typical SLS for such a service might include the ingress and egress point of the DiffServ domain that shall provide the service and a peak rate which can be guaranteed to the traffic stream.

The Assured Forwarding (AF) PHB group [HBWW99] provides different levels of forwarding assurances for IP packets. Four AF classes are defined with three drop precedences each. A typical SLS includes rates for low and medium drop priority packets and might also specify ingress and egress points. AF is considered as more complex to be configured in DiffServ domains, but it allows the provider to compose a more elaborate and fine-tuned quality-of-service support.

Management of a DiffServ domain can be done using so-called Bandwidth Brokers (BB) [NJZ99, TWOZ99]. Bandwidth brokers are software agents (see section 1.3) that manage DiffServ allocations on behalf of the provider organization (see section 2.2). The bandwidth brokers can be configured with organizational policies, keep track of the current allocation of marked traffic, and interpret new requests to mark traffic in the light of the policies and current allocation. Inter-domain DiffServ traffic is regulated by the bandwidth brokers according to bilateral SLAs.

1.3 Agent Technology

Software agent technology is an ongoing research issue in the computer sciences. The term ‘agent’ is occupied by several research communities. Researchers of the artificial intelligence community originally initiated work on so-called *intelligent agents* [MJ99] in order to study computational models of distributed intelligence. Later, the software engineering community (see e.g. [WJ99]) initiated a new wave of interest in software agents which should help to simplify the complexities of distributed computing and which could overcome the limitations of current user interface approaches [Bra97].

A software agent is a computer program acting autonomously on behalf of a person or organization. Software agents usually have one or several of the properties [Mil00] of the following list. Note, that different agent research communities focus on different sets of these properties. Software agents are:

- **Autonomous.** The agents are proactive; they work goal-directed. The intelligent agent research focuses on how artificial intelligence (inference systems, theorem provers) can enable the agent to autonomously find a solution to a given problem.

- **Adaptive and Reactive.** Agents can react and adapt their behavior to the current state of their environment. Thus, they are ‘aware’ of their current environment. This property renders agent-based solutions interesting for heterogeneous environments such as the Internet. Agents may also have the ability to learn and to adapt to uncertainty and to change. This makes agent technology suitable for the interaction with the real world.

- **Mobile.** The autonomy of the agent may also express itself as agent mobility. Such an agent is able to roam self-directed from one execution environment to another execution environment. So called *mobile agents* [Kna96] are usually smaller and less adaptive than intelligent agents.

- **Communicative and cooperative.** One strength of the agent paradigm lies in the rich functionality that may emerge when many (small) systems interact based on (even simple) rules. All agent systems provide facilities that let agents communicate (possibly across computer networks). Some researchers consider communication and cooperation aspects as so important to the agent paradigm that they simply *define* a software agent as an entity able to communicate in an Agent Communication Language (ACL). Research on ACLs has produced high level languages that do not only communicate sentences in some language, but rather communicate an attitude about the content (e.g. belief, assertion, query etc.). These languages are inspired by the speech act theory of linguistics. A recent language example which gains importance in the said research community is the Foundation for Intelligent Physical Agents (FIPA) ACL [http://www.fipa.org].

- **Interactive.** Agents can inter-operate with other agents, with legacy systems, other information sources, and with humans. The agent paradigm is also used as a metaphor to facilitate the human-to-computer interaction.
- **Delegation.** A human should be able to delegate some of his/her tasks to the agent which will filter, extract, and present the relevant information from bodies of information larger than the human could ordinarily digest. Often, the metaphor of a ‘digital butler’ is used in this context.

Since the agent paradigm is used by several research communities there is no consensus on a specific agent definition. Yet, there is a rough consensus that the presented properties are relevant. Properties that are relevant to all agent systems are the goal-driven autonomy, the environment awareness and the collaboration/communication. Intelligent agents and mobile agents are specialized instances of the software agent paradigm.

1.4 Network and Service Management

In order to be able to offer new IP services such as DiffServ or VPNs, the providers must deploy a management system. This system must set up the device configurations necessary, manage the available network resources and monitor the ongoing services. The telecommunication industry which is the largest player in the IP network provisioning business has standardized the Telecommunications Management Network (TMN) model [IT]. The model provides a way to think logically about how the business of a service provider is managed. The model consists of five layers where each layer provides capabilities to its upper neighbor and each layer imposes requirements on its lower neighbor. The components of the lower layers are more distributed and technically oriented. The higher the layer, the more information is concentrated into high-level abstractions. The higher layers can thus be more centralized which allows the management system to maintain consistency in the operations. The TMN model is thus usually depicted as a pyramid (see figure 1.5). The business layer contains processes that deal with the corporate strategy and customer relations of the provider. The service layer deals with the products that are offered to the customers, namely the services. The network management layer incorporates the management processes necessary for the provider’s overall network infrastructure. The element management deals with processes concerning single devices in the network (servers, routers, switches etc.). Finally, there is an element layer representing the heterogeneous hardware devices that form a network.

The processes at all layers go through a more or less similar life cycle (see figure 1.6). After planning (e.g. what equipment to buy, or what service to offer) and deployment there is a third phase consisting of operation, maintenance, and monitoring. This phase is supposed to generate revenues for the provider. At the end of the cycle is a evolution/upgrade phase which may lead to a new planning

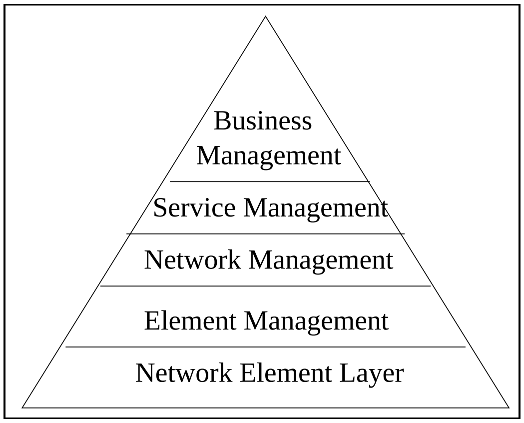

Figure 1.5: Telecommunication management network model.

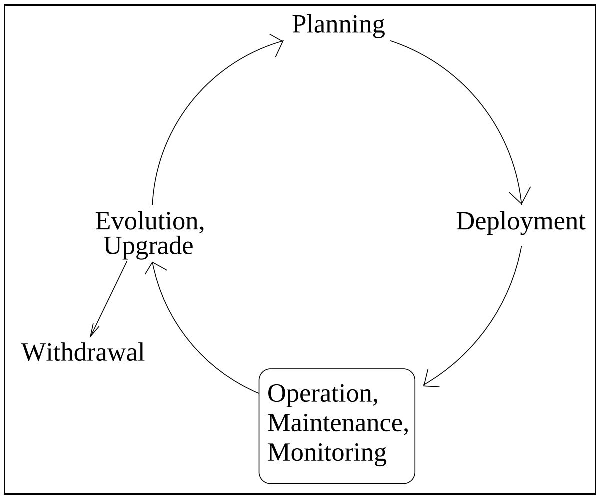

Figure 1.6: Life cycle of management processes.

phase or to withdrawal. The operation phase is ideally the longest phase and is not directly related to strategic decisions. It includes many repetitive tasks (monitoring, accounting etc.). For these reasons it offers a great potential in automation.

This thesis focuses on the service level of the TMN model. The particular goal of part I of this thesis is to design a provider network management system that allows the customer to request and to access new IP services on demand. The provider management system should thus be as much automated as possible. Part II focuses on a monitoring infrastructure for these services. Both parts of the thesis thus mainly deal with the operations phase of the service life cycle.

1.5 The Problems and the Proposed Approach

The TMN is just a reference model. Implementation efforts have been started but usually they start bottom-up. There is no standardized service management yet that would allow the provider to offer network services on demand, thus automate the service operation phase. The TMN is also insufficient to model the collaboration between providers for the provisioning of multi-provider services. Such enhanced Internet services need multi-provider support in order to be delivered end-to-end over the global Internet. Otherwise, the scope of the enhanced service is limited to single provider networks and it is questionable whether a critical mass of users will order the service. Further, the customers must be able to activate the enhanced service online and on demand. Today for example VPN services must be ordered off-line by fax or telephone. Also, the customer must have means to verify the enhancement of the IP service. Finally, in such a large environment as the Internet is, management systems face scalability problems.

This thesis is going to address these problem areas:

- How should the provider's service management architecture look like, which allows the provider to offer enhanced IP services such as VPN or DiffServ on demand?
- How does this architecture use electronic SLAs to automate the collaboration between providers?
- Is the management communication able to scale to the huge size of the public Internet?
- How can the correct operation of a multi-provider network service be verified (by either the customer or the providers) in a dynamic, convincing and scalable way?

Part I of the thesis presents a generic management architecture for new and enhanced IP network services. The architecture bases on intelligent software agents. It introduces a set of specialized agents with logically separated functionality. These agents form an architecture with the same layers as the TMN model. The agents act on behalf of the service provider, thus the provider delegates specific management functions to the agents. The agents have a variable level of autonomy which is constrained by rules (policies). The agents of adjacent providers collaborate to set up advanced IP services along several provider networks. Collaboration is expressed as SLA. The architecture shows how agent technology can be deployed to allow the service providers to offer on-demand multi-provider IP services.

An important aspect of part I of the thesis is the management communication, more specifically the communication between agents of different providers. The thesis particularly focuses on the scalability of the management communication since the sheer size and growth rate of the Internet make scalability a key concern. A newly developed simulator helps to evaluate the trade-off between communication complexity and end-to-end service quality guarantees on the example of DiffServ resource reservations.

Part II of the thesis presents a customer-based service monitoring infrastructure based on mobile software agents. Service monitoring is an important aspect of service management. Both customers and collaborating providers can use the infrastructure to test the smooth operation of the service and to gather traces and evidence of problems. The proposed infrastructure allows the user to delegate monitoring tasks to mobile agents. The agents are programmable, thus they can test any kind of emerging IP services. The mobility of the agents can be exploited to efficiently pre-process the monitoring data close to the data source. Further, mobile agent technology eases the deployment of new service testing procedures. Based on an implementation and practical examples (VPN monitoring, active and passive QoS monitoring) this thesis shows that service monitoring is a fruitful application area for mobile agent technology.

1.6 Outline

This thesis is structured into the following chapters:

- Chapter 2 motivates and describes a generic architecture that allows providers to offer enhanced IP services on demand. The architecture bases on intelligent software agents called *service brokers* that manage the provider networks and that collaborate in order to dynamically set up multi-provider services.

- Chapter 3 focuses on a special instance of the service broker architecture: the bandwidth broker for Differentiated Services. The chapter discusses the trade-offs between management communication complexity, signaling scalability, and end-to-end service quality.

This concludes the first part of the thesis. The second part presents a customer-based monitoring infrastructure for advanced IP services.

- Chapter 4 motivates why enhanced IP services need a monitoring infrastructure and how the unique abilities of mobile agents can be exploited to implement a flexible and secure monitoring system for advanced IP services. It introduces the architecture of a mobile agent based service monitoring infrastructure.

- Chapter 5 describes a customer-based service monitoring implementation based on the programming language Java. It focuses on the implementation of the execution environment for the agents. Further, an important aspect is the implementation of security and resource control mechanisms.

- Chapter 6 describes the implementation of mobile agents that monitor a number of advanced IP services such as a virtual private network service and Differentiated Services. The chapter also presents future applications.
- Chapter 7 presents performance statistics of the implemented monitoring infrastructure. Is shows that the performance is sufficient to enable interesting monitoring applications.
- Chapter 8 discusses related research efforts in the area of management and monitoring of advanced IP services. The chapter compares the related work with this thesis.
- Chapter 9 concludes the thesis.

Part I

Management of Advanced IP Services with Agents

Chapter 2

A Service Broker Architecture for Multi-Provider IP Services

2.1 Introduction to IP Service Management

The Internet technology was developed to inter-connect heterogeneous networks. The primary design goals were connectivity and the demonstration of the feasibility and economy of scale for simple packet forwarding networks. However, in recent years, the technology's enormous success and its original design goals are source of conflicts. Today's Internet is no longer seen as a shared resource. One instance of this problem is the network security. Internet users do not think of themselves as part of a big community, but they want to experience privacy when communicating. Furthermore, most of todays networks are commercial. Network carriers do not want to provide connectivity, unless somebody pays for it.

The Internet Engineering Task Force (IETF) has standardized new protocols for such upcoming needs. For policy based routing (BGP), for remote network management (SNMP), for secure communication (IPSec), for QoS support (IntServ and later DiffServ) to mention only a few. All these protocols struggle with the same problem, namely the 'stupidity' of the Internet [Ise97]. A fundamental difference between the Internet and connection-based networks such as the telephone networks is the idea of pushing the intelligence out of the network towards the end-user equipment. Personal computers are ubiquitous and get smarter every day. This is also referred to as the end-to-end argument [SRC84]. The idea is that PCs as end devices use the stupid packet delivery service to create complex services for the users.

While the rise of the Internet illustrates that this approach has many benefits, there are also severe drawbacks. Some services simply have to be implemented inside the network. The first problems occurred, when the routing system had to be changed. Two-tiered routing was introduced because of the rapid growth of the number of hosts, the routing became policy based because of the commercialization, and the routing became more fine-grained (classless) because of address shortage (CIDR). Another problem is the network resource reservation, which has to be solved inside of the networks. Security services and caching are further examples. After each of these problems had been identified, the IETF developed a protocol which had to be implemented in the network routers. Routers are thus constantly being upgraded. Today, they are able to support a large number of protocols, and thus are quite intelligent. However, the deployment time of a new protocol is very large, since all routers must be upgraded. This takes time and may eventually never happen (IPv6).

Furthermore, the new capabilities of todays network elements adds management complexity. Therefore, tools and protocols were developed to administer network equipment site-wide. However, for the most pending problem of internetwork services, no automated management support exists. This is not astonishing, since an administrative domain does not want to let others configure their network equipment. The misuse potential would be devastating. In practice, the administrators of peer networks negotiate with each other about all network configurations that have implications to each other. This results in a service level agreement, which is also a business contract. Each domain will then set up their network configurations with the tools and protocols of their choice.

In the domain of resource reservation another solution for this procedure is proposed. Intelligent software agents, with sufficient knowledge of the network they administer, negotiate automatically to trigger bandwidth reservations in their network. These so called bandwidth brokers can be seen as just one instance of a generic approach to the problem of inter-domain network configurations. This part of the thesis proposes a generic service management architecture based on the bandwidth-broker idea. It will also discuss scalability problems of broker communication on the example of differentiated services.

Project Context. The work presented in this part of the thesis was performed within the *Charging and Accounting Technology for the Internet* (CATI) project [SBGP98, CAT]. The main goal of the CATI project has been the design, evaluation and implementation of charging and accounting mechanisms for value-added Internet services such as Integrated Services, Differentiated Services and Virtual Private Networks (VPNs). CATI was a CNEC (Competence Network Electronic Commerce) project within the Swiss Priority Program for Information and Communications Structures (SPP ICS) of the Swiss National Science Foundation (SNF) running from July 1998 to March 2000.

2.2 Bandwidth Brokers

In the common usage of the term, a *broker* acts as an intermediary to negotiate contracts of purchase and sale. In the context of networks services these contracts are Service Level Agreements (SLA). The term *bandwidth broker* was introduced in [NJZ99] in the context of Differentiated Services. A Bandwidth Broker (BB) is a software agent that has some knowledge of an organization's priorities and policies and allocates bandwidth with respect to those policies. It acts autonomously and in behalf of its ISP. Thus, the bandwidth broker is an intelligent agent [MJ99] (see also section 1.3). Bandwidth brokers are agents that are responsible for resource allocation and traffic control of one administrative domain, as well as for maintaining bilateral agreements between peers in adjacent domains. BBs have their own policy databases that specify which customers can use the resources and how much they are allowed to use. Figure 2.1 illustrates an end-to-end communication using BBs. Between each network domain a bilateral agreement is established specifying the traffic profile each domain can send/receive. The traffic profile includes a DiffServ service class, and can include a service level specification with properties such as the rate, the maximum burst size, and the time period when the service is required. An end-to-end service guarantee is achieved through a chain of bilateral agreements (SLAs).

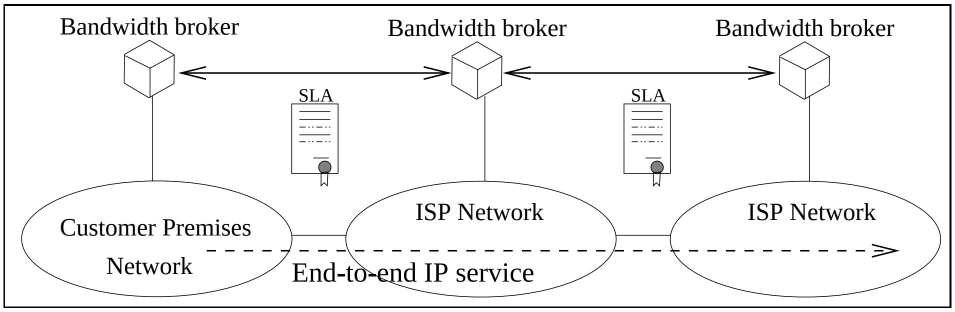

Figure 2.1: Bandwidth brokers.

Bandwidth brokers are an alternative to reservation schemes that use signaling to set and enforce flow specifications in routers throughout an end-to-end path. Bandwidth brokering has the following advantages:

- A bandwidth broker is a single point[1] of contact that acts as an intermediate between customer and provider. The (large number of) network elements do not have to deal directly with customer requests. The bandwidth allocation thus follows the organizational hierarchies in the Internet.

- Bandwidth brokers negotiate bilateral agreements. This simplifies the trust relationship because instead of a large number of network devices that must trust each other, the peering providers only need to establish trust between their bandwidth brokers.

- The bandwidth broker serializes the requests and can thus perform effective admission control.

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[1] Conceptually, the BB is a single entity, yet it may include redundancy to avoid reliability problems.

- The bandwidth brokers can keep abstract and thus compact network state information. Per-flow state representation kept in all network devices (routers) can become very large and also inconsistent.
- Bandwidth brokers can work on traffic aggregates which makes the approach scalable.

In the DiffServ architecture the bandwidth brokers are responsible for the following tasks:

- **Accept service requests.** The customer can negotiate an SLA with the bandwidth broker that specifies the DiffServ service level.
- **Admission control.** The BB ensures that all conditions (policy compliance, resource availability) are met before a given request can be fulfilled.
- **Resource management.** The bandwidth broker allocates available network resources. It optimizes the use of the available capacity and minimizes the risk of SLA non-conformance.
- **Provisioning through local configurations.** The broker organizes the roll-out of network device configurations when necessary. For DiffServ this mainly concerns the border routers. After the configurations are adapted the service for the customer runs without intervention of the broker.
- **Peering negotiations.** If the requested service level has implications on peering provider networks then the bandwidth broker negotiates with its peer. This task is crucial for the establishment of end-to-end DiffServ guarantees.

2.3 A Generic Broker Architecture for On-Demand Internet Network Services

Quality-of-service support with Differentiated Services is just one one of many services an Internet service provider (ISP) could offer. In order to make effective use of the available infrastructure, the ISPs needs to collaborate with each other and automate their interaction processes. You can compare this to exterior routing which is a multi-provider IP service. If the ISPs would not perform this routing then their networks would still exist but the global Internet would break apart. Thus, the total value of their networks increases drastically through collaboration.

The ISPs are eager to not only sell best effort transport services, but also to sell new and value added services. Such services can include QoS guarantees or privacy guarantees as offered by VPN. The planning, accounting and the management of these new services are further business services an ISP can provide. We can assume that the future Internet ISPs will have the following features:

- Networks are remotely controllable (configurable) by the ISP and whose network elements are able to support the new service. The rapid growth in size and complexity of the networks will force the providers to automate the element management.

- The intra domain resource management is able to provide service guarantees. This can be a fine grained mechanism (e.g. per flow) if the domain is small. New technologies such as MPLS [DR00] may accelerate this development.

- Application level interfaces exist for service requests by customers. Today, the world-wide web technology offers an ubiquitous graphical interface.

In order to produce the full revenue of these investments, the ISPs need to collaborate. One of the key advantages of the Internet is its global presence. If service providers support enhanced services only locally then these services are less valuable and may not be more interesting than alternative network technologies (e.g. ATM). Today the collaboration is done by human network administrators communicating with each other by phone or fax. However, with automatically configurable networks and appropriate communication protocols, an automated approach is much more favorable.

We envision the following requirements: Electronic bilateral SLAs exist between adjacent ISPs. Also, there is an inter domain resource management procedure which allows the new services to span multiple ISPs. For scalability in large backbone networks, this management must handle aggregations of the intra domain resource management entities; it must be coarse grained. The architecture we present in the following shall allow the automatic provision of new services spanning multiple ISPs based on the mentioned assumptions.

The bandwidth broker architecture for DiffServ (presented in section 2.2) was developed for exactly this scenario. Therefore, we took up this approach, made it service-independent and refined the architecture. All the advantages of the bandwidth broker approach listed in section 2.2 are also true for other enhanced IP services such as VPNs. The Internet Engineering Task Force (IETF) may also come up with new IP enhancements that pave the way for even more new IP services. Therefore, it makes sense to introduce a broker architecture that is able to cope with the common tasks of arbitrary new IP services. These include resource allocation and service negotiation and service management which is just what the BB does for DiffServ.

Generalizing the BB idea was also useful for the CATI project (see section 2.1), since we were looking into ways how to combine VPNs with DiffServ (see also section 2.3.5). Having a unified service management architecture simplifies this task. The architecture also allowed us to study charging and accounting problems for new IP services.

The architecture that is going to be presented identifies and describes the components and communications necessary for service brokering. The architecture consists of a hierarchy of service brokers. It is described in more detail in [GBK99].

2.3.1 Basic Components of the Service Broker Hierarchy

Service Brokers. A service broker accepts service specifications for the specific IP service it sells. It can query the cost of the service and negotiate its price with a customer. Upon agreement, the broker can setup the service. The broker keeps the knowledge about the services provided in the form of service level agreements. It can thus accept requests to change the specifications of a service for a given customer. Note that the service broker may synchronize and coordinate multiple service requests. Furthermore, a service broker is an autonomous entity. It can proactively change an SLA. For such decisions, it needs access to various policy databases.

Broker classifications. Services can be classified as follows:

(1)(a) The service can be provided by an ISP alone or
(b) it needs collaboration with other ISPs.
(2)(a) The service configuration is orthogonal to other services or
(b) it must be coordinated with configuration of other services.

For the case of (2a) (orthogonal) we propose two kinds of brokers. The *Internal Service Broker (ISB)* can be used to manage an ISP's service that is solely supported local to the ISP. The ISB can configure the ISP's network via an communication interface to *element managing agents* of each relevant network equipment (e.g. the border routers). The ISB manifests the fine grained resource management mentioned before. If the (orthogonal) service needs the collaboration of other ISPs we propose an *External Service Broker component (ESB)*. The ESB has knowledge of the adjacent ISPs and can negotiate the necessary services of the adjacent ISP through its peer ESB broker. Therefore, an ESB can control the corresponding ISBs and thus the network configurations. The ESB manifests the coarse grained resource management mentioned before. Note that ESB and ISB represent the Internet-wide used two-tier hierarchy which allows for a scalable solution. The separation matches the topology found in todays Internet. Figure 2.2 depicts the situation.

Class 2b services (non-orthogonal) must be handled by brokers that are specially designed to offer a service bundle. Such Composite Service Servers (CoSS) can use and coordinate several ISBs and ESBs (of the different services influenced by this special service). Note that the management of such services is very complex. In general such a service can only be automated if the different sub-services only interfere in few specific and well-known areas. A good example of such a service bundle is the provisioning of VPNs with QoS guarantees with DiffServ (see section 2.3.5).

Layering of the Broker Hierarchy. The broker hierarchy is layered. A component of a higher layer represents information in an abstract way (e.g. SLAs) while a component of lower layers represents information in a more concrete specific way (e.g. a router configuration script). Components issue configuration commands to

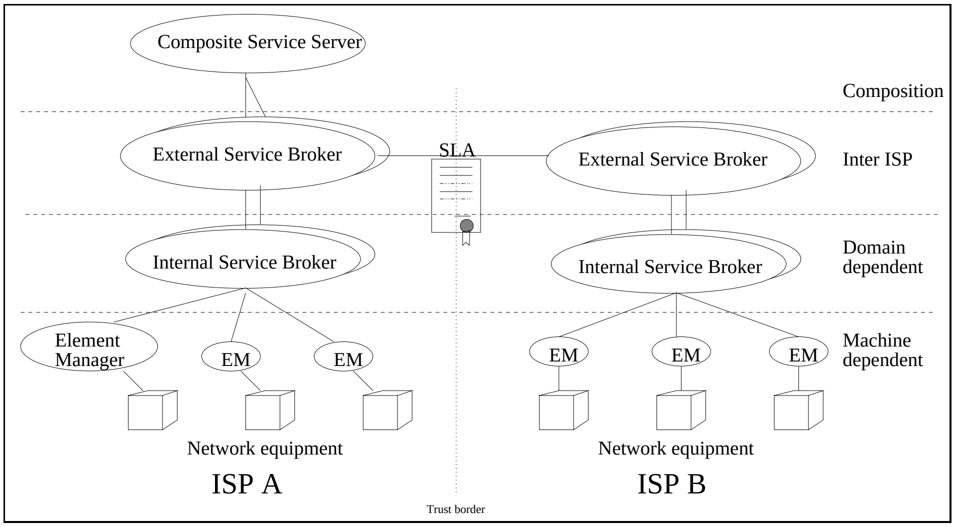

Figure 2.2: Service broker hierarchy.

components of the next lower layer. Components receive notifications of events from the next lower layer. The layering of the components is depicted in figure 2.3. It is compliant to the TMN model (see section 1.4).

The external service broker includes business related functionalities. It can negotiate prices and buy and sell network services. However, it focuses on the IP service that it sells so it is mainly located at the service management layer.

The internal service broker also focuses on a service, but it knows the implementation details of the service and hides them from the upper layer components. It has knowledge about the provider's network infrastructure and it knows how to trigger service relevant network management functions. The ISB is unaware of business issues.

The element managing agent knows a specific network device and hides the device specific details from the upper layer. The element managing agent (EM) focuses on a single network element.

Customer contact. Principally, only the external service brokers negotiate with a broker of another domain. Therefore, larger customers can simply run their own external service broker to order services. The smaller customers, however, may not want to run such a complex piece of software. Therefore, it is useful that also a human can interact with a foreign service broker. We propose a customer server that provides a graphical user interface and that translates between a human and an ESB. A straight forward solution is web based.

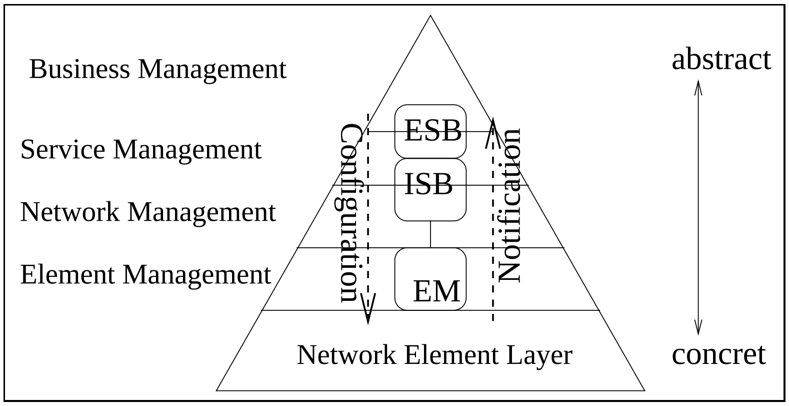

Figure 2.3: Service broker hierarchy in the TMN model.

2.3.2 The Structure of the Agents

The External Service Broker

The External Service Broker (ESB, see Figure 2.4) component bundles the most functionalities of all presented components. It is controllable by the network administrator via a master interface and it controls ISBs via a slave interface. The peer interface must implement an ESB-ESB protocol including form exchange, negotiations and electronic payment. The current state of the service collaborations between adjacent ISPs is stored in an SLA repository. The ESB can be equipped with a quite complex autonomous behavior because it should be able to automatically detect necessary updates to SLAs. Furthermore, it should be able to react to changes requested by the other ISPs and it can vary its behavior depending on the network state and the e.g. the daytime. A central module of the ESB must coordinate its own activities, since there may be a lot of requests being processed at a given time.

Internal Service Broker

The internal service broker has a similar agent structure as the ESB (see figure 2.5). The master interface includes an interface for the network administrator as well as for local ESBs. The Internal Service Broker (ISB) coordinates the configuration of a service across its network. Therefore it needs an interface to control EMs and a repository of the current configurations. An autonomous behavior module can be attached to an ISB that e.g. monitors a service relevant subset of the network equipment and triggers actions under certain conditions (e.g. alarms). The ISB needs coordination facilities as well.

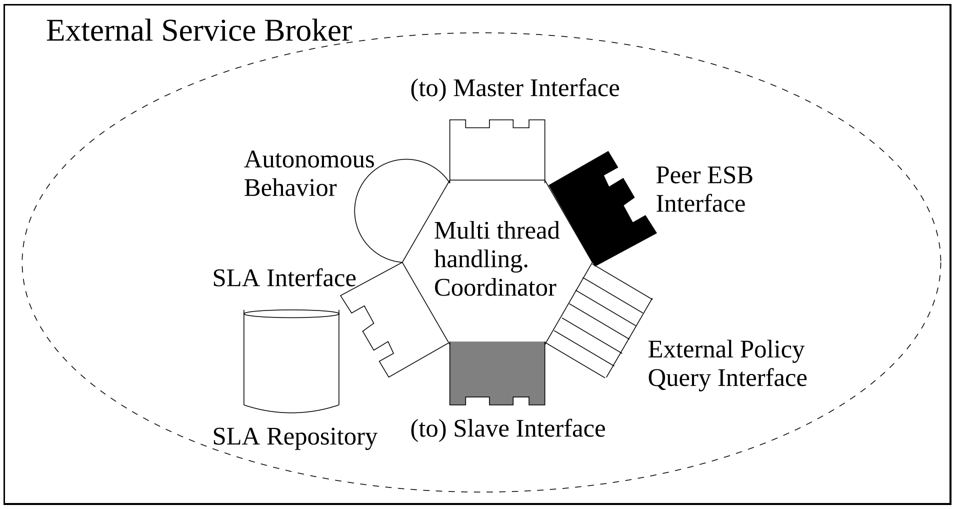

Figure 2.4: The external service broker.

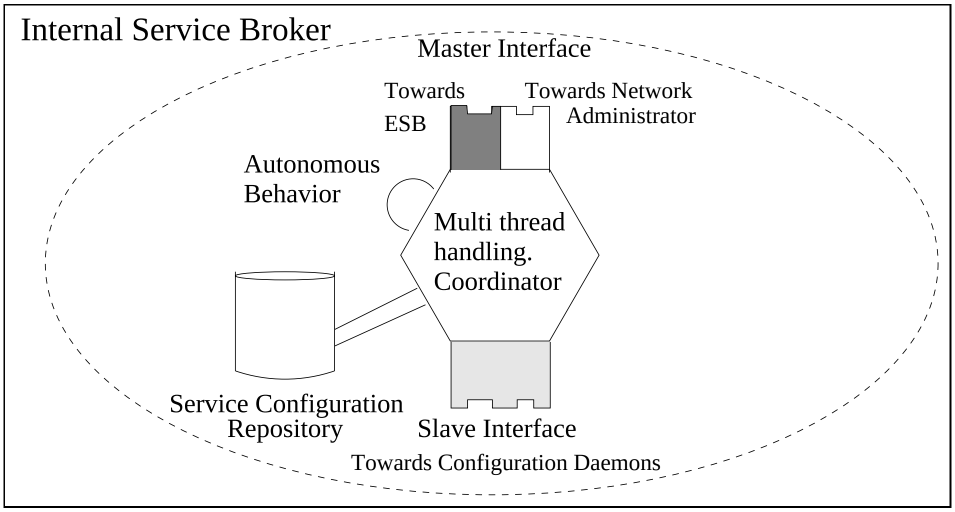

Figure 2.5: The internal service broker.

Element Managing Agent

The element managing agent (see figure 2.6) is controlled by its master interface (usually by an ISB). It can log its configuration actions and may use this log for rollbacks of configurations. Only a simple coordination module is necessary unless the underlying network equipment is hard to configure on-line. The EM can support a limited autonomous behavior for monitoring and notification of the network equipments state. The EM includes several modules for the support of different services (e.g. a tunnel establishment module or a DiffServ classifier configuration module). The slave interface of the EM depends on the the managed network element. If security would not be an issue here, the interface could use e.g. Telnet. Another possibility is to use the serial console port. Ideally, a secured management connection (e.g. SSH) to the network element exists.

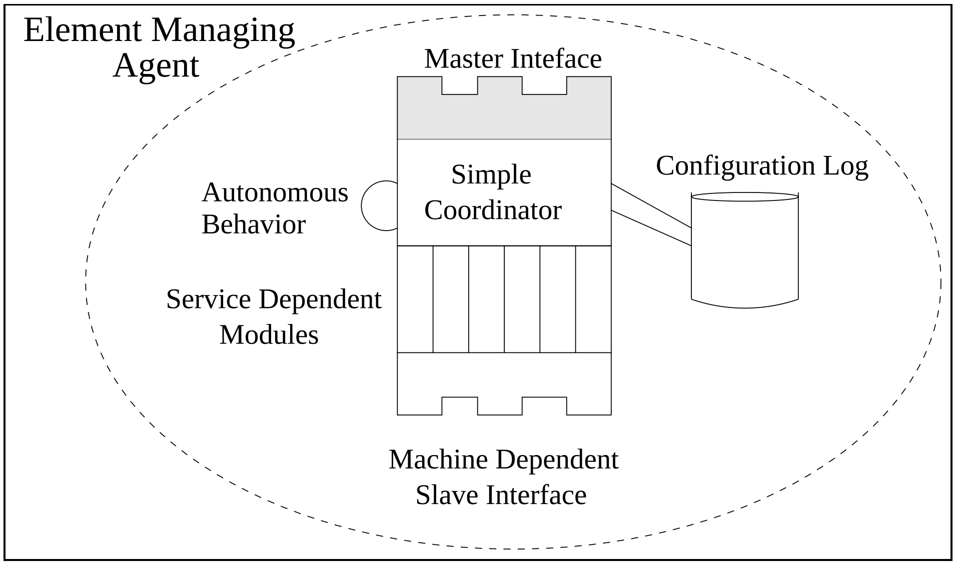

Figure 2.6: The element managing agent.

2.3.3 Interaction of the Components

The interaction of components is implemented with communication protocols. Note that there is no complete protocol suite for this service broker architecture available today. The next subsections describe the purpose of the different interactions between components.

Element Managing Agent - Network Equipment Interaction

The element managing agent (EM) is a configuration server specialized for a certain kind of network equipment such as one type of commercial routers from a specific vendor. It accepts a machine independent, abstract configuration request and then starts to interact with the network equipment through a secured channel. It uses whatever authorization and configuration mechanism the network equipment requires to satisfy the configuration request. The EM notifies when its network equipment has installed the new configuration. It can keep a log of configurations done or even a complete backup configuration.

Element Managing Agent - Internal Service Broker Interaction

The Internal Service Broker accepts requests concerning a service provided by the ISP's network. It uses an abstract configuration language to send configuration requests to EMs and waits for the correct establishment of the service at different places in the network. The configuration requests must be authenticated by the ISB. The ISB is responsible for guaranteeing that no two service requests that the ISB is handling interfere with each other. This can be complicated if an ISB is implemented in a distributed manner.

Internal Service Broker - External Service Broker Interaction

In order to handle external requests and agreeing on SLAs, an ESB must interact with the corresponding ISBs. It must be able to query the state of the current service configurations in the ISP's network. Furthermore, the ISP can signal changes to these configurations. The ESB must wait for ISBs to react, and coordinate their effort to provide given services before it can complete its negotiation with peer ESBs of adjacent providers. Note, that the brokers for each new service may use different (even proprietary) protocols to interact since there is no need for standardization of intra-domain management.

ESB - ESB Interaction

This is the most complex of the interactions we are going to discuss. Like in the previously described interactions we need an authenticated and possibly private connection between the ESB peers. This is more complicated to establish since the peers are not in the same domain. Therefore, the peers do not trust each other. In the interaction between two brokers, one broker plays the role of a customer (client) the other one the role of a provider (server). The ESBs store and manipulate SLAs. The ESB-to-ESB communication must be standardized because different broker implementations of different vendors must be able to communicate with each other. The communication protocol must be flexible to facilitate a rich negotiation scheme and various service descriptions. It must be extensible so that future IP services can be deployed easily. Here are some tasks that the ESB-ESB protocol should support:

- Advertise services (asynchronous)
- Query SLAs and their state.
- Negotiate SLAs.

- Establish SLAs.
- Cancel SLAs.
- Renegotiate/update SLAs.
- Regulate payment.
- Trigger error/ recovery procedures

Note that the ESB also communicates with other entities such as a network administrator and various policy databases (e.g. for pricing, authentication, action triggering thresholds etc.).

Composite Service Server Interactions

The composite service servers (CoSS) can be seen as an stub that has access to several ESBs. Their structure and interaction patterns very much depend on which services they bundle.

Customer - Customer Server

The Customer Service Server (CSS) must be accessible by a well known protocol such as HTTP. A customer contacting the CSS can choose a stub ESB for the desired service. With this graphically enhanced stub ESB the customer can negotiate a service level agreement. Note that the stub ESB has only reduced ESB functionalities, it cannot signal local ISBs or accepting another ESB as its customer. An Interaction Example for Provisioning a New Service A user learns about a service provided by an ISP through the WWW. She loads a GUI enhanced stub ESB (e.g. a Java Applet) which can invoke the appropriate ESB. The stub ESB lets the user negotiate with the ESB and visualizes the results. In general, the interaction takes place between the stub ESB (customer, controlled by a human) and the ISP's ESB (broker, automated) as follows:

1. Customer: Authenticated service request.
2. Broker: Answers a list of service forms. This list may include exemplars and partially pre-filled forms.
3. Customer: chooses and requests a form. Broker: sends form.
4. Customer: sends back the form now containing the parameters of the service requested.
5. Broker: internally checks the cost of the service (may also turn the request down rightaway).

6. Broker answers the cost of the request. Along with the message the broker may suggest a payment method.
7. Customer: accepts or rejects. May also start renegotiation. Here, a variety of negotiation schemes can be implemented.
8. Customer: triggers the payment method and signals acknowledgment.
9. Broker: provides the service and acknowledges the customer upon establishment.

Note that the forms contain unique identifiers. The customer must keep these identifiers in order to cancel the service contract later. The cancellation can be done with a single authenticated message to the broker. This description of the interaction between components allows us to derive a more detailed picture of the components of the architecture.

2.3.4 A Broker Signaling Protocol (BSP)

This section presents how the components exchange messages to accommodate service requests. The exact format of the messages is not specified in detail here but the section describes the message types, sequences, and proposes a generic message syntax.

The broker signaling protocol has the following requirements:

- It must be extensible. The protocol must be able to cope with new and emerging IP services. The protocol should be capable of describing the various service parameters of emerging services.
- The protocol must cope with synchronization problems. The service brokers will allocate resources in a distributed fashion thus synchronization is needed and must rely on the communication between the brokers.
- The protocol must be secure (see section 2.3.7).

The messages of the broker signaling protocol are exchanged top down (ESB (client) → ESB (server) → ISB → EM) and bottom up (EM → ISB → ESB (server) → ESB (client)). There are six message types: queries, requests, commitments and cancellations go top down, replies and notifications go bottom up.

Message Types

- **Queries.** A broker requests information from a peer or subordinate component about the service that the query target provides.
- **Request.** A broker announces that it will order a given service. Upon a request, resources for the service will be reserved, but the service will not yet

be established. This is the first part of a *two phase commitment* (as needed for distributed databases [RSS81]). A request number will be assigned with which the announced service request can be identified.

- **Commitment.** This communication message activates the service under the given conditions. Commitments are only accepted after a successful request. The commitment may carry the payment for the service. The commitment carries the request number of the request that it refers to.
- **Cancellation.** A broker cancels an established service or a service request.
- **Reply.** This message type carries the reply of a peer or subordinate component, e.g. the results of a query or the acknowledgment of a request.
- **Notification.** A subordinate component sends information updates that were triggered by a third party (e.g. a warning about a network congestion).

The two-phase commitment ensures the consistency the configuration of a service. In the request phase, the ISB takes care that the service to be established is consistent with the already installed services. This happens at many places in the network an may thus fail at some places. When the request phase terminates successfully, the service can be established by a commitment message which should not fail unless something drastic[2] has happened. The message sequence of both the request as well as the commit phase is the same. Here are the processing steps of a request message from the point of view of an ESB:

1. The ESB checks if the request is policy compliant (admission control). If not it replies a rejection message.
2. Then, the ESB forwards the request to the local service management (the ISB). The ISB tries to allocate the necessary local resources and replies whether this was successful. If not, the ESB replies a rejection message to the requesting party.
3. The ESB decides whether other provider networks are affected and if so it forwards the appropriate request to the involved ESB(s). If all involved peer ESB return an acknowledgment the ESB returns an acknowledgment.

Here is the processing of a commitment (see also figure 2.7):

1. The ESB checks if the commitment matches a successful request.
2. Then the ESB demands commitment for the local deployment of the service to the ISB.
3. The ESB also demands commitment from the involved peering ESBs.

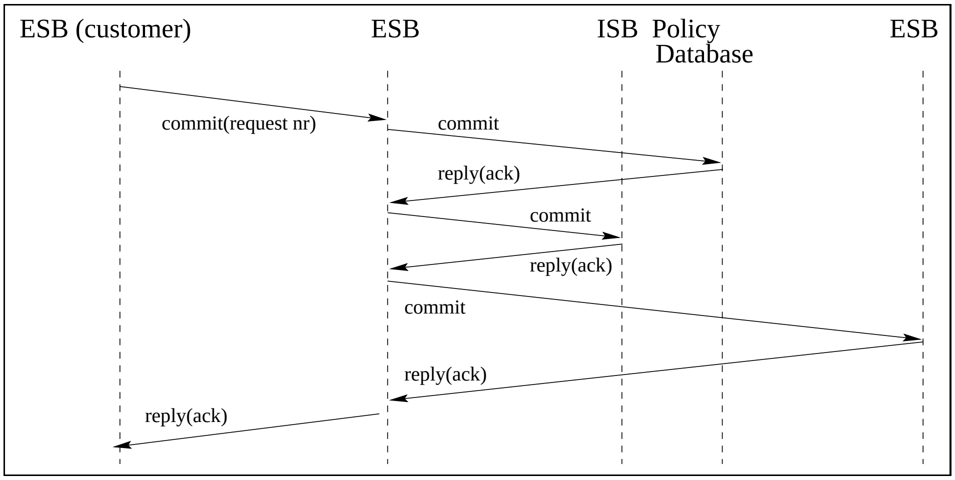

Figure 2.7: A successful request for a service establishment.

The domain internal forwarding of these messages may be implemented with various management protocols. Yet, the messages between ESBs cross domain boarders and thus need standardization. The main goal of these messages is to manage service level agreements between providers.

Contents of a Service Level Agreement

Here is the SLA definition that we developed for the CATI project. A service level agreement consists of a mandatory part and a procedure how to extend the agreement. Here's the mandatory part:

- The two involved business partners (legal entities).
- A service type identifier (e.g. VPN, DiffServ).
- The scope of the service.
- IP-addresses possibly using wildcards or autonomous system numbers.
- A service description, containing the concrete parameters of the service (e.g. delay, bandwidth, security level, tolerance level). May contain statistical statements such as: 99.9 percent of the customer's traffic presented to the provider of the service will experience the described treatment.
- Calculation base for the price (e.g. fixed costs, costs depending on reservation amount, costs depending on usage of service.)
- Start time and end time of the SLA.

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[2] For example destroyed infrastructure due to a natural disaster.

- A digital signature or certificate covering the whole contents of the SLA.

Here are some optional fields:

- Identifier for this SLA, which is unique to the SLAs of the SLA peers.
- Payment method description.
- Reimbursement method (e.g. in case of not delivered services).
- General terms of contract.
- Metering functions/ control procedures.

Note that these fields are rather pointers (e.g. URL) than complete descriptions of procedures. However such descriptions should be stored in trusted third-party locations.

Broker Signaling Protocol Message Syntax

The broker signaling protocol needs a flexible way of describing data. This is necessary because the SLA and especially the parameters of the service description to be negotiated are not known in advance. Therefore, a binary data format with fixed field lengths is not the appropriate choice. Instead, the proposed BSP protocol is byte oriented and uses three special bytes as listed in table 2.1. During transmission each protocol entity is surrounded by the byte value 123 indicating the start of an entity and a byte value 125 indicating the end of an entity. Whenever one of the three special bytes occur inside of an entity, the byte is preceded by a byte with value 92 (escape character).

Table 2.1: BSP special characters

Byte value	ASCII	Purpose
92	\	Escape character.
123	{	Start of a protocol entity.
125	}	End of a protocol entity.

The BSP protocol defines 5 data-types: *Entity, Collection, Object, List, and ObjectCollection*. All types other than the *Entity* are sub-types of *Entity*, thus all other types are BSP entities. *List* and *ObjectCollection* are sub-types of *Collection*. This situation is depicted in figure 2.8.

The sub-type inherits the byte structure of its super-type. The BSP data type *Entity* consists of the start byte, then a type byte (indicating one of the 5 data-types), and an arbitrary number of bytes followed by the end byte. Since all BSP types are sub-type of *Entity*, they are all structured like *Entity*.

Here is a list of the sub types of the BSP entity:

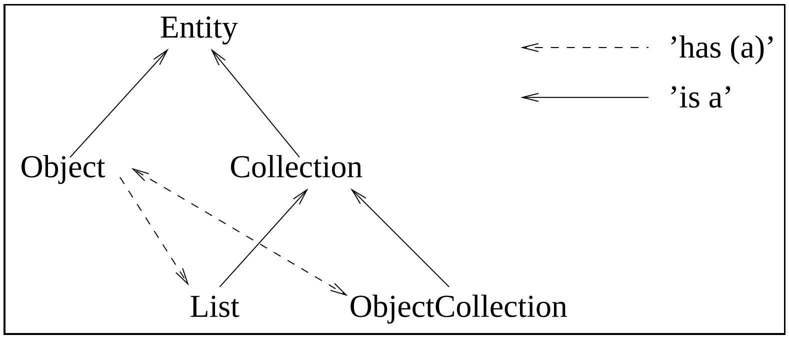


Figure 2.8: The BSP object types.

- **List.** Like all BSP entities the BSP list is surrounded with the start and the end byte and the second byte indicates the type of the entity. The type byte value for lists is the ASCII value for the letter ‘L’. The next byte of the list is interpreted as a contents type, followed by a byte stream of arbitrary length. The content type byte tells what primitive data type the list represents. Currently defined are the following byte values (as ASCII character values): ‘A’ for an ASCII string, ‘B’ for raw bytes, ‘H’ for a hexadecimal number, ‘E’ for a floating point number, ‘I’ for an IP address, ‘D’ for a date.

- **Collection.** The BSP collection represents a list of entities. The BSP collection is not used directly, but its sub-types *List* and *ObjectCollection* are.

- **ObjectCollection.** This entity holds an arbitrary number of BSP objects. The BSP type byte value for BSP object collections is the ASCII value for the letter ‘C’.

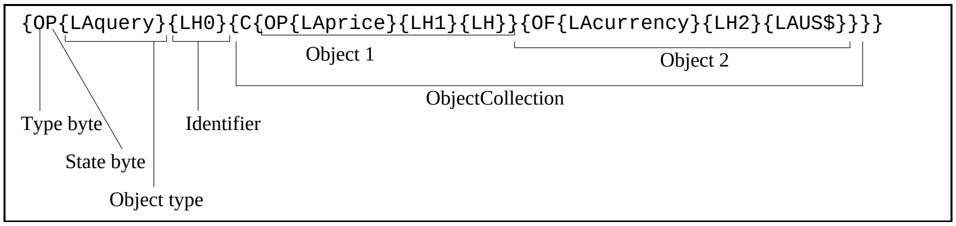
- **Object.** A BSP message (e.g. a query, a reply etc.) is encoded as one BSP object. The type byte value for objects is the ASCII value for the letter ‘O’. The next byte of the object is interpreted as the state of the object. Then there are two *List*s and finally a *Collection*. The state byte is used for the negotiation of service parameters. It shows the negotiation state of the particular parameters that are encoded in this BSP object. The first of the two lists within an object encodes the object type of this BSP object. The second list encodes an identifier of the object. Finally, the collection holds the contents of the object. This is either a *List* or an *ObjectCollection* consisting of a list of BSP objects. The *ObjectCollection* allow the BSP peers to construct complex data structures. An object of such a collection is also referred to as *field* of the object in which it is contained.

BSP messages as BSP objects. BSP messages (see section 2.3.4) are encoded as one BSP object. The BSP object type identifies the BSP message type. The BSP object identifier allows the BSP peers to keep track of the exchanged messages, for example to match a commit message to a previous request message. The IP service parameters to be negotiated can be encoded as fields (or fields of fields etc.) of the BSP message. With the BSP syntax arbitrary complex object hierarchies can be constructed, thus any kind of service parameter can be described.

BSP object state. The BSP object state byte shall allow the peers to dynamically negotiate the service parameters. Here are the currently supported states (noted as ASCII byte values):

- *Fixed* (value ‘F’): The contents of this object should not be changed during negotiation.
- *Please complete* (value ‘P’): The contents of this object is not complete and should be completed by the receiver of the object.
- *Erroneous* (value ‘E’): The contents of this object is flawed.
- *Unknown* (value ‘U’): The structure or contents of this object could not be interpreted.
- *Informational* (value ‘I’): The contents of this object may be ignored.
- *Omitted* (value ‘O’): The contents of this object was ignored.

Example. Figure 2.9 shows a simplified example of a BSP message. The message is encoded as an object with the identifier number zero (the number being encoded as a list of bytes that contain a hexadecimal number). The state of the object indicates that the receiver should insert missing parameters. The message is a BSP query as a customer may send it to a service broker. This is indicated by the BSP list that encodes the object type. The message contains an object collection with two fields (BSP objects). One field is incomplete. It contains a price object with an empty list that is supposed to contain a number (the price). The second field is fixed and it indicates a currency that shall be used for the answer to this query.



```
{OP{LAquery}{LH0}{C{OP{LAprice}{LH1}{LH}}{OF{LAcurrency}{LH2}{LAUS$}}}}
```

Figure 2.9: Example of the BSP message syntax.

Implementation of a BSP parser. The object-oriented implementation of a BSP object parser is straight forward. You implement an object hierarchy that mirrors the BSP type hierarchy (see figure 2.8). Each class must contain BSP type specific code to export itself to a byte stream and to parse itself from a byte stream. BSP entities that consist of other BSP entities parse their specific type bytes and delegate the parsing of the sub-entities to the respective classes.

Note, that BSP objects should be encrypted and authenticated. The work in [Gra00] describes how BSP messages can be secured (see also section 2.3.7). For more details of the BSP message syntax see [BG99].

The BSP protocol is now also being used by the StreamCom project [STR] for the communication with a DiffServ broker.

2.3.5 An Example of a New and Valuable Service: Quality-of-Service enabled VPNs

The reason why we introduced the generic service broker architecture was that our research was focusing on more than one network level service. The architecture should not only support both VPN and DiffServ but also a combination of both. Such a bundling is both feasible and economically interesting.

The major competitor of IP-VPNs are private leased lines (Frame Relay, ISDN). While the leased lines are more expensive because the user has to pay even when not using the line, they usually come with guaranteed QoS. Enhancing todays VPN solutions with QoS will eliminate the IP-VPN's only real disadvantage compared to the leased line solutions. Currently, the most promising technologies for implementing such a QoS-VPN service are DiffServ and IPSec. Differentiated services technology seems to be simple enough to enhance VPNs without restricting the global reachability of the Internet or without introducing scalability problems. In order to ensure interoperability between these technologies, the tunnel endpoints and the ISP ingress nodes must be located in the same machines. Otherwise, the tunneling and encryption of the VPN service may hide information necessary for DiffServ. But if an ISP provides both the VPN service and DiffServ support together, then it can unify the tunnel endpoint and the DiffServ border router. Although DiffServ and VPNs are two different services, they have similar concepts and can enhance each other: DiffServ can provide QoS guarantees for a VPN as a whole or it can be used to differentiate the treatment of traffic classes within a VPN. VPNs are traffic aggregations with known traffic destination points. DiffServ also operates on traffic aggregations. The fact that VPN tunnel endpoints are known and relatively static can furthermore ease the specification of the service level agreements [DGG$^+$99]. DiffServ and VPNs both need enhanced functionality of border routers of the ISP but not of intermediate routers. Both share some similar functionality in the border routers, e.g. the traffic classification. The simplicity and the coarse grained traffic classification make DiffServ a scalable technology. DiffServ is therefore suitable for the QoS support between different ISPs. On the other hand, a VPN tunnel that crosses intermediate ISPs is transparent to them and therefore does not allow fine grained QoS support.

Figure 2.10 shows an instance of the broker hierarchy which is able to provide QoS enabled VPN services. The customer contacts a service server that bundles QoS features to the VPN service. The external broker for VPN services can negotiate the implementation of a tunnel endpoint. The external QoS broker arranges resource reservation in other involved networks. The network devices support IPSec VPNs and DiffServ QoS support. The appropriate ISBs transform the service request they receive from the ESBs into IPSec and DiffServ configurations.

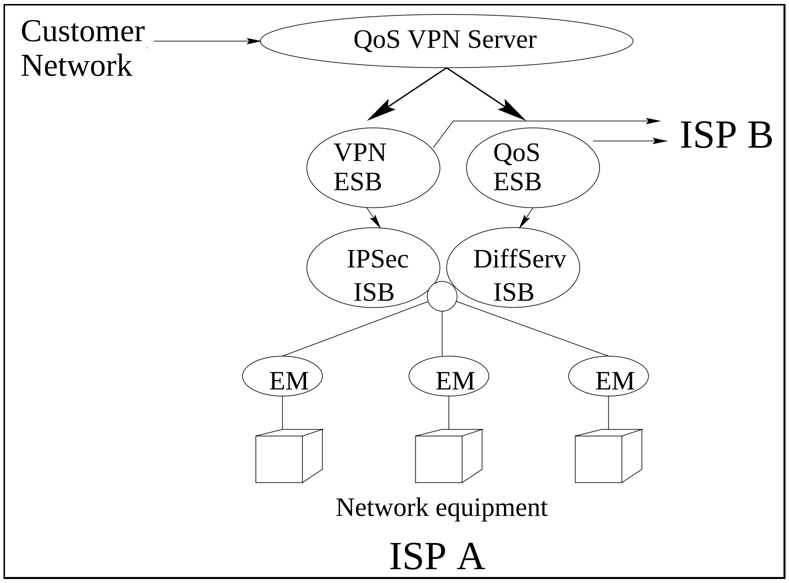


Figure 2.10: The broker hierarchy for establishing QoS VPNs.

Figure 2.11 shows a QoS enabled VPN tunnel that was set up through broker driven collaboration of several service providers.

2.3.6 Charging and Accounting Enhanced Services Operation

Our architecture does not restrict the choice of a payment method or pricing model to a given solution. In this section we discuss the access points for ISP individual charging and accounting modules. From a high-level view revenue is generated as follows. A customer (administrator of a customer premises network) needs an IP network service (e.g. wants to set up a branch office VPN). The customer is willing to pay for that service. This will be the revenue source. The customer contacts his ISP on-line via the ESB. It negotiates the service and the payment (price specs including payment method). In general, the initial deployment of the service will cost the customer a one time fee. In order to propose a price for the service, the ESB needs to check whether other ISPs are involved and ask their ESBs what they would charge. This leads to a query chain that involves all participating ISPs and results in the distribution of the revenue. Finally the customer agrees on a SLA.

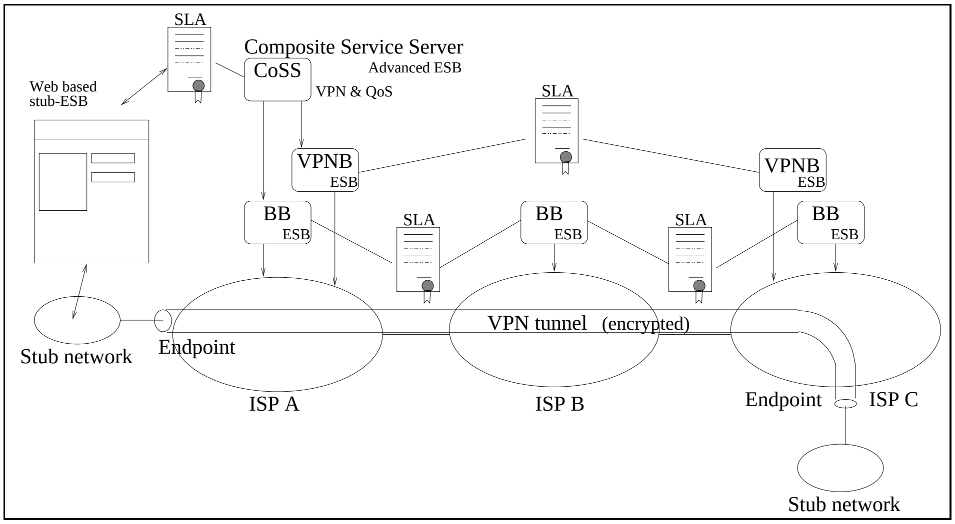


Figure 2.11: A multi-provider QoS enabled VPN.

From now on, the customer pays a flat- or usage based fee as negotiated in the SLA. The revenue is shared by the involved ISPs as described implicitly in the SLAs between the ISPs. The following subsections describe the different charging aspects.

One Time Charging

As mentioned before, the ESB - ESB communication may not be free of charge. The query messages can be served for free or for a small charge. The request and the commitment messages must contain a payment (digital cash) or a promise for a payment (e.g. digital checks). Cancellation of services may be subject to charging if this is legal. An ISP in the role of a service seller must take into account, that it may have to use other ISPs services and pay for them, when it prices its service. Beside of that, it is free to define its pricing policy for ESB-ESB communication. For example it might even reimburse costs to its customer when the customer decides to commit to the service. The ISP would then generate its revenues by continuous charging.

Continuous Charging

The price continuously charged for the provided configurable service is specified in the SLA. Thus the SLA record structure must be flexible enough to represent a vast variety of payment schemes. It may contain a usage and time of usage based price specification. Attributes can be bandwidth, peak traffic, total traffic, daytime and many others. The payment method must also be specified. When an ISP classifies incoming traffic (e.g. for tunneling or DiffServ marking) it can also account it. Later, it can accumulate the continuous costs for a customer by using this accounting information and the appropriate SLA price specification.

Cost Calculations

In the case of an end-customer, a human will probably decide whether a SLA is acceptable. On the ISP side however the ESB must be able to automatically handle most of the negotiations. Only in few cases it should be necessary to contact a human administrator. This is one of the big challenges for ESBs. The ISP is supposed to have its pricing models and policies available for the ESB. Upon a service request the ESB will contact other ESBs and also check with the local ISBs how much work and cost the request generates. Based on that it should be able to calculate a competitive price specification for the service. In this field, intelligent agent research results may be applied successfully. However, such business intelligence is out of the scope of this thesis.

2.3.7 Security Issues

This section discusses vulnerabilities of- and protection mechanisms for the components and interactions of the architecture.

General Security Observations and Conclusions

Some observations:

- Security adds overhead (it lower performance and increases management complexity).
- Threat potential compared to security overhead should be in a reasonable relation to each other.
- In general, the threat potential is underestimated.
- Threat potential composes of effort needed by an attacker to cause damage compared to the size of that damage. The size of the damage must also incorporate the time and effort to detect and repair the damage.

We can conclude that not every component and interaction necessarily needs the maximum of security mechanisms available. Looking at the architecture it is obvious, that the lower layer components and interactions (e.g. EM to network equipment) need less protection that the upper layer components. Of course, care must be taken that a security breach in the lower part of the architecture cannot corrupt the upper parts.

Simple but Mandatory Security Measures

The implementation of security measures depends also on the implementation of the architecture. This section discusses an implementation variant, that foresees the implementation of one (or more) architectural component as processes running on a server. Interaction between components not running on the same server use dedicated communication media, or if that is not available, they use the underlying[3] Internet infrastructure. Whenever possible, the infrastructure (servers, communication medium) should be physically protected. Servers should be located in secured areas, where only authorized personnel has access. Their access points should also be protected. Of course this is hard to accomplish for all network devices (routers/switches) of an ISP and completely impossible to accomplish with interconnecting communication lines due to the geographic extent and the number of equipments to protect.

Basic Security Measurements for Network Equipment and Components Implemented in Hosts.

- Internal network equipment (Routers / Switches) do not need extensive protection. A minimal physical protection (e.g. against theft and demolition) as well as the protection provided by a modern operating system can suffice. This holds also true for hosts running EMs, which are usually located near the equipment that they manage.
- Network equipment (and its EM) at the boundary of the ISPs domain must include (see later) additional security functions. Therefore they need stronger physical protection.
- Servers running brokers (internal and external) need strong physical security measurements. Intrusion of unauthorized personnel must be very hard to achieve. Authorized personnel must be monitored. Additional hardware mechanisms, such as an automatic alert (or even an emergency erase of the memory) in case that somebody physically opens the server, as well as special operating system support is necessary.
- The availability of network components can be improved by redundancy.

Note that all network devices should run an operating system which includes user authentication and protection of the local resources such as processes and storage. There should be a regular maintenance of the installed operating system.

Basic Security Measures for the Management Communication. Unfortunately, it is much harder to physically protect communication media. Still, some techniques are (or will become) available.

---

[3] An ISP should have Internet access.

- In case of short-distance connections (such as a connection from the EM to its managed device) the whole area may be physically secured (a secured server farm).
- Static management lines may be protected using link-layer cryptography techniques.
- Static management lines may use new fiber-optic based connections which are completely secured by quantum technology [TGG98].
- If management communication is in-band with data transfer, the ISPs have to ensure at their borders, that no management traffic (e.g. Telnet) bound for internal network equipment is allowed to enter the domain from external interfaces. Furthermore, the border routers discard traffic, that arrives at an exterior interface but pretends to be coming from the inside the domain (IP spoofing). With such a (relatively simple) firewall around its domain, the ISP can rule out many possible attacks.

Nevertheless, the communication between the components imposes the biggest security problems in the broker architecture.

Securing the Management Communication

The broker architecture imposes several management communication infrastructures. Unfortunately, (from the perspective of security) some of these communication infrastructure must rely on the data transport infrastructure. In our case this is the IP network that can also be used to transport management traffic (in-band). Special care must be taken, to protect management traffic from data traffic. Cryptography is the only solution for secure in-band management traffic available today. Figure 2.12 shows the components and communications of the architecture. We assume that the security measures described in the previous sections are installed to sufficiently protect the components. The management communication infrastructures depicted here can be physical or virtual lines. They can be in- or out-of-band and they can use specific protocols. The security of the architecture depends on how these protocols are implemented. Usually, the simple measures described earlier cannot fully protect the management traffic. In that case cryptography needs to be deployed [Sch96].

Intra-ISP communication management infrastructures

All management communication infrastructures except of the ESB-to-ESB communication (inter-ISP management communication) is within the responsibility of the service provider. If the provider neglects its internal security, it will mostly hurt itself to the point of going out of business. This section discusses requirements and security measures of this intra-ISP management communication. We start from

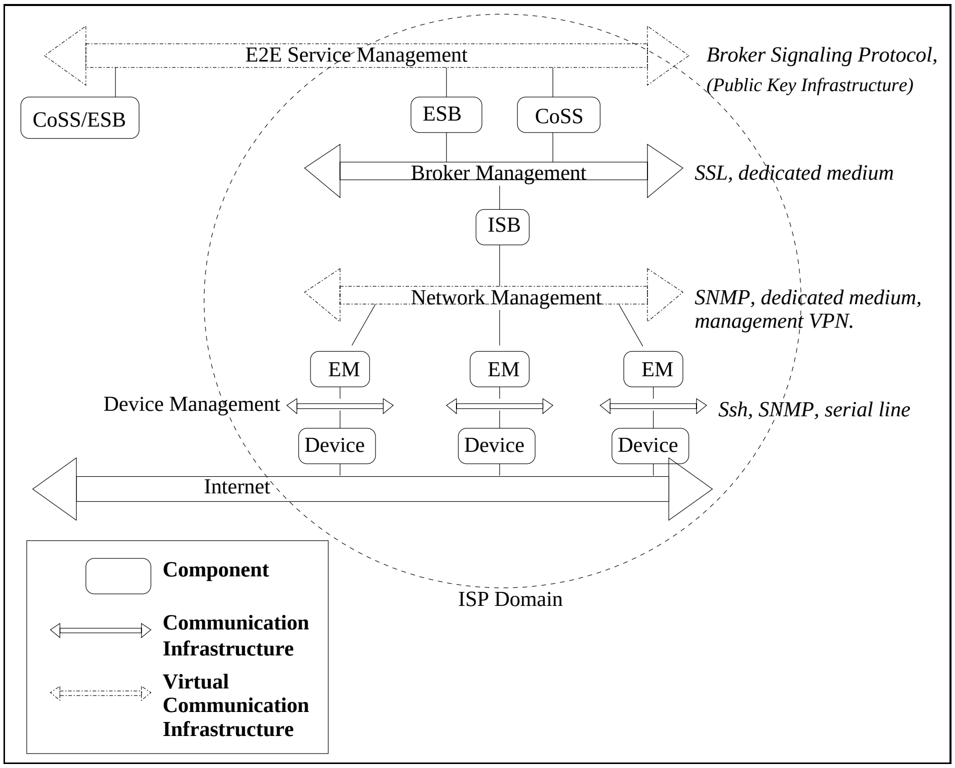


Figure 2.12: Components and communication in the broker hierarchy.

figure 2.12 in a bottom-up fashion The Internet is inherently insecure. All network equipment must be configured to accept management requests only from the device management infrastructure. This can be realized by blocking all management access from public interfaces and having a dedicated management line (e.g. serial cable) on a dedicated interface. Another possibility is only accepting configurations via secured shells (ssh).

The network management infrastructure must span the whole network under the ISP's control. It must be able to reach each EM. Thus, the network management medium is responsible for the dissemination of the management traffic. It is therefore very likely that this kind of management traffic must be in-band with the data traffic. Management protocols with built-in security features exist for exactly that purpose (e.g. SNMPv2). In order to increase the security, the network management infrastructure can also be implemented as a virtual private (management) network owned and used exclusively by the ISP. IPSec (see section 1.2.2) can be used to connect the ISBs host machine to the different hosts of the EMs.

The broker management communication infrastructure exposes a large threat potential, since external brokers have the authority to handle payment and charging information. Furthermore, a broker (that was corrupted via broker management) can misconfigure the complete network of the ISP and order misconfigurations of other networks in the name of the ISPs. Thus we propose to physically protect the broker management communication, by having the brokers running in the same protected area. Furthermore, (and especially if brokers need to be physically separated) the strongest available cryptography should be used. This includes the use of long keys (128 bits symmetric keys, 2048 bits for asymmetric keys) and the frequent refreshment of the keying material. Proprietary as well as open solutions for such application layer security protocols exist.

As mentioned before, the ISP can select the technologies of its own choice to implement and secure the internal parts of the broker architecture. However, for the establishment of end-to-end services an external broker communication protocol is needed, which must be standardized (see below).

The Security of the ESB-to-ESB Communication

The communication between peering brokers crosses the border of two administrative domains. Therefore, the communication has particular security requirements:

- **Authenticity.** Authenticity is the proof of the identity of a communication partner. The ESB protocol must allow the broker to authenticate itself as the intermediary of a service provider.

- **Integrity.** The brokers must be able to verify that the protocol data has not been changed in transit.

- **Confidentiality.** This is a nice-to-have feature. Nevertheless, confidentiality may not be necessary for some services. It is even possible that confidentiality is ruled out by local laws that enforce an open market or that forbid the use of strong cryptography for communication encryption.

- **Non-repudiation.** Once the ESB communication has led to the establishment of an SLA, both communication parties should be able to proof the other party’s commitment.
- **Availability.** The ESB communication protocol should discourage denial-of-service attacks.

Securing the ESB Protocol is a typical case of applying application layer security mechanisms. Integrity, authenticity and non-repudiation can be achieved by the brokers themselves by adding digital signatures to each message exchanged. The signature can be a message authentication code computed using a secret key only known by the sending broker and a Certificate Authority (CA) in the Public Key Infrastructure (PKI) and the contents of the message using a secure hash function. Upon request, the certificate authority can validate the message for the receiver. If the message was changed, or the wrong key was used, the message can be discarded. Another possibility is that the customer and the provider exchange public keys, which are certified by the PKI. Then, they can verify the authenticity of the exchanged messages without further interactions with the PKI. A PKI is useful for many other applications, too. Today, PKI become available. Yet, they are not subject of this thesis.

The receiver can store the messages of the sender in order to be able to prove that the message was sent (e.g. an order for a service was made). Note, that one message typically contains the payment method and a trusted payment provider. Having agreed on a trusted payment provider allows the settlement of abuse concerning payment (e.g. late payment, acknowledgment of payment that took place). A customer can also prove, that a provider sold a service with certain guarantees (e.g. guaranteed bandwidth). With the digital signature the receiver can verify and prove, that the sender has sent this message (e.g. request for a service or acknowledgment of a service) at least once. However, an attacker can record the message and send it again (e.g. request a service a thousand times). To prevent such replay-attacks, the message must contain an sequence number and a time stamp. The overflow of this number should happen infrequently (only after years), so that the service duration has exceeded already, when an attacker can safely replay the message.

2.4 Implementation of Service Brokers

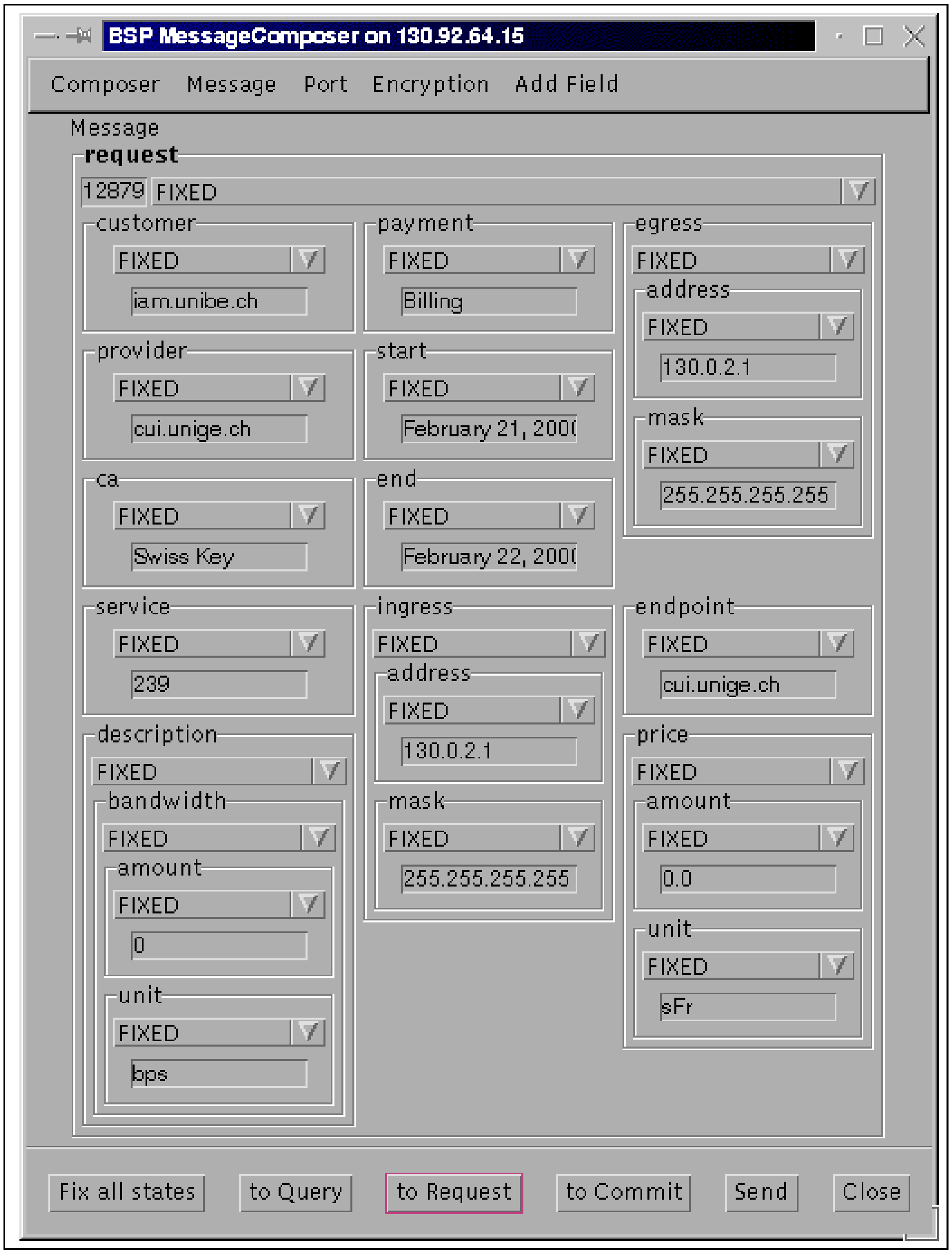
The proposed architecture was never fully implemented. The reason for that is twofold: First, implementing a complete version that ’solves’ all multi-provider problems was beyond our capacities. Second, only a consortium of large Internet providers can enforce the large-scale deployment of such a system. Nevertheless, the architecture led to several partial implementations in the area of DiffServ and VPN services. This section I presents two of these implementations.

2.4.1 A Bandwidth Broker Prototype implementing the Broker Signaling Protocol

In the Diploma work [Gra00] we developed a prototype of an external broker that is compliant with the architecture presented in section 2.3. The implemented broker is structured as it was depicted in figure 2.4 (see section 2.3.2). The prototype implements the broker signaling protocol (BSP - see section 2.3.4) in order to evaluate its flexibility and extensibility. DiffServ specifications can be represented as object hierarchies in order to be transmitted. The protocol allows the dynamic refinement of specifications using the state byte of the objects. Thus, the brokers can negotiate during several rounds and propose different kind of representations for specifications until both parties are satisfied. The communication protocol is secured using PGP [Zim01]. The prototype can be used to establish DiffServ SLAs as described section 2.3.4. However, the implementation does not include an underlying internal agent hierarchy (ISB and EMs). Nevertheless, the implementation also contains a customer GUI that allows the customer to dynamically guide the SLA negotiation process. The GUI dynamically updates its layout to represent any kind of BSP object hierarchy. Thus a user can interactively steer the service negotiation process. Figure 2.13 shows the GUI window for the composition of BSP message. Here, a user has composed a BSP request for an expedited forwarding SLA (encoded as service number 239). The request includes the customer and the provider ID, a proposed payment method, a proposed Certificate Authority (CA), the geographic scope of the service (service ingress and egress points), the temporal scope of the service (service start and end time), a price field, and a service description field. Note, that the GUI shows the object hierarchy by putting the fields of the objects into framed boxes. The service description, for example consists of two sub-objects (the bandwidth amount and the bandwidth unit).

2.4.2 A Prototype Implementation of Brokers for QoS-VPNs on Demand

Within the CATI project (see section 2.1) we have developed a prototype system [KBG00, BGK01] to demonstrate dynamically establish QoS enabled VPN tunnels. Upon customer requests the system can of generating user records. The implementation focuses on the single-provider case. This eased the implementation since the ESB-to-ESB interaction can be neglected. We implemented the remaining functionality of the ESB and the functionality of the ISB into a central component simply called Service Broker (SB). This broker is the heart of our VPN management system that acts as a QoS manager to optimally configure network resources and adaptively decides based on user preferences and resource availability. These decisions could take place with minimum user intervention with respect



Message

request

12879 FIXED

- customer
  - FIXED
  - iam.unibe.ch
- provider
  - FIXED
  - cui.unige.ch
- ca
  - FIXED
  - Swiss Key
- service
  - FIXED
  - 239
- description
  - FIXED
  - bandwidth
    - FIXED
    - amount
      - FIXED
      - 0
    - unit
      - FIXED
      - bps
- payment
  - FIXED
  - Billing
- start
  - FIXED
  - February 21, 200
- end
  - FIXED
  - February 22, 200
- ingress
  - FIXED
  - address
    - FIXED
    - 130.0.2.1
  - mask
    - FIXED
    - 255.255.255.255
- egress
  - FIXED
  - address
    - FIXED
    - 130.0.2.1
  - mask
    - FIXED
    - 255.255.255.255
- endpoint
  - FIXED
  - cui.unige.ch
- price
  - FIXED
  - amount
    - FIXED
    - 0.0
  - unit
    - FIXED
    - sFr

Figure 2.13: The BSP message composition window.

to specifying the user's requirements. The customer contacts the service broker through a web interface. The web interface bundles the DiffServ support and the VPN support (see figure 2.14). The customer does not have to hassle with all possible configuration combinations. Instead, the customer can select from a couple of useful service bundles that were composed by the provider.

User ID: Password:

Source Address: Remote Address:

Tunnel policies for VPN

POLICY # 1	POLICY # 2
Strong Encryption, Strong Authentication Tunnel Type: ipsec-isakmp Transform: ah-md5-hmac esp-des	Authentication only Tunnel Type: ipsec-isakmp Transform: ah-sha-hmac
POLICY # 3	**POLICY # 4**
Strong Encrytion, Authentication Tunnel Type: ipsec-isakmp Transform: esp-des esp-md5-hmac	Encryption Only Tunnel Type: GRE Encryption des

○ Dedicated Bandwidth 1Mbps
○ Dedicated Bandwidth 2Mbps
○ Dedicated Bandwidth 4 Mbps
○ Dedicated Bandwidth 5 Mbps
○ Dedicated Bandwidth 1.54 (T1 Eq) Mbps

Figure 2.14: VPN Web interface

Our service broker interacts with a specialized element managing agents (EM) that adapts the configuration of a network device. Our EM it script based. We wrote EMs for a commercial router and for a PC based Linux router [BGKL00a]. The structure of the Service Broker is compliant with the presented service broker architecture but simplified (see figure 2.15). The basic operation of the system is as follows: based on the selection made by the user, the SB first contacts a SLA database to check the validity of the user and it's request parameters. It then checks with the connection database whether a similar requested connection (VPN tunnel) already exists or not. If this is not the case, the SB looks at its resource database to identify if the tunnel can be established. A positive answer would then lead to a tunnel establishment by the element managers. When a user disconnects the VPN tunnel, the SB releases resources and invokes the pricing database to calculate the pricing for that tunnel.

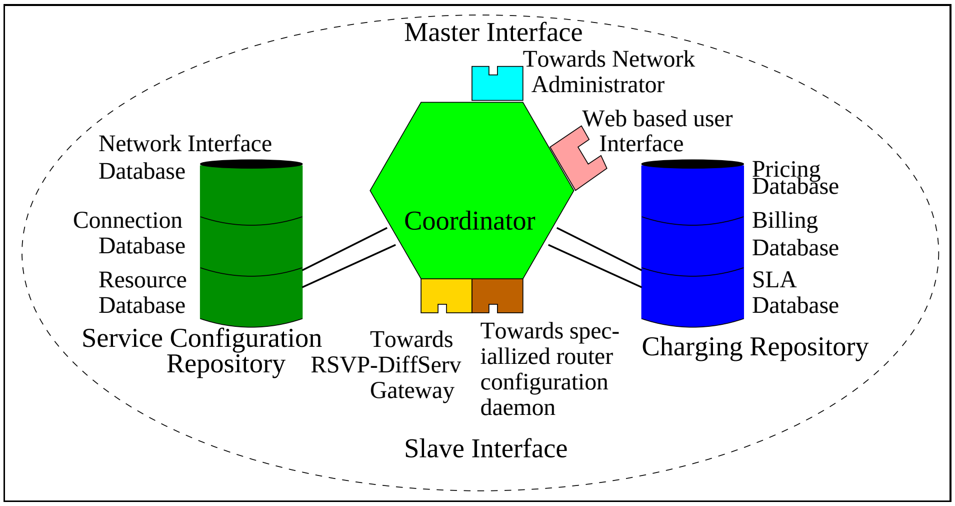


Figure 2.15: The structure of the implemented service broker.

2.5 Conclusions and Outlook

The presented service broker architecture refined the original proposal for DiffServ bandwidth brokers (see section 2.2). Instead of a single software agent that does everything the proposed architecture consists of a hierarchy of intelligent agents that are specialized to a specific task. These service brokers sell enhanced IP services on behalf of the Internet service provider organizations. The service brokers need to be: autonomous, rule-driven, heterogeneity hiding, distributed, collaborative, and interactive. Agent technology excels in providing these capabilities.

The proposed service broker architecture allows the provider to introduce and offer on-demand IP services. The agent architecture is layered according to the TMN reference model (see section 1.4). A novelty is the closer discussion of the communication between service brokers of peering providers which enables the provider to offer multi-provider IP services. The scope of such services is not limited to the network of a single provider but may span the whole Internet. Electronic service level agreements regulate the interaction between service brokers of peering providers. Service brokers use a broker signaling protocol to set up, renegotiated and cancel SLAs. The protocol can also support business aspects such as charging of the service and sharing of the revenues between collaborating providers (see section 2.3.6). Section 2.3.7 discusses the security threats that the architecture is exposed to and also countermeasures.

Two implementations used the proposed architecture (see section 2.4): A service broker for QoS-VPNs on demand and a external service broker implementation for DiffServ.

For DiffServ the inter-domain communication between brokers is particularly interesting. There is currently no consensus on how this should be done. The particular problem there is that the signaling complexity should not break the scalability of the DiffServ approach. The following chapter studies the problem in more detail.

Chapter 3

Differentiated Services Signaling

The broker architecture presented in the previous chapter automates and controls the deployment of multi-provider IP services. A multi-provider service is set up through brokers that communicate with each other. One instance of the service broker is the so called bandwidth broker for Differentiated Services that originally inspired the architecture. This section focuses on DiffServ because bandwidth brokers are the service brokers that will most probably be deployed. Furthermore, DiffServ broker communication has concrete and stringent requirements. For a given traffic flow potentially *all* brokers on the network path are involved. Also, the broker communication workload should not break the DiffServ philosophy of scalability. DiffServ was designed to scale to the size of the growing Internet. However, its scalability in the multi-provider case has not been studied. The communication (signaling) between the bandwidth brokers of different domains may become a problem. This study of real problems of the existing DiffServ bandwidth broker architecture may thus become exemplary for other multi-provider network services.

3.1 Signaling Granularity and End-to-End QoS

3.1.1 Trade-off

When the customer wishes end-to-end service guarantees for traffic that crosses several networks then DiffServ becomes a multi-provider service. This is for example the case when the customer wishes guarantees about e.g. latency and throughput that hold for his/her premium traffic independent of the traffic source or destination. Obviously, all network providers on the traffic path must reserve sufficient resources for such a service guarantee. As said before, the broker architecture proposes a chain of service level agreements that reflect the aggregated resource requirements on a per-peer basis. The service level agreements are set up in advance and can be updated by means of ESB communication (see section 2.3.3). Figure 3.1 shows an example of a working DiffServ scenario. Here, two host networks (H1 and H2) have each established an SLA with an ISP A for 500 Kbit per second guarantee for DiffServ traffic. They inject that amount of DiffServ traffic plus a large amount of best-effort traffic through fast access links. ISP A forwards all traffic to ISP B. The brokers of the two ISPs have already established a sufficient SLA (1Mbps) between them, thus the DiffServ traffic can continue on its path to the destinations. The link between ISP A and B is only of limited size, thus it can be congested. However, this congestion only affects the best-effort traffic.

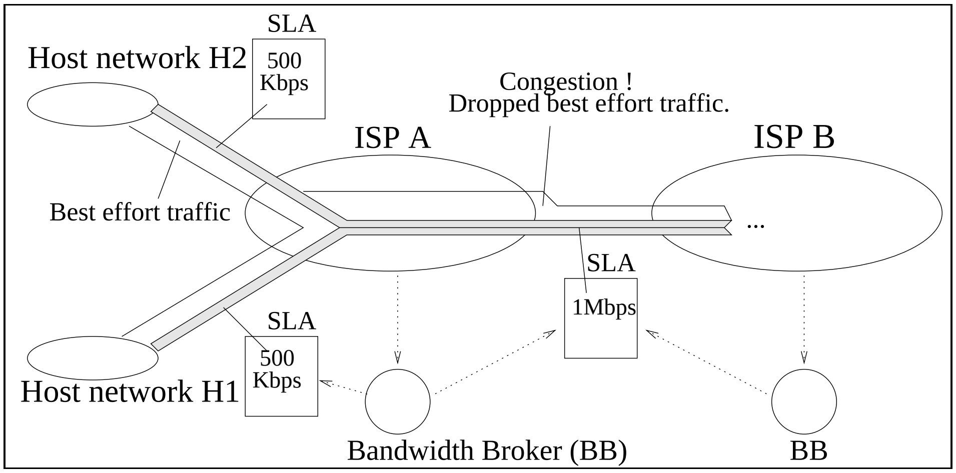


Figure 3.1: The ideal DiffServ scenario.

Unfortunately, the DiffServ architecture does not describe how the SLAs are established in the first place. The only thing said is that the brokers communicate with each other. The problem addressed in this chapter is how frequent such communication takes place and how the service guarantees and the scalability are affected. In one extreme case each customer application signals its QoS requirements to the bandwidth brokers of the access ISP. The brokers forward these requirements from one to another in order to assure end-to-end QoS. The advantage of this approach is that the application which knows them best) signals the requirements. Furthermore, the application may block the traffic and wait for an acknowledgment by the brokers. The brokers can thus perform a fine-grained *admission control*. The brokers have total knowledge about all traffic flows that they have to accommodate. However, this centralization of information is also a huge problem since a broker of a backbone network would have to keep track of millions of traffic flows. The Integrated Services architecture pursued this fine-grained QoS approach. Yet, it could not be deployed successfully in the global Internet because of this huge complexity it introduces to the Internet backbone management. It simply did not scale. The DiffServ architecture has been designed with scalability in mind. The DiffServ broker signaling must therefore be more coarse grained than the presented extreme approach. However, if the brokers do not have the fine-grained view of the network traffic demand then admission control is less efficient and end-to-end service delivery may be affected. This chapter is going to discuss alternative coarse-grained signaling schemes. It studies the trade-off between end-to-end service guarantees and scalability given a signaling granularity level.

3.1.2 Signaling and SLA Update Options

All of the options that follow are more coarse grained than the like IntServ approach. The traffic is not treated on a per-micro-flow[1] basis as in IntServ. All proposed signaling options deal with traffic aggregates. The fate of the IntServ architecture showed that this is necessary. So it is not the customer application that signals a micro-flow. Instead, customers negotiate SLAs with the brokers of their ISPs. These customer-provider SLAs may have various granularity levels, but they too should not deal with single flows but with traffic aggregates. They may for example deal with traffic between two IP addresses or even two autonomous systems numbers. The broker can react to customer SLA requests by updating its SLAs with peer providers and/or by signaling the event to them. Note, that the customer SLA request is thus used as an implicit signal. The SLA updates between providers can also be used as an implicit signal, but the following results show that this is not to be recommended (see section 3.4.1). Here are the three basic options for the reaction of brokers that are studied in the rest of this chapter: adaptive reservation, limited signaling and end-to-end signaling. The first two options were presented in [GB99] and the third option was discussed in [DGBS00].

Adaptive Reservation. The broker does not react to SLA changes. Instead, it constantly measures its SLA conformance. Once it sees that in fact it sends more DiffServ traffic to the upstream provider than agreed in the SLA then it updates the SLA. This option does not use any signaling at all.

Limited signaling. The broker forwards signals only in certain cases. The broker thus needs a heuristic to decide which requests have a heavier impact and thus need to be forwarded to other brokers. For example, large DiffServ requirements can be signaled and an admission control can take place. However, during normal operation no signals need to be exchanged.

End-to-end signaling. For each signaled event the broker checks if it must adapt its SLAs. It always forwards the signal. Each signaled aggregated flow is subject to admission control.

In the following sections (3.3, 3.4, and 3.5) refine these three options, describe the advantages and problems of them in terms of scalability, uncertainty of service guarantees and SLA update rates. Data provided by a specialized simulator underline the findings.

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[1] A micro-flow is a end-to-end communication identified by a source and destination address pair, a protocol number and (if these exist) a pair of port numbers. A TCP socket communication is a typical example of a micro-flow.

3.2 Differentiated Services Signaling Simulator

At the time when we carried out this work there was no public simulator available that was useful to simulate bandwidth broker signaling. Therefore we wrote a simulator using the programming language Java [Fla96, Sunb]. The simulator should to provide insight into the big picture of broker signaling. The simulator simulates the behavior between autonomous provider network. To simulate at such a large scale the simulator must omit details like e.g. arrival times of single packets etc. Even more than traditional Internet simulations [PF97] the DiffServ simulation must deal with many variables of which little is known, for example the user behavior. The user behavior is influenced by the service differentiation and the pricing scheme [EV99] of future DiffServ providers. The simulations waive to predict the exact quantitative influence of choosing a signaling scheme. The simulator produces qualitative results instead in order to point out weaknesses of schemes.

3.2.1 Terminology and Assumptions of the Simulation

Our simulation uses a coarse grained Internet model. The inter-network is modeled as interconnected autonomous systems. Some of these systems are customer networks, which act as traffic sources and sinks, the rest are ISP networks[2] which act as pure transport networks. The routing between the network is dynamically calculated based on the distance vector routing algorithm using the the number of intermediate networks as distance metric.

Business Assumptions. Each bandwidth broker represents a business entity, namely the ISP of the network that it controls. Business models for traffic forwarding may be complex. The simulator reflects the following three basic assumptions:

1. ISPs demand money from other networks that want to reserve for the injection of DiffServ traffic into their networks.
2. Customer networks do not demand money for incoming DiffServ traffic.
3. ISPs avoid breaking SLAs.

The assumptions (1) and (2) enable the simulator to simulate the exchange of money between the brokers. However, this is not subject of this thesis. Assumption (3) is highly important in the context of this paper. This is because the desired end-to-end QoS can only be achieved if the ISPs are collaborative. Customer network do not need to stick to their SLAs, since their traffic is policed by the ISPs.

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[2] For notation convenience we will often refer to such networks simply as 'ISPs'.

Service Level Agreements. The service level is described as reserved bandwidth for the traffic of one service class. The SLA simply declares the maximum bit-rate with which one network can send traffic of that class to its neighbor network. For the purpose of this simulation it was not necessary to introduce more complex service level specification (SLS) such as token bucket based rate descriptions or delay bounds. For such SLS the simulator is not suited well.

DiffServ Traffic. The simulator only models one prioritized service class. The assumption is that the DiffServ marking mechanism sufficiently protects this service class from best-effort traffic. So the simulation omits to generate best effort traffic. It simulates only the behavior of one prioritized service class. The focus is on how reservations for this traffic class are set up. The simulation keeps track if too little or too much is reserved and what the reservation effort is (e.g. number of notification messages exchanged). If not enough capacity was reserved for the upcoming traffic load then the simulation ’eliminates’ the overhead traffic. We refer to this overhead as traffic *loss*. The DiffServ architecture foresees that such out-profile traffic be either remarked (AF changes the traffic class) or be dropped (EF service). So either way, the traffic is not part of the simulated service class any more so calling it loss makes sense. Note, that in the simulation all ISPs perform such *policing* at the network edge.

The simulation models DiffServ traffic as traffic aggregates. The simulation does not generate micro-flows micro-flows. The simulation generates *aggregated flows* which are not resolved down to IP addresses but only down to customer networks.

3.2.2 Simulation Rounds

The simulator runs a given number of atomic simulation steps also referred to as *rounds*. A single round has four different phases. Thus, a round represents the temporal resolution of the simulation. Here are the four phases of a simulation round:

Traffic calculation. Based on the previous traffic load the simulation generates the new load of the next round. The load is represented as aggregated flows. The traffic property (amount and variance) are parameterizable. The traffic models are described in section 3.2.4. Note, that the simulation usually starts with an empty network.

Traffic notification and injection. All generated flows are now forwarded through the network. This can be preluded by notification and reservations between the bandwidth brokers. A notification signals an (aggregated) flow possibly along several domains. A reservation is equivalent to an SLA renegotiation. In case notifications are used the flows may also be subject to admission control. Furthermore, the traffic is policed if at any point an SLA is violated. Dynamically, measurements are taken and stored.

Usage based charging. The traffic is charged according to the measured usage.

Adaptive reservation. The ISPs can adapt their SLAs based on the usage measurements. Note, that these reservations do not trigger notifications.

3.2.3 Simulator Architecture and the Control Flow

The main object of the simulation is of class is `NetworkSimulator`. It controls the program flow and holds the `main` routine. Figure 3.2 shows the data and control flow of a simulation run.

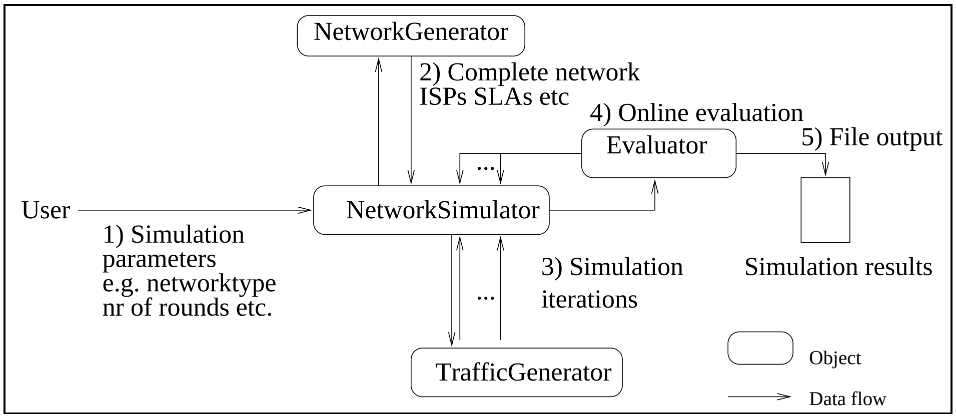

Figure 3.2: The data flow of the simulation.

1. The user starts the simulation with various parameters describing the reservation and notification options the broker signaling should use, as well as the number of simulation rounds, and the network type to use.
2. The class `NetworkGenerator` can generate different types of parameterizable networks (see section 3.2.5).
3. The simulator iterates for the specified number of simulation rounds.
4. The class `Evaluator` describes what measurements an values to extract in each round.
5. After the simulation, the extracted measurements are written to a log file.

At run time, the ISP objects are interlinked via channel objects and SLA objects. A channel object represents the peering link(s) between two ISP networks. The SLA objects are set up and updated by bandwidth brokers. Figure 3.3 shows two interlinked ISPs objects. For one ISP object, the object relations are described in more detail.

Without going into detail, each ISP needs a routing instance to forward traffic and a bandwidth broker to renegotiate SLAs. For each connection between ISPs

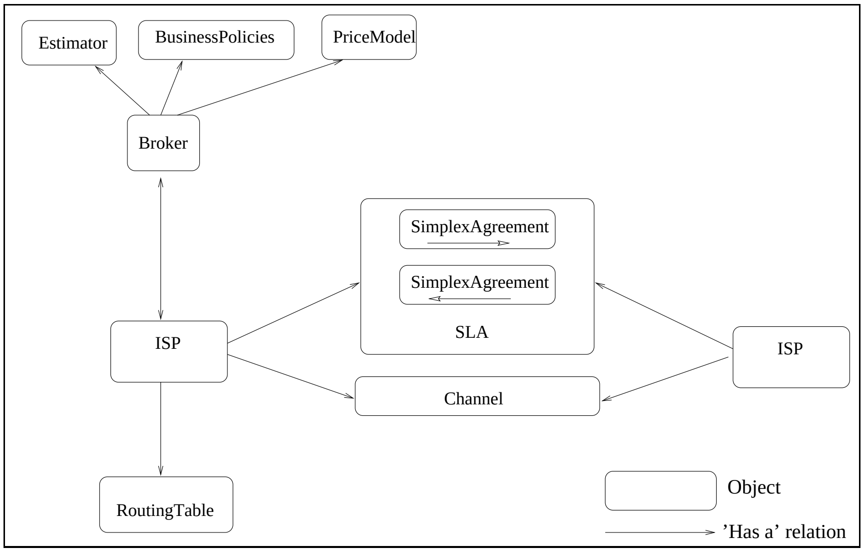

Figure 3.3: The implementation of an ISP-ISP relation.

(channels) there is an SLA describing the inbound and outbound differentiated service agreements. The broker uses a price model to individually negotiate prices for DiffServ offerings. Furthermore, it has a business policy, which e.g. describes how to treat notifications, when to request SLA negotiation (when to buy bandwidth) and the chosen level of overprovisioning. An estimator object helps to analyze traffic tendencies in the network.

3.2.4 Traffic Generation.

Throughout the simulation, the customer networks do not generate more traffic than permitted by the SLA with their access provider. Thus, if the simulation shows lost traffic then this indicates insufficient SLA provisioning between providers.

The simulation uses two traffic models: a Markovian model which is heavily aggregated and used for the study of the adaptive reservation and the limited signaling scenario, and a more fine grained binomial one for the study end-to-end signaling.

Markovian traffic model. In an inter-network with n customer networks, each customer network generates $n-1$ aggregated flows, one for each destination network. This adds up to a total of $n(n-1)$ aggregated flows. The simulation allows the flow generation to be parameterized in two ways: (1) The total amount of traffic that a single customer network generates can randomly vary between a minimum and a maximum value. (2) The percentage of traffic assigned to an aggregated flow can change randomly with a parameterized speed which we call the *fluctuation* of the traffic distribution.

Binomial traffic model. At each customer network a limited number of new flow aggregates can be generated in each simulation round. In each round each customer network checks for a maximum number of times m, if a new flow has to be generated. For each check the probability that a new flow is generated is p_n. For each simulation round each existing flow may terminate with a given probability p_t.

Our basic setting is: $p_t = p_n = 0.1$ and $ma = 10$ (Binomial-distribution). Thus, for each host network, an average of 1 new flow is injected per round. The average lifetime of a flow is $1/p_t = 10$ rounds. Note, that the lifetime is distributed exponentially. At the beginning of the simulation, more new flows are created than old flow terminate. Then, the network reaches a more or less stable state where about the same number of flows are newly created as existing flows terminate. We can use this fact to calculate the expected number of flows e in the simulated internetwork (with n customer networks):

$$\underbrace{p_n mn}_{\text{average new flows}} = \underbrace{ep_t}_{\text{average terminated flows}} \tag{3.1}$$

The equation can be solved for e:

$$e = \frac{p_n}{p_t} nm \tag{3.2}$$

This formula allows the simulation user to parameterizes the average total load for a simulation setting.

The simulation generates flows at the source networks. The destination network is chosen by random. However, the simulation implements a limiting factor for destination networks for a given source network. This factor can reflect, that most of the time the users call only a specific subset of the destinations. The factor represents the ratio of selectable destinations compared to all possible destinations[3]. The selectable destinations are the ones that have a close network number. The network number is assigned by the network generator (see next section). Note, that in the generated networks a close network number in general means that the networks are also geographically close to each other. Thus the limiting factor can also be used to express locality of the communication.

3.2.5 Networks Types

For the evaluation of the adaptive reservation and the limited signaling scenario the simulations used two kinds of customizable networks: the `Dumbbell`- and the `Slalom` networks.

`Dumbbell.` This network has two interconnected backbone networks. As shown in figure 3.4 there is an equal number of n customer networks attached to each of the two core network. Thus, the channel between the two core networks is a possible bottleneck.

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[3] There is always at least one destination available, even if the ratio is set to zero.

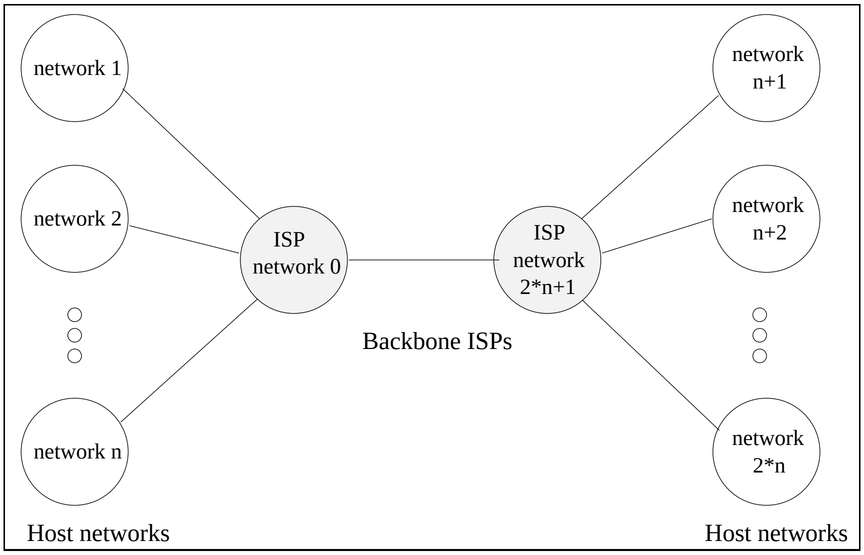

Figure 3.4: The `Dumbbell` network.

`Slalom.` This network is shown in figure 3.5. The number of backbone networks is customizable. The purpose of this network is to evaluate the end-to-end QoS behavior, when the DiffServ traffic crosses many autonomous systems.

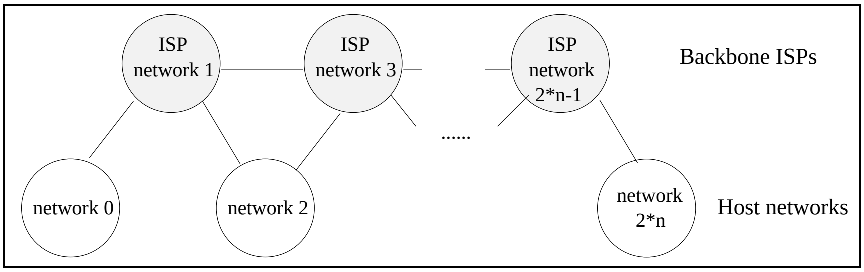

Figure 3.5: The `Slalom` network.

A Hierarchical Network Model. For the evaluation of the end-to-end signaling option we introduced a richer network model. The model (depicted in figure 3.6) is hierarchical albeit not as complete as e.g. the method described in [ZCD97] (e.g. no multi-homing). Our network generator for this model creates backbone networks rings at different hierarchy levels. Each backbone network can have a downlink to a backbone network ring of one level below. The number of ISP network per ring is random and parameterizable, and so is the number of downlinks. The final network rings in the backbone hierarchy represent the access providers. Each of these ISP networks can have a random number of customer networks. The capacity of the links is proportional to the hierarchy level. The hierarchy depth is parameterizable. Note, that the dumbbell network model is a special case of the hierarchical model, where the hierarchy depth is set to one (only one backbone ring), and where the ring is fixed two two provider networks. Figure 3.7 shows a screenshot of an inter-network with three hierarchical levels that was generated by the network simulator. Note, that disks represent networks and bars links. The thickness of the bars indicate the capacity. The simulator's display tool distorts the backbone rings towards the network edges so that the networks are not drawn over each other, as far as this is possible. Note, that the display tool is also able to show the traffic load of the links during an ongoing simulation.

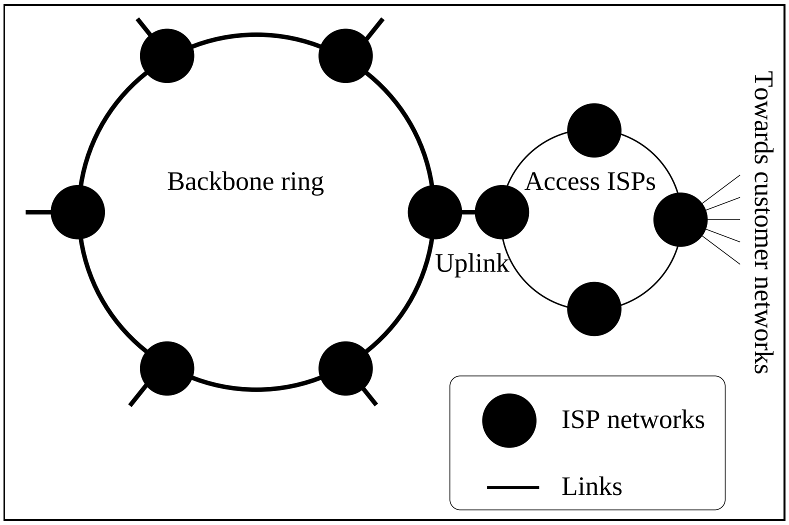

Figure 3.6: The hiearchical network model.

After this presentation of the context, terminology, assumptions, and structure of the simulations, the next section presents the simulation results.

3.3 The Adaptive Reservation Scenario

3.3.1 Reservations Based on Traffic Measurements

In this scenario here, the bandwidth brokers do not exchange notifications. They simply measure the current outgoing DiffServ load and check whether this is compliant with the peering SLAs. If not, they renegotiate the SLAs. In the simulation this takes one round. So for one round overhead traffic is lost. Stringent service guarantees in the adaptive reservation scenario can therefore only be achieved using massive overprovisioning. We used concrete numbers for Frame Relay overprovisioning from [FH98b]. There, a Frame Relay provider would conduct network capacity management on a weekly basis. They provision new trunks between Frame Relay switches when trunk utilization exceeds 50 percent. The provider will reimburse a user if the delivery success rate is below 99.8 percent. This maps nicely

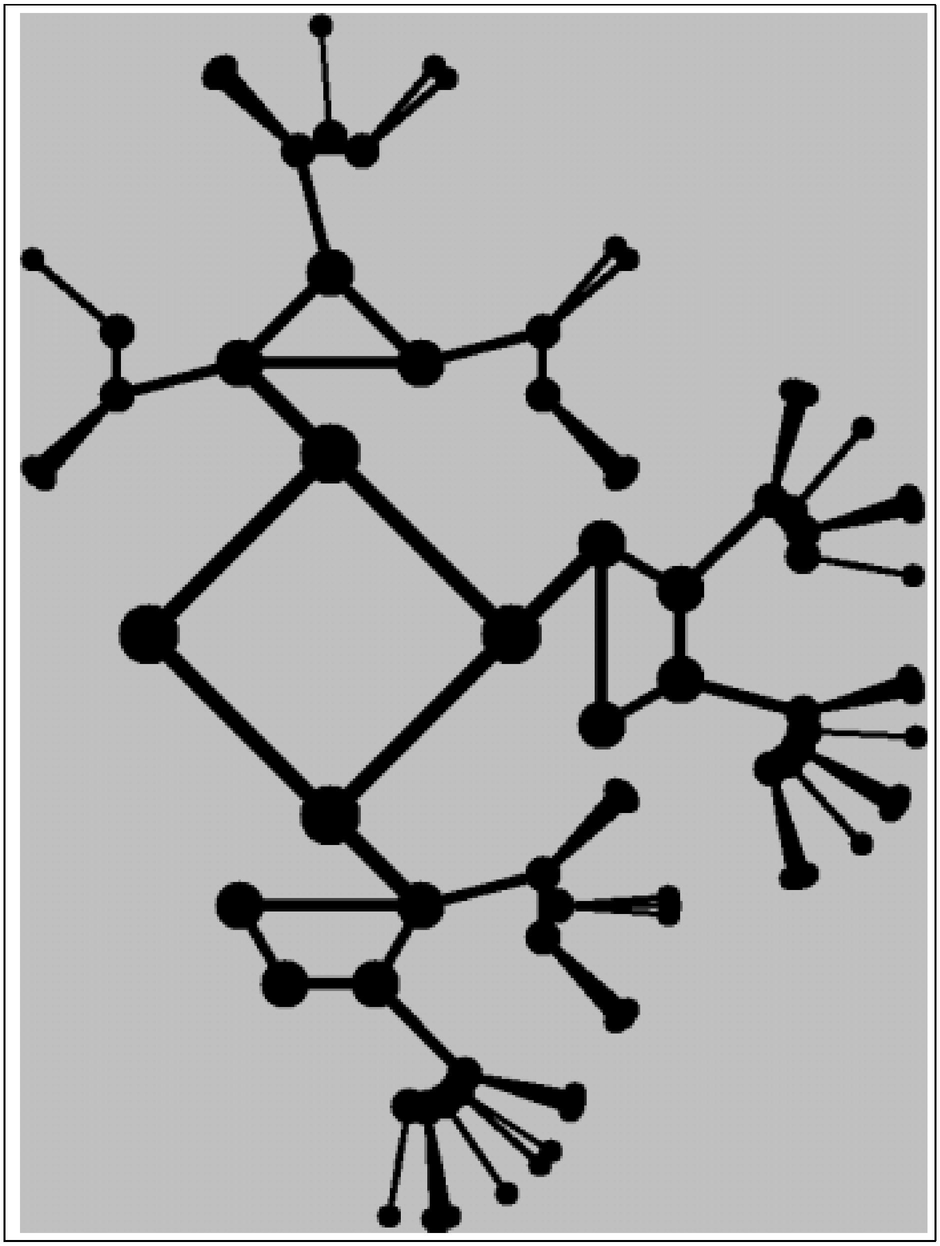

Figure 3.7: Screenshot of a generated inter-network scenario.

to a DiffServ simulation where the corresponding overprovisioning is 100 percent. Thus, if a broker measures, that outgoing DiffServ traffic exceeds 50 percent of the agreed value in the appropriate SLA, it will renegotiate the SLA. Using only a medium traffic fluctuation our simulation showed that 99.87 percent of the injected DiffServ traffic reached the destination (0.13 percent loss). This seems to be an encouraging result because it shows that the coarse grained nature of the simulator can still produce appropriate results, and because the end-to-end QoS in this scenario is economically interesting. However, it cannot be assumed, that all ISPs will want to deploy such a high overprovisioning. Furthermore, measurements with larger traffic fluctuation and with more intermediate ISPs showed a poorer end-to-end behavior. Namely, more reserved traffic was lost, as the following figures and numbers show.

Figures 3.8 and 3.9 each show the results of a simulation of 100 rounds on the Slalom network with 9 backbone ISPs and 10 customer networks. There are therefore 90 different aggregated flows. A total amount of 200 traffic units[4] is injected into the network at each simulation round. The simulation depicted in figure 3.8 uses a moderate traffic fluctuation factor, while the traffic that led to figure 3.9 changes its amount and destination quickly (see section 3.2.4). The brokers arrange for an overprovisioning of 30 percent. Both graphs illustrate a similar behavior: At the beginning of the simulation, no SLAs were set up, thus there is no reservation. All DiffServ traffic generated from the customer networks is therefore not policy-conform and is ’lost’. After the 10th round, the content of the provider SLAs are adapted and the loss reaches a stable level. Furthermore, the reservation and usage is shown as *average per channel*. The graphs reflects the overprovisioning as the difference between the average reserved bandwidth and the average used bandwidth. In figure 3.8 there is already a non-negligible loss rate even after the initial adaption phase. This is due to the fact that we use a network where some flows must travel through many networks. In the scenario depicted in figure 3.9 there is a massive loss of DiffServ traffic (about 20 percent) because of the heavy traffic fluctuations.

The adaptive reservation scheme imposes no inter-provider signaling overhead. However, the simulations suggest the conclusion that adaptive reservation has problems delivering end-to-end QoS guarantees in the following situations:

- When there are many intermediate ISPs.
- When traffic destinations vary quickly.
- When there are rapid global traffic trends, e.g. when all sources begin to send in the beginning of the simulation.

In order to still provide reasonable end-to-end guarantees *all* providers must overprovision their SLAs. Overprovisioning leads to inefficient network usage.

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[4] Given the coarse grained structure of the simulator, it would be misleading to use concrete traffic units. Furthermore, the units used here allow a nice integration into the figures.

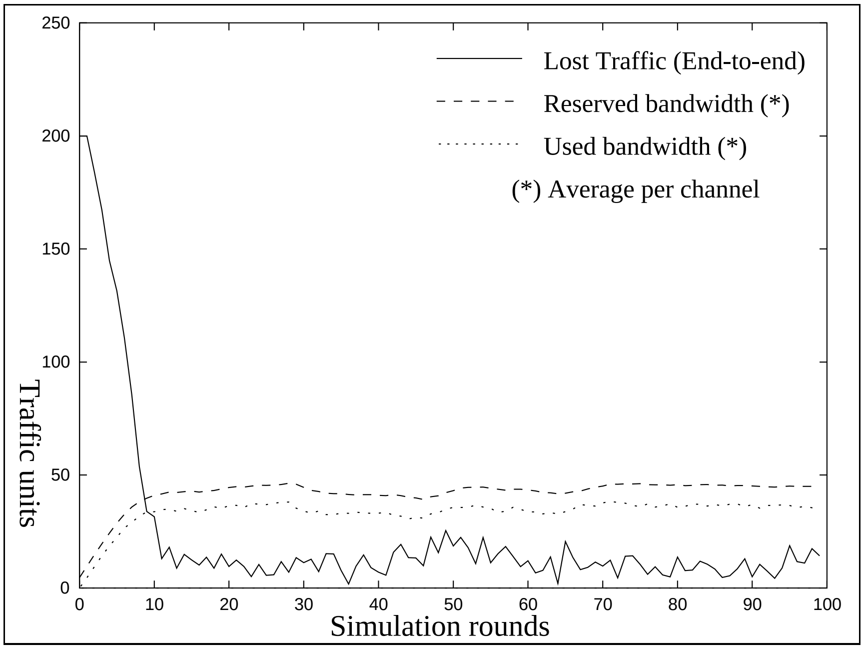

Figure 3.8: Adaptive reservation with weak fluctuations.

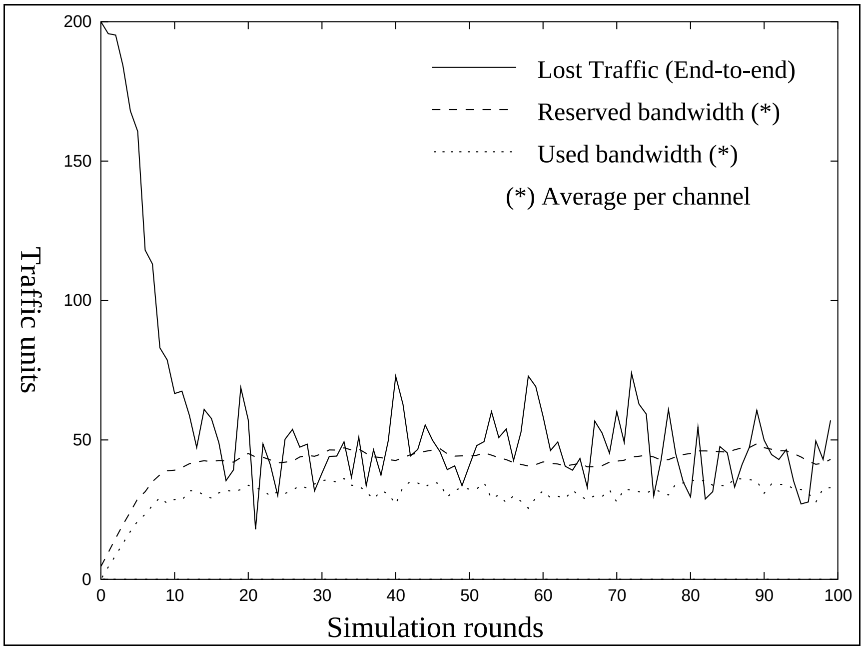

Figure 3.9: Adaptive reservation with strong fluctuations.

However, DiffServ allows the best-effort traffic to use up free reserved capacity. Another problem is admission control of customer SLAs. The bandwidth brokers at the network edge cannot know if an SLA request can be supported in the backbone, because there is no signaling. The performance of the adaptive reservation scheme also depends on the transformation from measurements to reservations. The simulation uses a simple estimation function to calculate the new reservation.

3.3.2 Traffic Estimation

In order to estimate the upcoming traffic load t_{n+1} (and to reserve for it) at round $n+1$ the broker uses the exponential average $\tau(n+1)$ of the previously measured loads $t_1 ... t_n$. The exponential average is defined recursively as:

$$\tau(n+1) = \alpha t_n + (1-\alpha)\tau(n) \tag{3.3}$$

The properties of the exponential average are: 1) It uses only the assumption that the more recently measured values are more significant than older values. 2) Averaging smoothes the estimations thus making it more robust (stable) against ’runaway’ values (outliers). 3) It is very fast to calculate and needs almost no memory. Because of these nice properties the exponential average is used in many applications to estimate future values. Examples are the estimation of the round-trip time and its standard deviation in TCP [Jac88] (which is crucial for the TCP timer management [Tan96]), estimation of the mean allowed cell rate in ATM (ATM-Forum) and estimation of burst times for CPU scheduling [SG98]. However, in [GB01] we show that estimations based on the exponential average global trends are not good in predicting global trends. We propose an improved alternative with similar properties. Figure 3.10 shows measurement data with an trend to increase over time. The proposed alternative exploits the trend while the exponential average keeps lacking behind the measurement values. The high loss rate of the initial simulation phase illustrated in the figures 3.8 and 3.9 is thus not only due to the adaptive reservation approach but also due to the estimation function used. Figure 3.11 shows how the new proposed estimator reduces the duration of the initial loss phase significantly. With the exponential average estimation the loss and the reservation reach a stable state not before round 15. With the improved estimation the simulation reaches a stable loss and reservation state at round 7. Thus the adaptive reservation scheme can be improved by more elaborate estimation schemes.

3.4 Limited Notification Scenario

In the limited notification scenario, a broker only notifies and reserves upon significant notifications. The idea is to avoid signaling that is not necessary and thus improve the scalability of the approach. Figure 3.12 illustrates the approach. The customer network H1 establishes an SLA with its access ISP A. The broker of ISP a sees that it should establish an SLA with ISP B in order to provide service

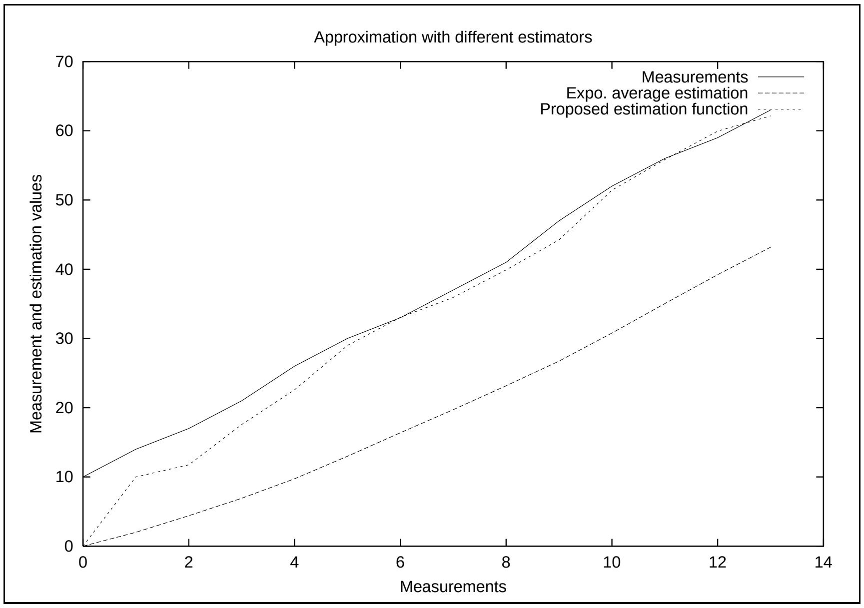

Figure 3.10: Performance of the exponential average estimation.

guarantee. The broker B sees that its SLA with C is sufficient and stops negotiating further. The DiffServ traffic of H1 is then admitted. There are two kind of problems here. The first is the ’dumbbell’ problem, named after the network type that reveals this problem. The other problem is that of the missing destination information in notifications. The next sections describe the problems and propose particular solutions.

3.4.1 The Dumbbell Problem

The first approach for limited notification was to see the notification and reservation as one process. Thus, a broker reacts upon reservation requests by checking its outgoing SLAs and propagating reservation requests, if necessary. In this approach, the broker includes a reservation threshold. If a new inbound reservation causes the reservation on an outbound SLA to exceed this threshold, the broker would issue a new reservation there, before accepting the inbound request. The threshold effectively limits the number of notifications. However, it can have severe impact on the end-to-end QoS as the following simulation run indicates:

In the dumbbell network of the simulator (presented in figure 3.4), the customer networks have only one channel to an access ISP. Using the naive limited notification approach, the customer networks reserve a constant amount of DiffServ traffic which suffices all their future needs. Although the weight of the traffic sent for the different destinations changes during the simulation, the total amount of the traffic a customer network presents to its access ISP stays within the SLA. However, since the traffic distribution scheme of each customer network changes, the traffic going

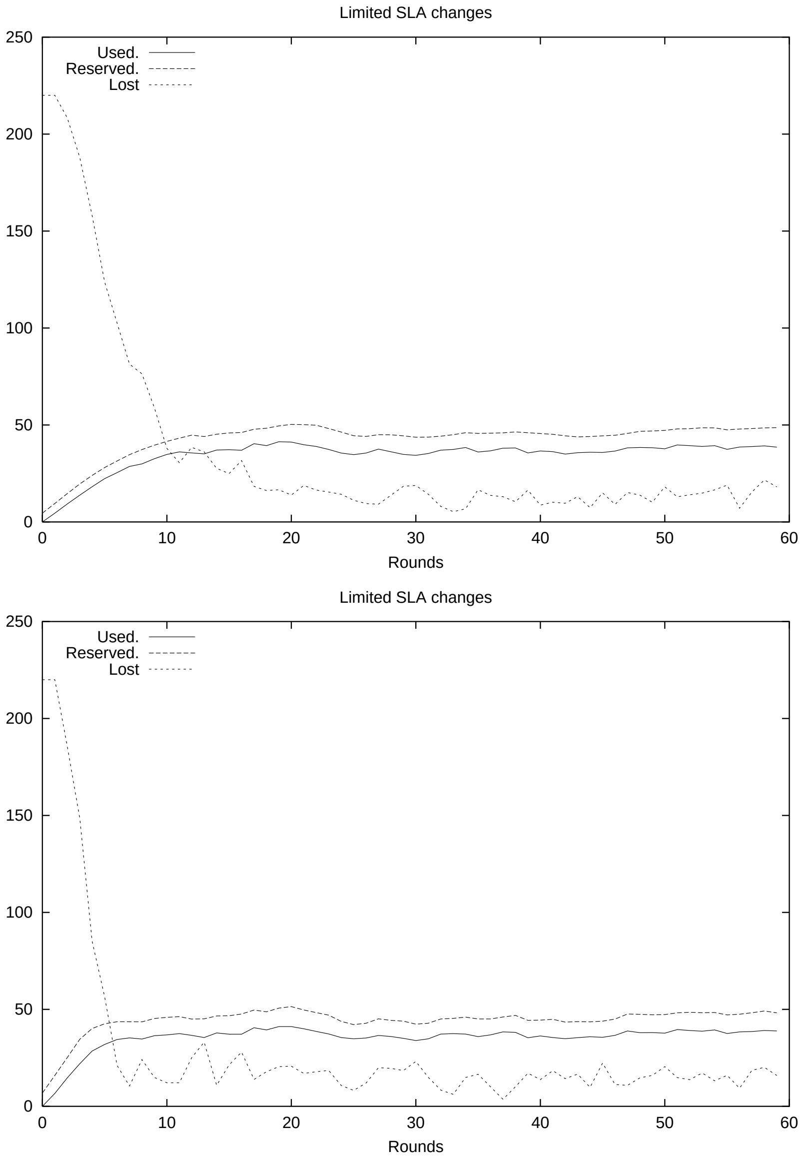

Figure 3.11: Longer initial loss phase with exponential average estimation (bottom) than with the proposed estimation (top).

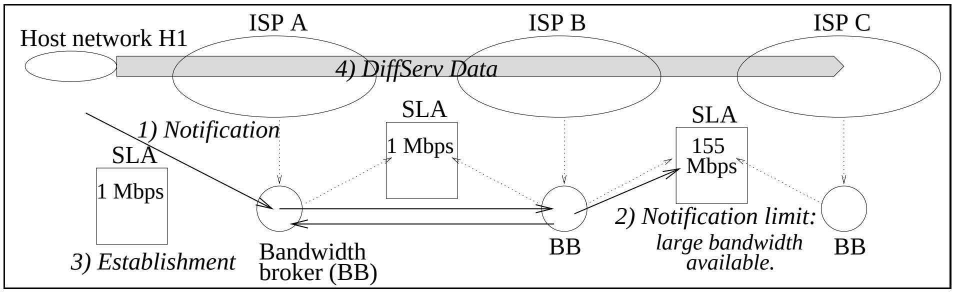

Figure 3.12: Limited notification.

through the bottleneck channel between the backbone ISPs may also change. Unfortunately, since the customer networks don't reserve new bandwidth, there is no notification sent, and thus no renegotiation of the SLA between the backbone ISP takes place. Consequently, traffic is shaped at the bottleneck channel. Figure 3.13 shows the situation for the `Dumbbell` network with four customer networks on each side. Only in the first round, when no reservation is set up at all, notifications are exchanged. Then, no notification is sent at all for the reason mentioned above. Therefore, as reflected in the figure, the reservation stays constant. Subsequently, traffic is lost without hope for the better. Therefore, SLA updates should not be used as implicit notifications.

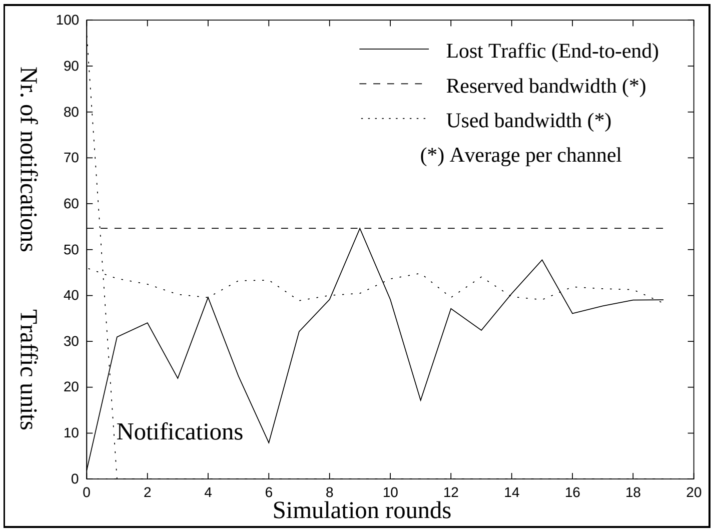

Figure 3.13: The dumbbell problem.

3.4.2 Lack of Destination Information in Notifications

One approach to limit the notifications is to use one notification to cover several subsequent aggregated flows. Usually, when customer networks set up SLAs these

SLAs should last some time, thus covering several subsequent flows. However, in that case the notification of such an SLA cannot (in general) include the information of the destination of these flows. There are some special cases however, such as virtual private networks (VPN) (see section 1.2.1). If a customer network wants to establish a QoS enabled VPN (see section 2.3.5) it could set up an SLA describing the VPN requested. Usually, the VPN peers are known in advance, such as a company's head-quarters and its branch offices. Therefore, the notification of a new QoS VPN can lead to SLAs that cover several aggregated flows and can include their destination information.

3.4.3 Proposed Solutions

For the two presented problems with limited notification this section proposes several solutions and show their viability by simulation. The dumbbell problem can be addressed by decoupling notification from reservation. The dumbbell problem occurs, because necessary notifications are not propagated. The notification chain was interrupted, because it did not lead to a reservation in some place. For the problem concerning the lack of destination information we propose the use of estimation based on measurements.

Decoupled Notification Limitation Mechanism. The decoupled notification limitation mechanism is only a small extension to the presented reservation threshold mechanism. Here, the notification is not directly coupled to a reservation. Upon the reception of a notification, that announces DiffServ traffic on an incoming channel, the bandwidth broker reacts according to the following scheme:

- Estimate the impact on the local network.
- Estimate the impact on the outgoing channels. Use destination information if provided.
- Use the estimation and a *reservation threshold* to determine whether to reserve bandwidth (renegotiate the SLA).
- Use the estimation and a *notification threshold* to determine whether to notify other bandwidth brokers. Typically, this threshold is lower than the reservation threshold. Furthermore, the ISPs should all agree on the value of this threshold.
- Use a *minimal notification size* threshold that stops the propagation of notifications concerning only small changes of DiffServ traffic. Such small notifications might occur when estimating the impact of incoming notifications in absence of destination information (see next paragraph).

Further, the brokers should use adaptive reservation and overprovisioning to smooth out the coarse grained nature of the limited notification approach. For the estimation of the size of the needed reservation and notification in case of missing destination information we propose to use the measurements described in the next section.

Destination Estimation. An ISP with n channels ($n > 1$) can use a distribution matrix D ($n \times n$ matrix). The entry d_{ij} of the matrix D contains the probability that DiffServ traffic coming in on channel i will leave on channel j. Initially, D contains equal probabilities. However, under the assumption that no routing loops occur, no traffic will leave the ISP the same way it entered it. Furthermore, as mentioned before, the ISPs do not act as traffic sinks. Thus the initial D is:

$$d_{ij} = \begin{cases} 0 & : \quad i = j \\ \frac{1}{n-1} & : \quad i \neq j \end{cases}$$

Periodically, the ISP can compile measurements of DiffServ traffic into the matrix M, where m_{ij} contains the amount of traffic measured, that entered the network from channel i and left it through channel j. The matrix M can be used to update the matrix D in the following way:

$$D_{\text{new}} = \alpha D_{\text{old}} + (1 - \alpha)\text{normRows}(M)$$

Here $\alpha \in [0..1]$ expresses, to what extend the old estimation is still valid after new measurements. In the simulations, α was set to 0.5. The $normRows()$ function normalizes the absolute traffic measurements to relative values:

$$\text{normRows}(m_{ij}) = \frac{m_{ij}}{\sum_{k=1}^{n} m_{ik}}$$

To estimate the impact p on an outbound channel j of a notification about DiffServ traffic of the amount a coming from channel i we can simply calculate $p = ad_{ij}$. Note, that the proposed destination estimation is also based on an approach related to the exponential average (see section 3.3.2). It is possible that more elaborate estimation schemes may improve the accuracy.

The next section shows, how using such exponential estimation together with the extended limited notification mechanism improved the DiffServ performance in the simulation.

3.4.4 Simulation Results of the Proposed Solutions

Without having the destination information of aggregated flows, there are more unknown factors, and there need to be more notifications. However, this more realistic scenario is feasible and reasonable as the following example will show. Figure 3.14 shows the performance under the same conditions as the example for the adaptive reservation scenario (figure 3.9). Even though there are up to nine intermediate ISPs for a flow, high traffic fluctuation, little overprovisioning (30 percent), and the destination information is not included in the notifications, the performance is reasonable. The percentage of DiffServ traffic that is lost is only[5]

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[5] Compared to the adaptive reservation that lost 20 percent in the same situation.

11 percent of the total amount of DiffServ traffic presented to the network.

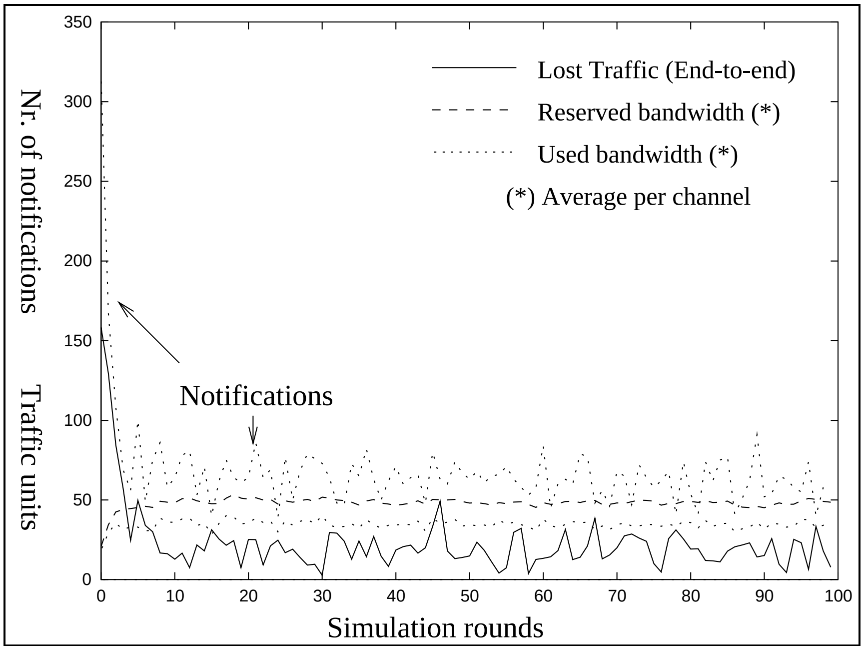


Figure 3.14: Performance of proposed solution.

In the first rounds of the simulation, many notifications are necessary to set up the SLAs, but soon the notification limitations restrict the number of notifications to a reasonable level. The heavy signaling at the beginning has the positive effect that there phase of initial loss is much shorter than for adaptive reservation.

Assuming the special case, when the destination information is included in the notifications (e.g. for VPN flows) the result is even improving. Figure 3.15 depicts the simulation results in this case, using the same harsh network conditions as in the previous example. The shaping decreases to 8 percent of the total DiffServ traffic and there are also less notifications necessary.

Clearly, the proposed limited signaling approach is also sensitive to the traffic fluctuation. The next section studies the limited signaling's sensitivity to the number of intermediate networks.

3.4.5 Impact of the Backbone Size

For the limited signaling the size of the backbone (the average number of ISP networks between two communicating customer networks) may have two kinds of negative impact: (1) Just as for adaptive reservation the end-to-end QoS may decrease when more networks are traversed. (2) The signaling effort may increase thus hurting the scalability of the approach. In order to test the impact we ran a series simulations on the slalom network (see section 3.2.5). Between each run the size of the backbone was increased. All runs used a mild traffic fluctuation and rel-

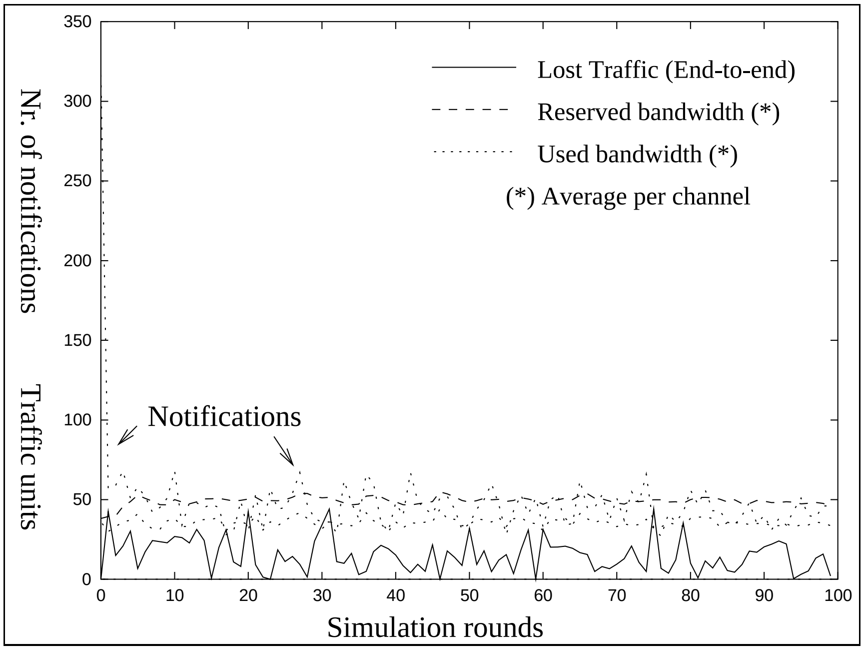


Figure 3.15: Proposed solution using destination information.

atively little overprovisioning (20%). The simulation measures the average number of notification propagation per aggregated flow. We also measured the loss rate and compared it to the loss rate generated when adaptive reservation is used under the same conditions. Note, that the limited signaling performs destination estimation here. The graph of figure 3.16 shows the result. The result is interesting. While the adaptive reservation is indeed sensitive to the number of intermediate backbone networks, the proposed limited signaling seems less affected. In fact for a large number of ISPs the loss rate even shrinks. The signal limiting is effective. For 40 intermediate ISPs in the slalom network the flows travel through an average of about 20 ISPs. Nevertheless, the signal is only forwarded 2.45 times in average. The graph indicates that this notification number does not linearly grow with the number of intermediate ISPs. These results are encouraging. However, the simulation does not prove that the limited signaling would indeed perform as expected in a real life network with real traffic. Yet, the simulation runs were encouraging even for unfavorable (simulated) network conditions.

3.5 End-to-End Signaling

The effort for end-to-end signaling directly depends on the scope of the SLAs that the customers establishes with their ISPs. There are the following problems:

- The customer SLA scope must be coarse grained. If such SLAs are negotiated per IP address then there is a significant signaling overhead because

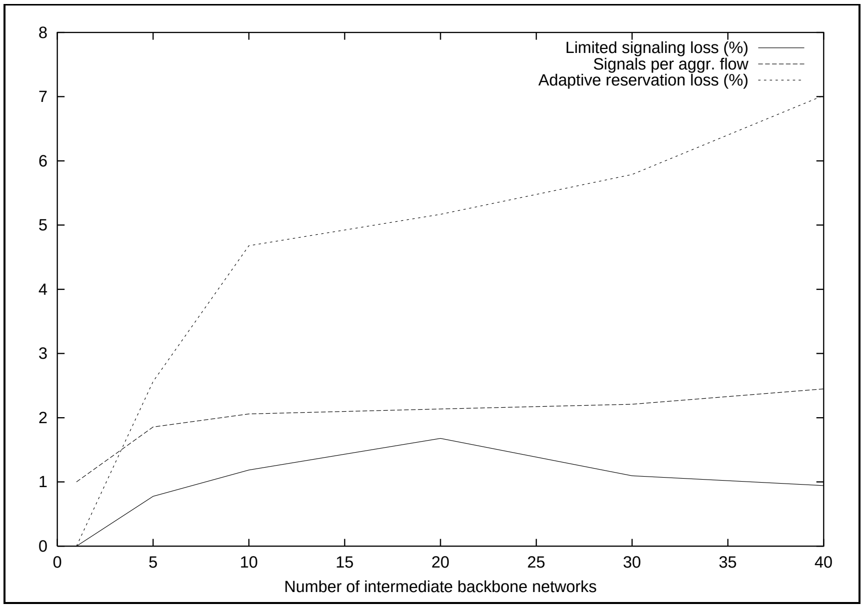


Figure 3.16: Limited Signaling in a growing inter-network.

the traffic of each DiffServ host must be signal through the whole backbone network.

- The destination of the DiffServ traffic must be known else no end-to-end signaling can take place.

For work presented next the assumption is that the SLA scope deals with traffic between two autonomous systems. It is thus quite coarse grained. Still, the end-to-end signaling will produce a significant overhead (compared to limited signaling), but this may be manageable. Note, that the end-to-end signaling approach presented here is more scalable than IntServ because the reservations are not stored in each router but by the brokers. Furthermore, the SLA between two ISPs does not distinguish between different flow reservations but reflects the aggregate of all these reservation. On the positive side, end-to-end signaling allows the the providers to reserve the exact amount of resources. Therefore, end-to-end service quality can be assured; there is no ’loss’ as in the previous signaling options. However, there are other issues that can be analyzed here. SLA updates are an expensive operation. Therefore, it is desirable that the resource allocation takes place in advance and accommodates several flows. Thus an SLA between providers should be overprovisioned. Then, some signals can be forwarded without an SLA update. This reduces the number of SLA updates but it increases the number of admission denials that were not really necessary, because capacity is reserved that is not used. Thus, the trade-off between frequent SLA updates and overprovisioned SLAs is the main topic of this section.

3.5.1 The SLA Update Decision

An SLA update is a heavy operation. Two brokers of different ISPs have to negotiate with each other, not only about traffic rates, but also about prices and payment. Strong cryptographic measures and protocols that guarantee non-repudiation are necessary. Therefore, the number of SLA updates should be limited. Not every signaled new or terminated flow should cause an SLA update. In our simulation, we propose a scalable and parameterized mechanisms using two thresholds, namely the increase-threshold (i) and the decrease-threshold (d). The thresholds are proportional to the reservation. An i of 0.9 means that if the total signaled traffic exceeds 90% of the total reserved bandwidth, the SLA should be renegotiated (more bandwidth should be reserved). The situation with d is analogous. If the proportion of signaled traffic is smaller that d, the SLA should also be renegotiated (reserve less bandwidth). The amount of the new reservation is calculated so that the new proportion of signaled to reserved traffic has a maximum distance to both thresholds (it is placed in the middle):

$$\text{newReservation} = \frac{\text{totalSignaled}}{0.5i + 0.5d} \tag{3.4}$$

Usually, i is set to 1.0. This means that a new flow triggers an update only if the reservation is not sufficient any more. The value d can parameterize the overprovisioning. Overprovisioning in this context means, that the SLA has reserved more bandwidth than actually requested through signaling. Overprovisioning allows the broker to accept some calls without renegotiating the SLA. With the presented mechanism, the overprovisioned bandwidth o averages to $o = (i - d)/2$. One special case is worth mentioning, namely when $d = i = 1.0$. In this case every new flow, triggers an update, as well as every deleted flow. It can be easily seen from the formulae that the reservation then always equals the signaled bandwidth, and that there is no overprovisioning. This case is very similar to the situation in IntServ. Thus, $d = i = 1.0$ is a benchmark of our simulation results.

3.5.2 The Relation of Overprovisioning, SLA Updates, and Utilization

The first test series use the network depicted in figure 3.17, with sufficient capacity. Every flow passes the admission-control, no flow is rejected. Here we investigate how overprovisioning affects the number of (expensive) SLA updates. Note, that there is a financial trade-off, since overprovisioning comes at a cost. Figure 3.18 shows the average reservations (for the complete inter-network) over time, for simulation runs using different decrease-threshold values (d). It shows the overprovisioning compared to the benchmark ($d = 1.0$). Figure 3.19 shows the number of SLA updates that occurred during these simulations. Note, that since the simulation runs used the same initialization for the random generator, the traffic pattern is exactly the same for all four runs.

Clearly, there is a significant reduction of updates, when the decrease-threshold is equal or smaller than 0.6. On the other hand, a small d-threshold causes more

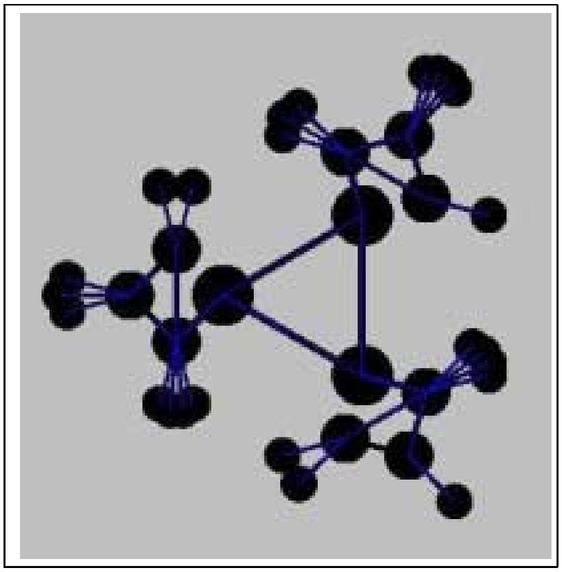


Figure 3.17: The hierarchical inter-network for E2E simulations.

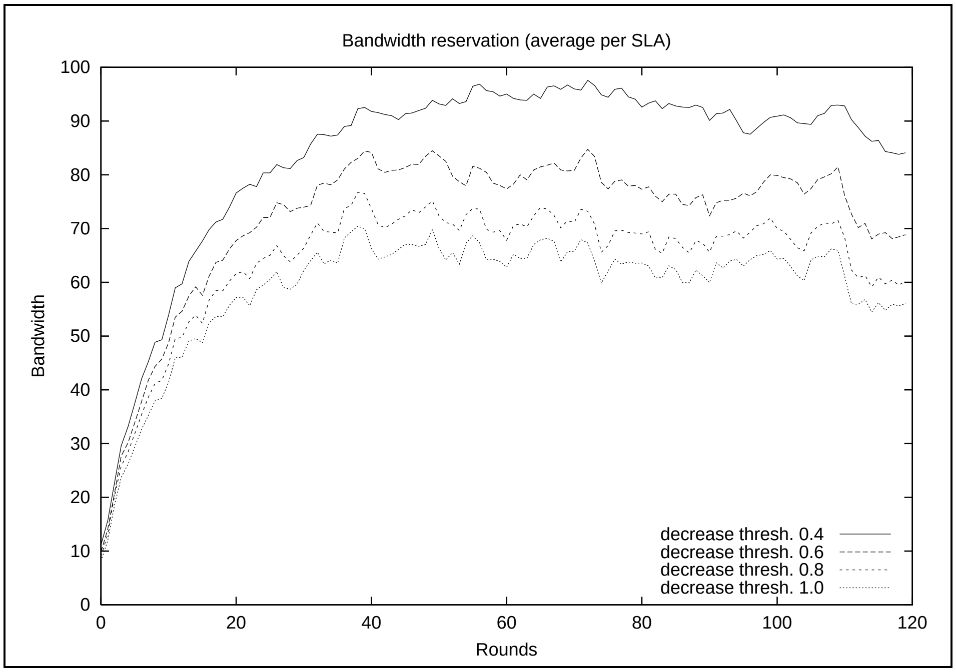


Figure 3.18: Overprovisioning given different decrease thresholds.

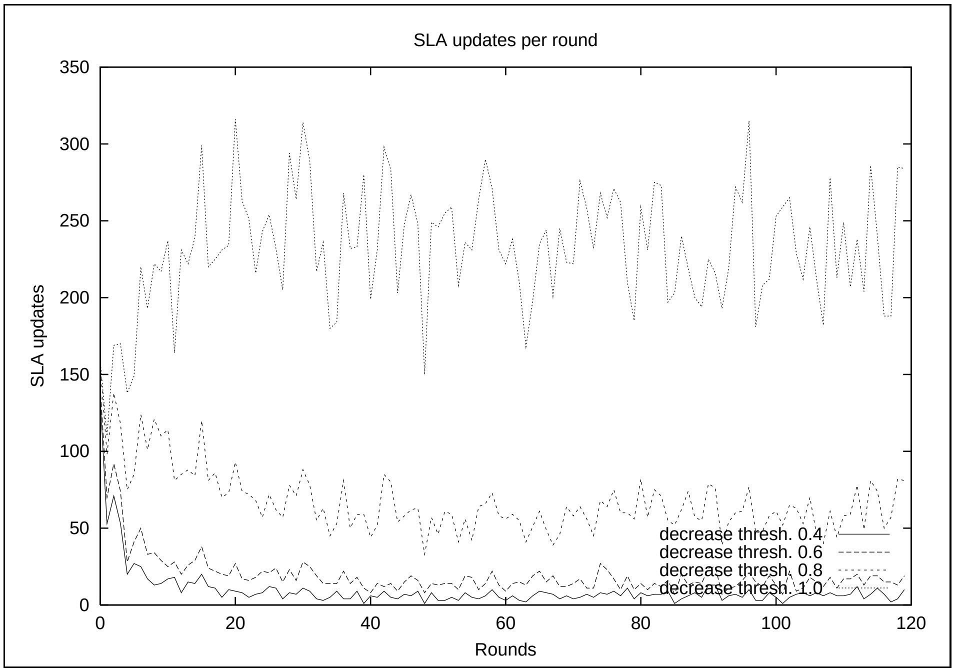


Figure 3.19: The number of SLA updates given different decrease thresholds.

overprovisioning (reserved, but 'unused' bandwidth). Reserving additional bandwidth introduces additional costs. However, if all providers use the same d, these costs are leveled out to zero over the whole network (each provider pays more to its neighbor, but also gets more from its neighbor). Nevertheless, overprovisioning blocks some of the available capacity, which leads to a sub-optimal usage of the network. The simulation reveals this when it uses a modified inter-network that has reduced interconnection capacity. While most of the traffic still fits in the network, some flows have to be rejected by the broker at the bottlenecks. The results show, that a small d leads to unnecessary rejections. Table 3.1 shows the number of rejections during a 60 round simulation. Note, that again the $d = 1.0$ case is the benchmark since it shows which rejections are due to true capacity limitations, and not due to overprovisioning inefficiency.

Table 3.1: Denied admissions due to overprovisioning.

d	Rejected flows	Unnecessary rejections
1.0:	79	0
0.8:	90	11
0.6:	107	28
0.4:	132	53

Clearly, overprovisioning leads to sub-optimal network utilization, but there are other factors that influence the number of rejections. Using the same limited-capacity network the next simulation shows, how different user behavior can influence the number of rejected calls. For that purpose the simulation uses different limiting factor for destination customer networks for a given source network (see section 3.2.4). All previous results were calculated with a limiting factor of 1.0, which means that the destination of a flow is not restricted. For the following locality test series d is set to 0.4, which showed many unnecessary flow rejections in the previous table.

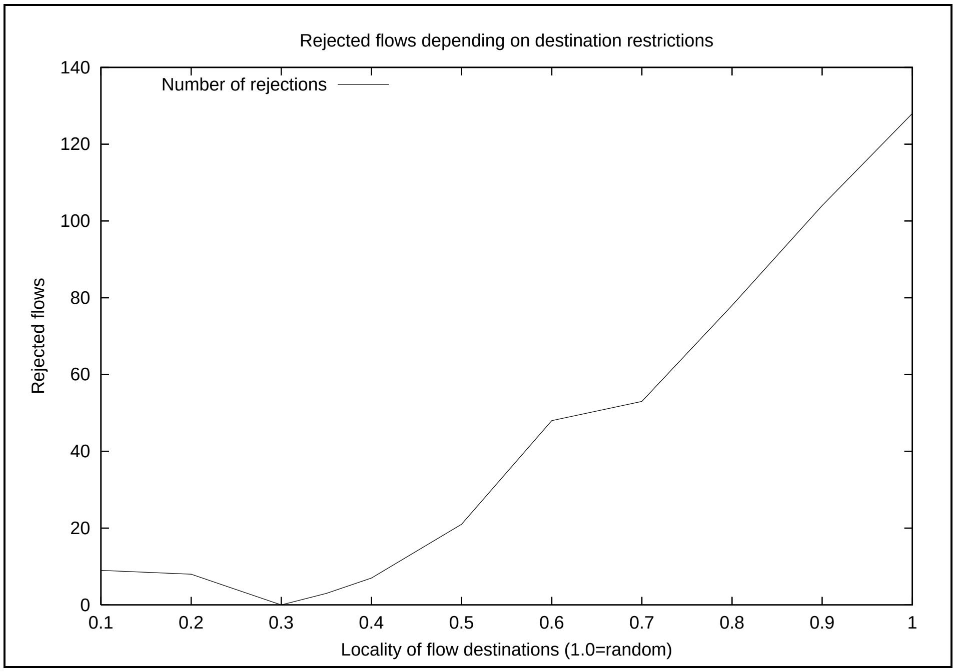


Figure 3.20: Influence of traffic destination patterns.

The result depicted in figure 3.20 shows, that here the traffic destination patterns have a more relevant influence on the number of rejected flows than the overprovisioning has. When the individual destinations are limited to 30 percent, there was not a single rejected call. Note, that the destination limitation is not random. Note, that limited traffic destinations are more local destinations. The rise of rejected calls in the range of 0.2-0.1 is due to the fact that the access networks get congested because all traffic is sent to neighbor ISPs. The rise of rejected flows for locality factor larger than 0.3 is due to congested backbone networks.

SLA Update Rate Limits

SLA updates are heavy and probably relatively slow. Therefore, the next simulation results deal with SLA update rate limitations applied to each SLA. The simulation implements an update-wait time parameter w (in rounds). If $w = 0$, this means, that an SLA can be updated at any time. If $w = 1$, then after an update the broker has to wait for the next round for the next update (only one update per round). If $w = 2$ and the broker performs an update in round r, then it has to wait for the next update until round $r + 2$ (in general $r + w$). I tested this mechanism for different d. If d is large, then the overprovisioning is small and thus there are a lot of SLA updates. However, these updates are necessary. If the updates are restricted, new flows cannot be admitted, thus the rejected flow rate rises. With $d = 0.8$ and $w = 2$ the simulation shows the unacceptable behavior that 60% of all new flows are rejected.

The situation is different when there is more overprovisioning, e.g. with $d = 0.4$. Figure 3.21 serves as benchmark, it depicts the SLA updates and overprovisioning when there is no restriction on the updates. With this larger overprovisioning an update limit of $w = 2$ is still acceptable. This is shown in figure 3.22. The rejection rate drops to a low stable state. However, this adaptation to global traffic changes happens only slowly. At the beginning of the simulation, there are no flows, so many new flows are generated and few terminated. With $w = 2$ the network needs about 50 rounds to adjust to this situation. For comparison, there is also the results with w=0 (no restriction). Here, there are no rejections. In the first round, there are many more SLA updates (134). Then, the network rapidly adapts and is stable after round 20. Note, that overprovisioning and rejected flows are plotted in percent, while the number of reservations are plotted in absolute numbers.

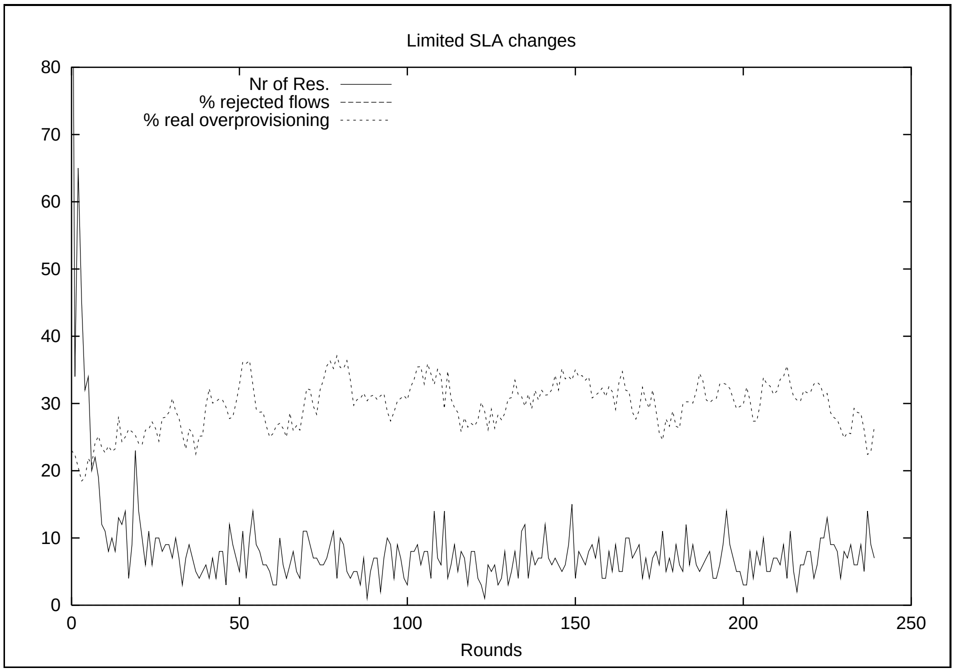


Figure 3.21: Unrestricted update rate.

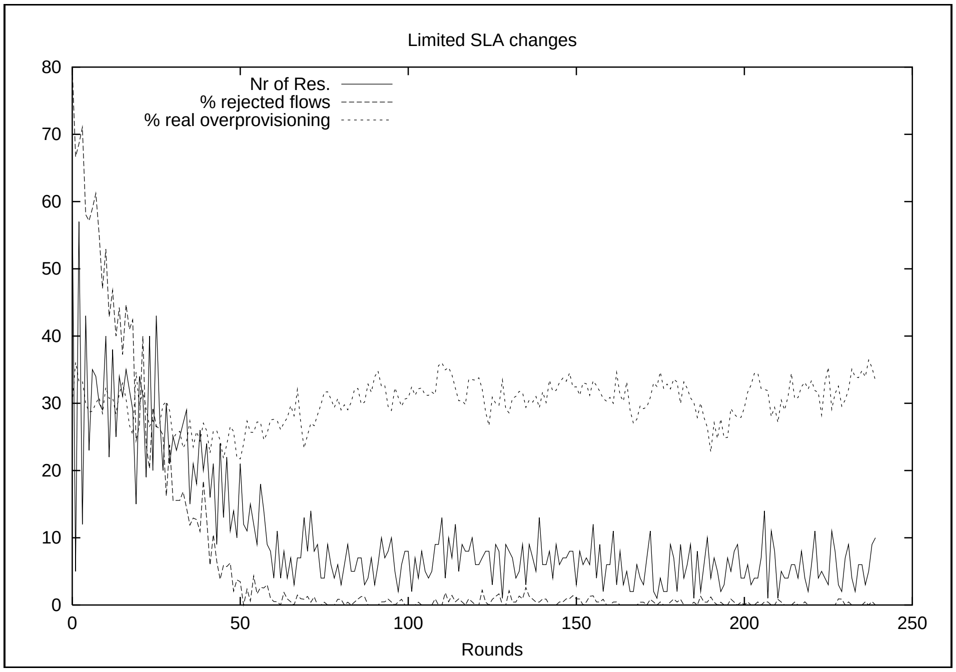


Figure 3.22: SLA update rate limited to w=2.

3.6 Evaluation of the Signaling Options

DiffServ broker signaling is only vaguely described in the DiffServ architecture. However, it coordinates the ISPs in their effort to provide a multi-provider network service. This thesis therefore studied different options of broker signaling. The presented options cover different signaling granularity levels. The results do not clearly favor one of the options but they provide a framework to judge future approaches. Here is a comprehensive overview of the trade-offs that broker signaling faces:

- **Adaptive reservation.**
  - Advantages: The approach is light-weight because the brokers do not need to communicate with each other.
  - Problems: The approach is sensitive to both local and global traffic behavior and to the size of the backbone. Reasonable end-to-end guarantees can only be provided with large overprovisioning. Customer SLA admission control is not supported.
  - Open issues: The collection of measurements and the estimation function to extract reservation needs from the measurement data.
- **Limited signaling.**

  - Advantages: The approach is relatively insensitive to the size of the backbone. It needs significantly less signaling effort than end-to-end signaling. It does not need destination information.
  - Problems: We must make sure that the signaling is not limited in the wrong places (dumbbell problem). The scheme is sensitive to the local traffic behavior. The improvements over the adaptive reservation scheme are not ground-breaking.
  - Open issues: Instead of the two thresholds more intelligent (maybe heuristic) notification decisions could be implemented.

- **End-to-end signaling.**
  - Advantages: The approach ensures that no DiffServ traffic is lost (hard guarantees). Overprovisioning reduces the SLA update effort (but not the signaling effort).
  - Problems: The customer SLAs must contain specific destination information. The scalability of the approach depends on the scope of these SLAs and on how frequent the customer updates the SLAs.
  - Open issues: specification of the scope of customer SLAs.

Business Issues. As mentioned before, the simulation also includes money exchange between brokers. SLA based reservations come at a price (see also section 2.3.6). Therefore, some providers may try to save money by not renegotiating their SLAs (reserve enough resources). However, if only one single provider of a multi-provider service (such as DiffServ is) does not reserve enough resources then this already hurts the end-to-end service performance. Therefore, the providers of multi-provider services have a vital interest to ensure that all peers collaborate. Note, that it does not suffice to test if the bilateral SLAs are met. For the adaptive reservation the providers must e.g. all use the same thresholds and they must use the correct measurements. For notification based approaches the providers must react to notifications by upgrading SLAs if necessary. Therefore, providers that collaborate to deploy a multi-provider service need a monitoring infrastructure that allows them to detect misbehavior of peer providers. The service monitoring infrastructure that proposed in part II of this thesis is ideal for this work.

Outlook. The DiffServ architecture is not yet mature enough that an end-to-end signaling infrastructure will be built for it (see also section 8.1). The limited signaling approach seems to be the best of both worlds but in fact it needs a signaling infrastructure and still it is unable to provide hard service guarantees. The adaptive reservation scheme can be deployed incrementally and needs relatively little infrastructure. It is able to provide soft guarantees, especially in small DiffServ clouds. The service is going to be overprovisioned but this is not so dramatic because if no DiffServ traffic is using the reservations then best effort traffic can fill out the available capacity. So it is probably the adaptive reservation scheme that is going to be deployed in the near future. The adaptive reservation scheme requires a measurement infrastructure that the bandwidth broker can access. The infrastructure that the thesis proposes in part II is one possible candidate but it can provide more than that. The service monitoring infrastructure described there would allow the broker to take measurements in foreign ISPs. These measurement probes can thus warn the broker early about incoming DiffServ traffic.

Part II

Customer-Based Service Monitoring

Chapter 4

Architecture

4.1 Introduction and Motivation

Traditional network management includes monitoring of the network. The monitoring serves several purposes: it verifies the smooth operation of the network, it alarms the administration in case of an anomaly and it provides usage and performance data for future network provisioning and planning [CC98]. The customers of an Internet service provider are neither directly interested in monitoring the network of the provider nor should they be allowed to do so. However, the customers may want to monitor their enhanced IP service. The enhancement of the service is normally transparent to the customer, because it consists of packet processing that happens in the provider networks. The providers offer enhanced services to generate new revenues. Therefore, enhanced services will cost more than basic IP services. Since the customer pays for the service enhancement, the customer has a vital interest to possess an explicit mean to verify the enhancement and thus justify the additional expenses.

The monitoring needs vary from customer to customer and from service to service. In order to convince the customer of the usefulness and stability of a new service the provider must offer a generic service monitoring interface. The interface should allow the customer to verify the correct operation of the service functionalities sold by the provider. We refer to this process as Customer-based Service Monitoring (CSM). The provisioning of such a monitoring interface may be crucial for the successful introduction of new commercial Internet services because only that way the customer sees what (s)he buys. Consider the virtual private network service described in chapter 1.2.1. How can a customer know that the traffic traveling through the Internet is indeed encrypted by the provider and e.g. not just compressed? How can the customer see if regular Internet traffic backs off when the customer sends prioritized DiffServ traffic? How can the customer find out that prioritized traffic has been dropped in the network (and not e.g. by an application) and where (by whom) it was dropped? How can the customer verify that a specific service level agreement with the provider is indeed fulfilled?

A generic Internet service monitoring infrastructure provided by the ISPs to their customers can answer such questions. It provides a mean for the service providers to convince customers of the usefulness of new Internet services. The provider can also describe the service level guarantees in terms of the monitoring infrastructure. The more powerful the monitoring interface is the more sophisticated service level agreements can be formulated. Thus, a generic CSM infrastructure allows the provider to differentiate their service offerings. There are however many problems that make customer-based service monitoring significantly more complex than simple network monitoring:

- **Service-specific monitoring.** New Internet services provide different add-on features to traditional IP forwarding. These features can have all kinds of service specific parameters. The monitoring infrastructure must be generic enough to support different metrics for service-specific traffic parameters.

- **Individual customer wishes.** The customers may order a service based on different requirements resulting from different business backgrounds. It should be possible for each customer to test the service against his/her individual requirements using customer defined metrics. The customer should also be able to test the service at any time.

- **Multiple providers.** In case several providers collaborate to provide an end-to-end service, the monitoring should provide per-provider information. This is desirable especially when providers are customers of each other and to detect malicious/cheating providers.

- **Security.** Network monitoring data is sensitive, revealing it to others violates the customers' and the providers' privacy. The data may reveal organizational details that competitors can use against a provider. Also, a provider will lose its customers if they ever find out that other parties may monitor customer service traffic. Thus, the service monitoring infrastructure must be protected against malicious customers. Further, the integrity of the monitoring data must be protected. It is desirable that the monitoring infrastructure discourages malicious providers.

- **Standardization.** Although the parameters to be monitored may vary greatly, the monitoring infrastructure should be standardized. This eases the deployment in a multi-provider scenario and allows for rapid development of application software by third-parties.

Today, no service monitoring infrastructure exists that meets these requirements. If a customer happens to detect a problem (which is usually when the customer needs that service badly and does not get it), phone-calls between administrators, local measurements, and manual browsing of log-files will eventually lead to the identification of the problem source. Unfortunately, it is also not uncommon that the involved parties will suspect each other and repudiate any guilt. Note, that this problem not only concerns the relation between customer and provider but also between providers themselves. It is to be expected that the problem becomes worse when new and more expensive network services are deployed that require provider collaboration. First steps towards a service monitoring infrastructure are SLA reports [Ver99]. The provider calculates a performance statistic over a regular period of time (e.g. a month). The statistic usually reflects the traffic properties guaranteed in the SLA (e.g. uptime and response time). The provider then delivers this statistic to its customer on a regular basis (usually once a month). This approach does not satisfy the requirements to a generic service monitoring infrastructure. The customer is not able to formulate individual queries whenever (s)he feels like. The provider can very easily manipulate the statistics to meet a given SLA. The statistics, the collection of their raw data and their delivery to the customer are not standardized and the customer cannot tailor them to individual wishes.

This part of the thesis proposes a generic service monitoring infrastructure based on mobile agents. Mobile agents provide a flexible way to monitor the services *within* provider networks (for further motivation see section 4.2). The customer thus sends mobile test agents to relevant locations in the provider networks. The agents perform tests on behalf of the customer. Mobile agents thus allow the customer to test the service where it is delivered. A customer-based service monitoring infrastructure based on mobile agents can solve the problems mentioned above. With agent technology service performance is no longer formulated as statistics of some network parameters. Agents are programmable and can thus measure any metrics on the raw data. Therefore, agent technology provides a generic interface that the customers, providers or third-party vendors can easily adapt to new services or individual customer wishes. The mobility of the agents reduces communication overhead and supports the distribution of monitoring tasks which increases the scalability of the approach. The mobility of the agents also helps to detect misbehavior of providers since the customer can collect distributed measurements and compare their global consistency. Agent security is a well-known research area where complete solutions exist today. Standardization and internationalization can be achieved through the use of state of the art technology such as the Java programming language.

Project Context. The work presented in this part of the thesis was performed within the *Advanced Network and Agent Infrastructure for the Support of Federations Of Workflow Trading Systems* (ANAISOFT) project [ANA]. The main goal of the ANAISOFT project is to study and the creation of secure and responsive Federations of Workflow Trading Systems (FWTS) using intelligent and mobile agent technology. Customer-based service monitoring with mobile agents is one task of the project. ANAISOFT is a project in the framework of the 2nd phase of the Competence Network for Electronic Commerce (CNEC) within the Swiss Priority Program for Information and Communications Structures (SPP ICS) of the Swiss National Science Foundation (SNF) running from January 2000 to December 2001.

4.2 Mobility and Service Monitoring

4.2.1 Terminology

Mobile agents [Whi94, CHK97] are program instances that are able to move self-directed through a network to locally perform a task on behalf of their sender. Different mobile agent platforms have been proposed e.g. for the programming languages Java [LO98, VB99, Fün98] and Tcl [Gra98]. Mobile agents are proposed for different tasks such as network search (more recently e-commerce [HGF$^+$99]), network management [BGP97] and network intrusion detection [JMKM99].

On the network level, the emerging mobile agents technology is called *active networking* [TSS$^+$97, CBZS98]. There, a mobile agent is often referred to as *capsule* and is directly integrated into the network traffic packets. Thus, the code flows directly on the communication path that is subject of the code's computation and it can be executed on a per-packet granularity. Here, the abstraction and intelligence aspect is secondary. The focus is on the interaction with the network infrastructure. Active network packets access the networking functionalities of the routers they pass (e.g. forwarding and routing) and change these functionalities for packets or classes of packets. Furthermore, performance is a crucial issue, since the code should be able to manipulate data at the line speed (in todays backbone network this can be up to several gigabits per second). Active networking is often proposed for intelligent multicasting. Another possible application is secure communication [GBB01, Bro00, Tsc00].

There is no solid line between mobile agents and active networking. For example the active networking testbed ANTS [WGT98] can also be seen as a mobile agent testbed, since capsules are Java objects, and the code is not included in network data packets but is dynamically loaded upon need. The approach that we describe in this paper is mobile agent based. This is because the monitoring code (the mobile agents) is transported out-of-band. Yet, service monitoring agents examine network services down to the structure of forwarded network packets. Also, the performance of the CSM agents is an issue since one of their goals can be to monitor the network at wire speed. For these reasons, CSM can also be seen as an application of active networking. The implementation of the CSM system presented in this part of the thesis is mobile agent based. Nevertheless, similar results could have been achieved when choosing active networking technology instead.

4.2.2 Advantages of Service Monitoring with Mobile Agents

Mobile Agents have the questionable reputation of being a solution in search of a problem (J. Ousterhout). However, there are application areas where the use of mobile agents has undeniable benefits [Kna96]. This section outlines their benefits for service monitoring. The programmability of mobile agents has the following advantages already mentioned in the beginning of this part: flexibility, available security solutions and standard technology. The mobility of the agents also brings substantial benefits:

- **Working at the monitored site.** Network services are per-definition delivered *in* the provider network. In the case of multi-provider services the service enabling functions even take place in several networks. On the other hand it is mainly the customer who wants to perform the service tests and not the administrator of the networks in question. Given the already mentioned advantages of being able to formulate service test as programs the solution obviously is that the customer *sends* the test program to the interesting locations in the network. The proper way to do so from the software engineering point of view given security and multi-user requirements is to send mobile agents.

- **Performance.** Generic measurements such as packet traces produce a huge amount of raw data which is of the same order of magnitude as the traffic being monitored. Therefore, traditional customer-based monitoring infrastructures always calculate statistics over the raw data for a medium to large period of time. Thus, the raw data is compressed before delivered to the customer. Mobile agents can do this compression in a flexible way thus keeping the communication path short. This can also reduce latency between a service anomaly and the appropriate reaction. Further, the mobile agents can implement the extraction of relevant data in optimized ways. Thus, the may execute faster than general purpose filters. If one compression step does not reduce the communication sufficiently, the mobility of the agents can be exploited to built a communication hierarchy. In general, mobile agents are a powerful method to structure distributed computing thereby enabling the customer to collect computing power to analyze the traffic.

- **Global view of the service.** A malicious provider can easily fool a customer that relies on the measurements published by the provider. In a multi-provider service scenario the situation is even worse. CSM agents can be sent out to perform active measurements by producing and measuring traffic at different sites that are out of the administrative domain of the provider to be tested. The agents can thus provide different views of the current service state, that a malicious provider cannot directly influence. In general, provider that tries to fake a service state cannot keep the views consistent. Mobility therefore allows the agents to virtually 'track-down' the problem source (see section 6.4).

- **Independence.** In case of a service interruption (e.g. a complete network failure) at least some CSM agents are still running and can continue to record the service performance. Later, that information may help to find the source of the problem or to negotiate about refunding.

4.3 A Supporting Infrastructure for Service Monitoring Agents

Like any other network monitoring system, the CSM agents need a supporting infrastructure. In this section we discuss the required components and their location in the providers' networks.

4.3.1 Location of the Control Points

The Internet is a heterogeneous network, it consists of thousands of administrative domains. The interior network of these domains is administered in different ways and consists of different kinds of networking technologies such as Frame Relay, ATM, MPLS or Sonet. This may render the access to the traffic inside of the domain very difficult (e.g. for optically switched technology). The least common denominator of these networks is the Internet Protocol (IP). The IP traffic is exchanged between the domains at so-called peering points, according to peering- or service level agreements. While the network engineering and management of the interior network of the domains is usually hidden, the peering points are by their nature open (at least to the peer). For service monitoring the peering points are thus of high interest. Note, that for CSM it suffices to track down a problem to a provider. Once the problem is found to relate to a given administrative domain, it is up to its administration to further locate the problem in the inside of their network, using the network management system of their choice. Therefore, the CSM agent nodes should be located at the peering points. This guarantees, that the monitoring has access to the IP traffic and that the control can relate identified problems to a specific provider. Note, that not all CSM applications will need a platform at all peering points. Of course, a provider can also offer additional node environments in the inside of its network as an additional service to its customers or for its own service and network monitoring purposes.

Figure 4.1 illustrates CSM agents which were sent out by a customer application running on a machine owned by the customer. The customer application also coordinates the agents, processes their feedback and forwards the results to the user. The agents migrate to the peering points to perform particular local checks on the service.

4.3.2 Node Architecture

The CSM agents should be able to perform any kind of passive measurements, however they should not be able to eavesdrop or analyze traffic of other customers. Spoofing of foreign IP addresses or denial-of-service attacks should not be facilitated. Given these requirements we propose the following node architecture as depicted in figure 4.2: At the peering router, there is a *T-component* that serves as a high-performance and configurable packet copying mechanism. The T-component can be configured to copy network packets according to filtering rules based on

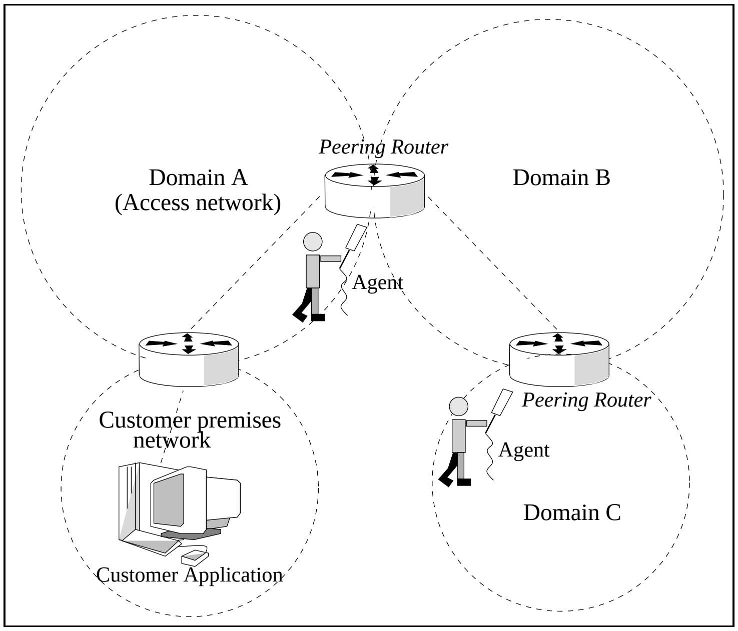


Figure 4.1: Measuring at peering points.

IP packet information such as source and destination address (see section 4.3.3). It adds a high-accuracy time-stamp to the packet. Note, that this is in fact the *generic Internet service monitoring interface*. By being able to examine all relevant IP packets and their arrival times, each IP service and its service level can be analyzed. The T-component forwards the requested packet copies to the *Node environment*. Note, that for security reasons the agents do *not* have direct access to the T-component.

The *node environment* is hosting and executing the CSM agents. Separating the node environment and the T-component enables the provider to run the node environment on a separate machine (with network connection to the T-component). Most providers probably won't want to run foreign code on such a crucial machine as the peering router. Customers send their agents to the node using a standardized protocol (see section 5.1). The agent does not necessarily have to be encrypted, but a strong authentication protocol is needed. This ensures that the node can properly authorize the agent. When the agent arrives at a node, it has to undergo a welcome procedure. After the authentication, the agent asks the node for resources (CPU time, memory and specific traffic). The agent also specifies a packet filter for the bypassing packets it is interested in (see section 4.3.3). Based on policies, the node authorizes the agent for these resources. It provides an execution environment that protects the node from the agent and agents from other agents. The agent execution environment also contains an inbound and an outbound packet queue. The inbound queue provides the agent with the monitored IP packets. The outbound queue lets the agent communicate across the Internet. Using another pair of queues the agent

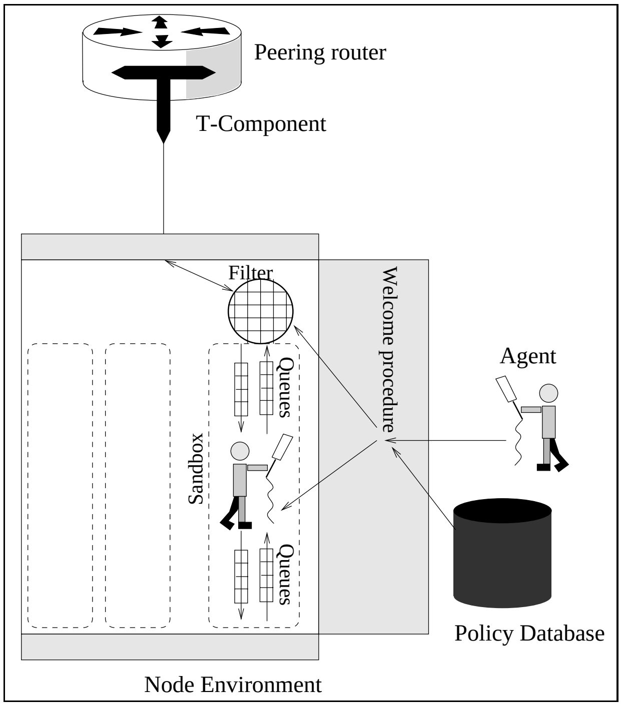


Figure 4.2: The node environment.

can order services from the node and receive the results of these services (e.g. information about neighbor nodes - see section 5.3.4).

4.3.3 Authorization and Filtering

Each agent is associated with a customer of Internet services and has to authenticate itself as an agent of that customer. The customer digitally signs the agent to guarantee its authenticity. Note, that in some cases customers may want the possibility to send anonymous agents. These agents should not be signed in order not to reveal the identity of the customer. Anonymous agents must have little access rights.

The node has access to profiles that describe amongst other things the administrative domain of the customer (e.g. what subnets are owned by that customer - see also section 5.3.5). The profiles also refer to a agent policy which describes what kind of actions the agents of that customer are allowed to perform. An important part of that descriptions is the *filter*. It describes what IP packets can be forwarded to the agents of that customer. The filter holds a set of integer numbers for different parts of the IP header (source and destination addresses, and protocol numbers). A filter can also contain a maximum number of matches, a maximum number of bytes per packet to be copied and a matching probability. The filter will only match packets until the maximum number of matches is reached. The agent will be terminated afterwards. The maximum number can be set to infinity. The maximum number of bytes per packet can be used e.g. to formulate an agent that only analyses the IP header. This reduces the workload of both node and T-component significantly. The maximum number of bytes per packet can be set to any (2^{16} bytes). The matching probability is usually set to 1.0. The matching probability is useful to support an Embedded Advanced Sampling Environment (EASE) [CC98] architecture where only a certain percentage (usually 2%) of the traffic is analyzed. The matching probability also provides a mean to reduce the workload of the CSM infrastructure especially in backbone environments.

The node will only serve the agent those IP packets that match the set. The agent also carries a filter with it to tell the node what kind of IP packets it is interested in. The node calculates the mathematical cut between the policy filter and the agents filter and uses this newly created filter to serve packets to the agent. The new filter forwards all packets that were requested by the agent (that match the agent's filter) and that are also compliant with the filter of the policy. The agent can query if the new filter is empty (matches no packets at all) or not equal to what it has requested, and react upon this (e.g. terminate gracefully). The node holds generic filters in its policies so that it does not need to keep a filter for each potential customer. See section 5.3.5 for implementation details.

4.3.4 Security Issues

The security of the proposed infrastructure bases on three concepts. First and foremost, the agents must authenticate themselves with strong cryptography. Developing these mechanisms from scratch is tedious and probably insecure. Rather the CSM implementation relies on existing and stable technology such as PGP [Zim01], or built-in mechanisms of available agent platforms. Authentication allows the node to relate each agent to a customer, which is responsible for the behavior of the agent. Second, the agents do not run on the controlled network devices but rather on a dedicated general-purpose computer. Thirdly, the agents run in a sand-box. They have no direct access to neither node nor network resources. Their only communication mechanism uses the in- and outbound queues which are controlled by node filters. The cutting of agent filters with a default filter provided by the node assures in a convenient way that the agents cannot eavesdrop or spoof other peoples traffic. The implementation of these security features is described in more detail in section 5.5.

4.4 Mobility Models and Agent Forwarding

CSM uses a simple mobility model that is inspired more by the active networking community than by the mobile agent community. One reason is that the envisioned applications for mobile measurement agents can be implemented by agents that are sent to a location, perform their measurement there while sending some results and then terminate. For such an application it is simply not necessary that the agent can roam self-directed through the networks [BLP00]. Self-directed agents need well funded knowledge about the network and a more complex communication infrastructure. But measurement agents should be small and simple so that customers can program them. This favors a simple send-execute-terminate style of mobility. Nevertheless, sending out many agents one-by-one is a tedious and inefficient procedure. Therefore, this thesis proposes mobility support that is simple, secure and efficient.

4.4.1 Supported Mobility Models

As mentioned above the proposed mobility model is inspired by active networking. There, executable data packets (capsules) are forwarded through the network and get executed wherever there is an execution environment. Ideally, they are executed in every router. This is convenient because then the capsules do not need sophisticated knowledge about the network. They can rely on the local routing information. For CSM however there is no built-in support that extracts the agents from the data stream. CSM is a non-intrusive Internet application that does not assume CSM specific execution environments in the routers. Instead, the CSM nodes provide *agent forwarding* functionality: an agent that arrives at a node is copied, just like a data packet would have been and the copy is forwarded to other nodes, if requested.

We foresee different kinds of forwarding modes:

- **No forwarding.** An agent arriving in this trivial mode is executed at the node but not forwarded to any other node. This model is also referred to as sending an agent *end-to-end*.

- **Broadcast.** A broadcasted agent is first started in the target node. If the agent starts without causing problems (e.g. false authentication) the agent is forwarded (in broadcast mode) to all neighbor nodes. Agents have an identity which is defined by a serial number and the owner's identifier. Each execution environment executes only one agent of a given identity. Thus, the broadcast terminates similarly to a flooding algorithm.

- **Hop-by-hop.** The agent carries a destination IP or node address. The node starts the agent. If the agent starts without causing problems the node forwards it (in hop-by-hop mode) to the next node on the route towards the destination address. For that purpose the nodes need access to routing information (see section 5.7.2).

The broadcast mode allows the customer to easily and efficiently spread agents e.g. to monitor a service at as many locations as possible. The hop-by-hop mode is useful to watch the service behavior along a path, e.g. between two customer subnets connected through the Internet with a VPN tunnel (see chapter 6). It is obvious that both broadcasting and hop-by-hop forwarding save communication capacity when a user wants to install an agent at many nodes. Of course the forwarding of the agents must be limited. Therefore, the agent transmission protocol should carry a time-to-live field that is decremented for each agent instance that is executed. Also, it is important that a node only executes an agent if no agent of that type and of the same user is currently running. This is necessary to avoid that a broadcasted agent fills all available agent places. Another interesting feature is the use of forwarding probabilities. For example, broadcasting an agent with a small forwarding probability could be used to cover a local area with the agent. Another interesting scheme is the hop-by-hop scheme combined with a probability regulated broadcast to cover an area around a network path. The probability idea could be extended with the introduction of an execution probability. The forwarding would then be decoupled from the execution. Some nodes would e.g. just forward an agent but not execute it. This allows sparse distribution of agents. Yet, when only agents that execute without a problem are forwarded this increases security and reduces the possibility of a denial-of-service attack. Note, that a possible model extension is described in section 6.5.2.

4.4.2 Forwarding Security

Since forwarding of agents allows a customer to request resources at many places at (almost) the same time, all agents that request forwarding (and thus multiplying) must be strongly authenticated. The customer signs the agent before sending it. Note that this scheme rules out strong mobility for the agent. To support strong mobility the node has to send the run-time state of the agent. The state changes when the agent is roaming in the network and so the signature is invalidated. The solution would be that the executing node signs the agent. But how can the node take responsibility for the agent in the new state? Think of an agent that develops malicious behavior if it gets in a certain state. The customer signs the static code while the node signs the state. Who is to blame for the malicious behavior? Maybe a previous node manipulated the state so that the agent became unsafe or maybe the customer planned the whole attack. In the CSM approach the customer is fully responsible and it signs the whole agent code. The node only forwards copies of that code. The customer's signature stays valid. However, the node first executes the agent and thus when it forwards the agent it guarantees that the agent is executable. The node can also additionally sign the forwarded agent to increase security. As mentioned before, the forwarding must be limited to a finite number of executions by a time-to-live field value which may be authenticated by the nodes. It cannot be authenticated by the customer because the hosting nodes decrement the number in the field.

4.5 Deployment of the CSM Infrastructure in the Internet

The CSM architecture is non-intrusive. It can be deployed step-by-step. There is no need to change the network topology or the protocol stacks. The CSM infrastructure be deployed based on off-the-shelf technology (see chapter 5). The CSM node can e.g. run in any Java enabled device; it does not require specialized hardware. The architecture can be deployed by a single provider in order to offer an additional service to its customers that offers transparency in the providers service operation and thus builds trust. Of course, the more providers deploy the CSM infrastructure the more value it will get.

4.5.1 Advanced Infrastructure Support

If the customer only uses the end-to-end transmission of agents and if the customer only sends agents to a handful of well-known nodes then no further infrastructure support is needed. However, if there are thousands of nodes and some of their network addresses change from time to time then the customer will have trouble to distribute its agents to interesting places. One option that the customer has is to use the forwarding modes when sending agents. However, then it is the providers that face the same problem. Especially for the hop-by-hop mode the node then needs solve a node routing problem. There are three distinct problems to be addressed:

- **Naming.** CSM nodes and the customers need a name space in which they posses a unique identity. This is also important for signing and encrypting messages. There, the name must identify a public key.
- **Contact information.** Nodes may have different addresses than the routers to be monitored. Nodes may also be moved. Several nodes may be located on a single machine. There must be a way to lookup the contact information matching a node name. This may include the IP address, port numbers and eventually a public key.
- **Routing information.** For agent broadcasting each node must know its neighbor nodes. For hop-by-hop forwarding each node must have access to the IP routing and must also know the node topology.

A solution to these problems must be flexible. It must automatically adapt to changes. The solution should also scale to the large size of the Internet. Nevertheless, these problems are not new. Other IP technologies such as electronic mail have faced the naming and contact information problem. Also, IP routing was improved to meet the requirements. Therefore, these solutions can also be extended to incorporate support for the CSM infrastructure.

The naming and contact information could rely on the domain name lookup system (DNS) [Moc87a, Moc87b]. Nodes and providers are thus identified by email-style names. The DNS node records are extended to contain a record which contains the contact information. Customer can then use DNS queries that use the available name server hierarchy to learn about the CSM nodes.

For the routing information a node should be able to query the routing table of the router that it monitors. This provides IP routing support. For node routing, the border gateway protocol (BGP-4) [RL95] could be extended. BGP is the state-of-the-art Internet routing protocol for the routing between autonomous systems (provider networks). The node routing also takes place at the inter-domain level. Therefore, it makes sense to add CSM parameters to BGP's optional parameters in order to propagate reachability information of CSM nodes. Note, that we did not specify or implement these extensions in more detail. The implementation provides this functionality with an overlay routing system (see section 5.7.2) and is prototypical (see section 5.7).

4.5.2 Integration of the CSM Infrastructure with the Service Broker Architecture

The service brokers are the central part of an architecture to setup new Internet services for customers (see section 2.3 in part I). Providing the service and checking if it is delivered as promised are complementary tasks. However, the delivery may itself depend on service measurement functionality:

- The service broker must know about problems in the operation of the service in order to stop selling the same service to other customers.

- The service broker may need detailed information about the current state of the network in order to calculate if new service request can be admitted. The adaptive reservation scheme for DiffServ is such an example (see section 3.3).

- The service broker may want to find local problem sources of the service operation. This is necessary for trouble-shooting which may also happen automatically,for the start of fail-over procedures (e.g. the use of backup links).

- The service broker may want to find peering providers that do not keep up with the guarantees fixed in inter-provider SLAs. The service broker negotiates new SLAs. It may then generate test agents on the fly that monitor the SLA.

With CSM the broker architecture has access to distributed measurement functionalities. It can use privileged agents on the broker's administrative domain and regular agents to monitor service level agreements.

This presented customer-based service monitoring architecture is the basis for service monitoring with mobile agents. Since the architecture is non-intrusive and only relies on basic agent mechanisms such as authentication and an execution sand-box which is state of the art, such a platform can be deployed in the Internet.

Chapter 5

Implementation of a Customer-based Service Monitoring System

This chapter describes an instance of the proposed customer-based service monitoring infrastructure that is implemented in Java [Sunb, Fla96] (version 1.1.8). For several reasons the Java language is suitable for the implementation. First of all Java is a modern and object-oriented language with powerful built-in support for Internetworking (see section 5.1.2). Java is platform independent, supports character internationalization and is a widely-accepted industry standard. Today, most of the modern mobile agent platforms are implemented in Java (see e.g. the mobile agent list [Hoh], [LO98, VB99, Fün98, SBB+00] to mention but a few).

The implementation is divided into three distinct programs that communicate over TCP sockets as depicted in figure 5.1. A *home application* allows the customer to send agents into the network. The program provides a graphical user interface that can also display the measurement and monitoring results that the agents send back. The application can also store these results on non-volatile media for analysis with other tools. Section 5.6 describes the home application in more detail.

The *CSM node* executes the customers' agents ensuring that no policy is violated. The program is run by the providers. The CSM node is the most complex part of the CSM implementation and is described in section 5.3. It is connected to one or several border routers and aware of the neighbor providers' peer nodes. This is necessary for agent forwarding which was described in section 4.4.

The CSM node gets the monitored IP packets form the T-component. The node tells the T-component what traffic its agents want to monitor and then gets matching IP packets encapsulated in a TCP connection.

This chapter first describes the CSM protocol (section 5.1) because this protocol provides the interface between the customer (home application) and the provider (CSM node). Then section 5.2 describes the T-component and the protocol to transmit the IP packet copies towards the CSM node. After these two protocols which

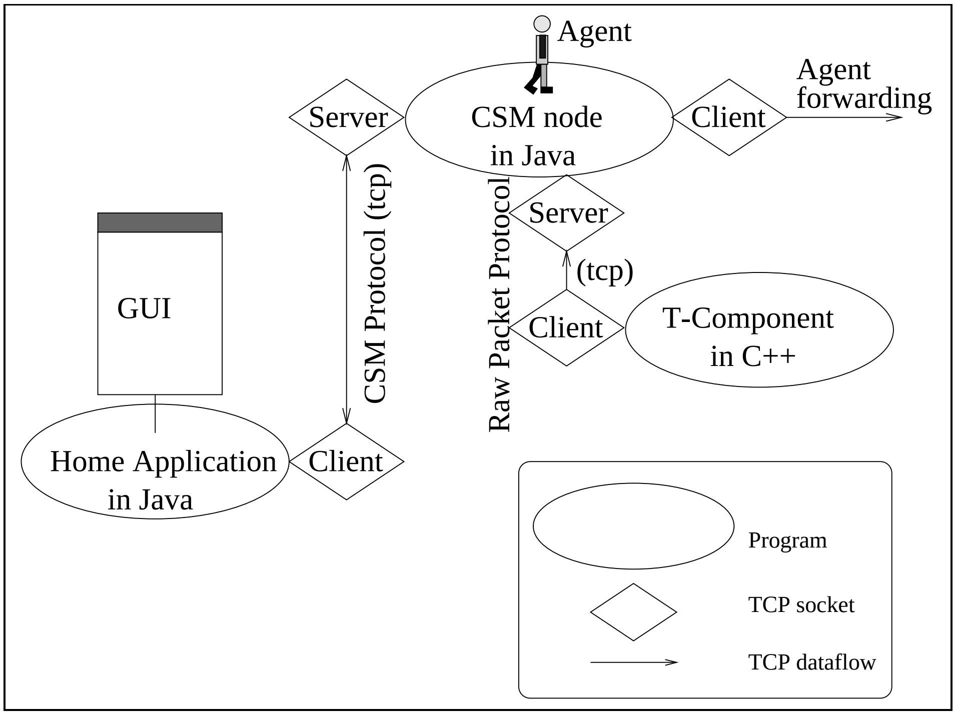


Figure 5.1: Implementation overview.

are important to the CSM node are described, section 5.3 describes the node implementation. Section 5.4 describes the CSM agent interface that customer agents must implement. Then, section 5.5 discusses the implemented security features of the agents, the node, and the CSM protocol. Section 5.6 describes the implementation of a home application. Section 5.7 presents the implemented Internetworking support (routing, naming) and section 5.8 presents the implementation's source code packaging.

5.1 The CSM Protocol

5.1.1 Overview

The CSM protocol mainly implements the sending of an agent to the CSM node. However, it also provides further means of communication between the home application and the node. The home application can e.g. query the node about the node policies and available resources. Furthermore, the forwarding/multicast of an agent from one node to other nodes is also implemented by the CSM protocol. The CSM protocol is a client-server protocol. The home application (or a forwarding node) acts as a client and contacts the server of a CSM node. Messages are encoded as Java objects. The Java object serialization [Suna] is used to transform the objects into a byte stream that can be transmitted along a TCP connection.

5.1.2 Internet Communication with Java

This section presents useful Java Internetworking features that made Java the first choice for the implementation of an agent platform. It also presents how these features be combined to create an open, extensible, and generic interface for CSM communication. Java is the first programming language designed from the ground up with networking in mind [Har97]. The necessary classes are bundled in the `java.net` and the `java.io` package. Network programming in Java is simple and intuitive. The client creates a new socket object, opens the socket and writes to the sockets output stream or reads from its input stream. The `accept` method of a server socket returns an open (client) socket, that can be used by a separate thread to allow multiple clients to connect to the server concurrently. Java provides built-in primitives for the handling and coordination of concurrent threads [Lea97]. Furthermore, Java includes a uniform concept for exception handling that allows the programmer to catch network exceptions and to react in appropriate ways. With Java the programmer can thus more easily write compact networking code than with other comparable languages such as C or C++.

Besides of these basic Java features the implementation of the CSM protocol uses two higher level networking concepts of the Java programming language: object serialization and class loaders.

Object serialization. In object oriented languages [Bud91, BL94] such as Java the data at run-time is represented as objects. An object holds a reference to its class which in turn defines the methods (operations) that can be called on that object. The class also defines the instance variables that each object holds during its lifetime. The instance variables can be primitive data types such as integer numbers or they can hold references to other objects. Thus, at run-time data is usually represented in object hierarchies (objects that recursively refer to other objects via instance variables). Java's object serialization [Suna] provides the programmer a powerful mechanism to transform an object (and recursively all objects referenced by instance variables) into a byte stream. Of course, the serialization mechanism also allows objects of the same class to be instantiated by such a byte stream (deserialization). The bytes of a byte stream can e.g. be stored on disk for later retrieval and deserialization (new instantiation) of an object. The byte stream is also ideal for the transmission of an entire object hierarchy along a network connection.

With few exceptions (such as e.g. `java.io.Stream`) all Java objects and objects of user defined classes can be serialized. All the programmer has to do is to declare his/her new class to be serializable. A user defined class is serializable when it implements the interface `java.io.Serializable`. Doing this is in fact trivial since the declaration does not imply the implementation of new methods. Note, that all classes of the instance variables must be declared serializable as well, else a runtime exception will occur.

Java's object serialization renders the tedious task of defining a message data format superfluous. We do not have to fix the format of the messages exchanged in the CSM protocol down to the bits and bytes. Instead, the CSM implementation provides a message class who's objects carry the necessary data in instance variables. The protocol is thus very easily extendible through subclassing of the message class. To wrap up, the serialization mechanism allows us to use objects as flexible and extensible data structures that can be sent over a network connection. Furthermore, Java's object serialization also features basic version control. If the class definition has changed between serialization and deserialization Java throws an exception.

Class loader. The Java class loader [Mac96] enables the programmer to load new classes at runtime and instantiate objects of these new classes. All the class loader needs to know is an abstract super class or a Java interface of the new object's class. `java.io.Classloader` implements the instantiation functionalities. However, it is an abstract class; the programmer must add a method to fetch the byte code. The method could e.g. load the byte code from disk or download it from a URL. Java capable web browsers for example extend the class loader to fetch applets. All their class loader knows in advance is the abstract class `java.applet.Applet`. When an applet is started, the class loader fetches the applet's byte code from the URL provided in the `html` tag `<applet>`. CSM implements a class loader that gets the byte code of CSM agents from message objects sent across a socket. Java's class loader concepts allows the CSM nodes to dynamically load the agents code thus it provides code mobility. The class loader concept is well integrated into other Java concepts (e.g. security), it is well tested and ubiquitously used in modern web browsers.

5.1.3 Layering of the CSM Protocol

The developers of a CSM application can structure their internal data representation the way they think will fit best. The CSM protocol describes how information is exchanged between a CSM client and a CSM server including involved data structures. The implementation bundles the CSM protocol in a Java package called `clientserver` (see section 5.8). The package contains classes to transmit CSM information across the Internet. The classes provide a layered protocol stack which is described in table 5.1. Transmission of CSM information is processed top-down and receiving is processed bottom-up.

5.1.4 The Protocol Object

The class `clientserver.ProtocolObject` encapsulates all messages that can be exchanged in the CSM protocol. This simplifies the protocol since only one class of objects is transmitted. The object's class is declared to be serializable so that it can be sent across the network.

Table 5.1: CSM communication layers.

Layer	Functionality	Data representation
Semantics	Processes, stores, and generates data in application specific ways.	Application specific objects.
CSM Protocol	Generates and parses the CSM message sequences.	`clientserver.Message` objects
CSM Connection	Opens and closes connections. Encodes (encrypts) message objects and packs them into ProtocolObjects.	`clientserver.ProtocolObject` objects
Network	Byte transmission over TCP.	Serialized `clientserver.ProtocolObject` objects

```
public class ProtocolObject implements Serializable {
    public String senderID;
    public byte encoding;
    public byte messageType;
    public ForwardingDescriptor forwarding;
    public ByteArray message;
...
}
```

The `senderID` field holds an identifier of the sender. This instance variable is also used by the node to associate an agent with a customer. The message itself is serialized into the byte array which is hold by the instance variable `message`. The byte array may hold a message that is signed or encrypted in different ways. The instance variable `encoding` tells what kind of encoding/encryption scheme is used. The CSM protocol implementation supports PGP encryption, PGP signatures [Zim01] and plain byte code. Note, that PGP also compresses the messages. The instance variable `messageType` encodes the communication purpose of this object. It signals the type of the object stored in the `message` instance variable (see also section 5.1.5). The forwarding descriptor is a class of its own, that encodes if this message is handled only by the receiver or if it has to be forwarded and if so, in what way (see section 4.4). The implementation supports two special forwarding modes: broadcasting and hop-by-hop routing. Both forwarding modes are limited by the time-to-live field in the forwarding descriptor, which is decremented for every execution of the agent. As mentioned before, the `message` instance variable holds the encoded protocol message. To put a message (object of a subclass of `clientserver.Message` - see next section) into a ByteArray, the message is first serialized. Then, the resulting byte stream may be additionally encoded/encrypted. This is a transformation from a byte stream into another byte stream. The resulting bytes are finally stored in the instance variable of the ProtocolObject. Figure 5.2 shows how messages are encapsulated in the protocol object, which is then transmitted over the network. The CSM protocol can be easily extended by subclassing the message class and adding the newly desired data and features to it. Also, new encoding/encryption schemes can be added.

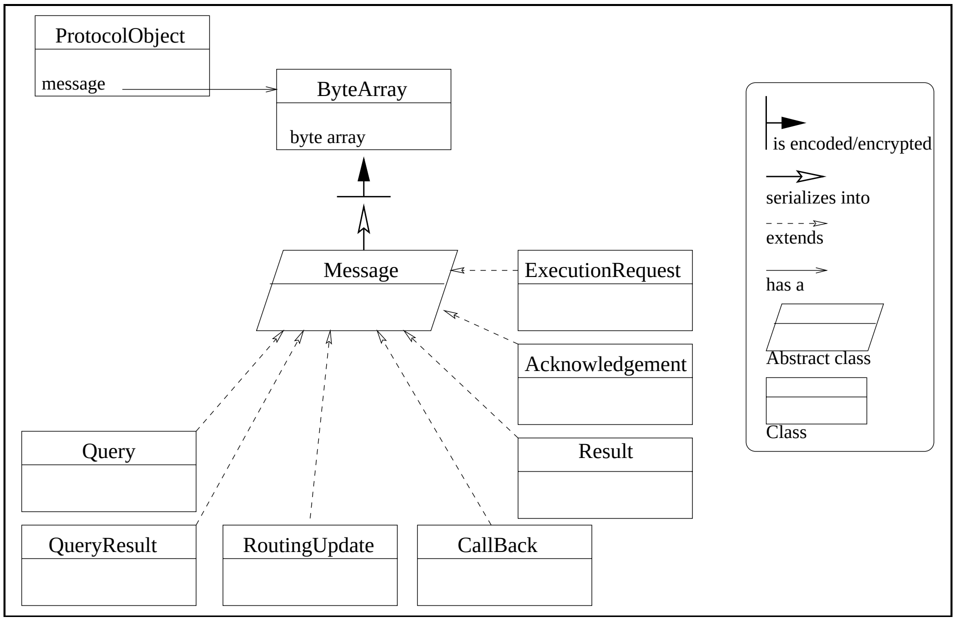


Figure 5.2: The protocol object and the message objects.

5.1.5 Message Objects

Table 5.2 briefly describes the seven message objects (see also figure 5.2) defined for CSM communication purposes and their message type code.

Supported Queries. The CSM query is an instrument for the customer to get information about the available CSM support offered by the providers. Basically, the customer sends a query message to a node. The query contains a type code and optional arguments. Like all CSM messages the query is sent within a ProtocolObject. The node can therefore associate the query with a customer and authenticate the query if necessary. The QueryResult contains a character string that holds a human readable query result. This is sufficient because queries are intended for the human operators of the customer home application. The character string of an answer can simply be written into a Graphical User Interface (GUI) window. Nev-

Table 5.2: CSM message objects.

Type code	Message class	Purpose
1	Query	The customer sends this message to a CSM node to query it about the state of the node or local agents.
2	QueryResult	The node uses this object to answer to a query.
3	ExecutionRequest	The customer sends this message to the node to request the execution of an agent. The message contains the byte code of the agent and a filter describing the IP traffic that the agent wishes to monitor.
4	Acknowledgement	The node sends this object to acknowledge that an agent has been started. It also uses this object to deny access to the node. It then includes a short message as to why the execution was denied.
5	Result	This message is sent from the node to the home application of the customer. It contains results that the agent has calculated at that node.
7	CallBack	The node sends this message to a customer's home application to inform it that an agent likes to send results.
8	Routing Update	A node sends this message to another node to inform it about neighbour nodes.

ertheless, the query classes can be extended to provide machine parsable answers if there is a need for doing so. Here are the currently supported query types:

- **Agent places.** Let the customer query how many agents can run in a node and how many of these agent places are currently free.
- **Agent state.** This query lets the customer know which of his/her agents are currently running on a node and some performance statistics of the agents such as how many packet it has consumed and how long it has been running so far.
- **Node policy.** The node answers with a report of the policy that is applied to the contacting customer's agents. This includes e.g. what filters will apply (see section 4.3.3) the maximum total CPU time an agent can use and the transmission rate that the node provides to an agent.
- **Node services.** Provides a list of the services that an agent can request from a node together with a short description of each service (see section 5.3.4).
- **Neighbors.** This query delivers contact information such as IP addresses and port numbers of neighbor nodes of the queried node.
- **Routing.** The customer can ask the node to what node it would route an agent that is heading for a specific IP address. This query was used for the debugging of the agent forwarding.

5.1.6 CSM Message Exchange Sequences

All CSM communication is implemented using TCP connections. This is useful since the CSM protocol is not time-critical but should be reliable. The CSM client connects to the server on a well-known port. A TCP connection is only used for one transaction (complete and valid sequence of messages exchanged), thus the message objects do not have to contain a sequence number. The CSM communication transactions are grouped according to their three purposes: information of customers (queries), transfer of agents and agent results, and node topology administration.

Queries follow a simple pattern. The client (the home application) opens a connection to the CSM server port of a node. It sends a query object and receives a query result. Afterwards both communication parties close the connection (see figure 5.3).

For agent execution the client wraps an agent into an ExecutionRequest message. It sends this message and receives an Acknowledge message (see figure 5.3). The message contains a bit that signals whether the execution is accepted by the node or not (Nack). If the node executes the agent it hands the open connection to the node service handler. By requesting the *result transmission* node service the agent can now use the open connection to send an arbitrary amount of Result messages. The result message can indicate if the agent wishes to close the connection. Note, that the node can close the connection at any time if it detects a policy violation.

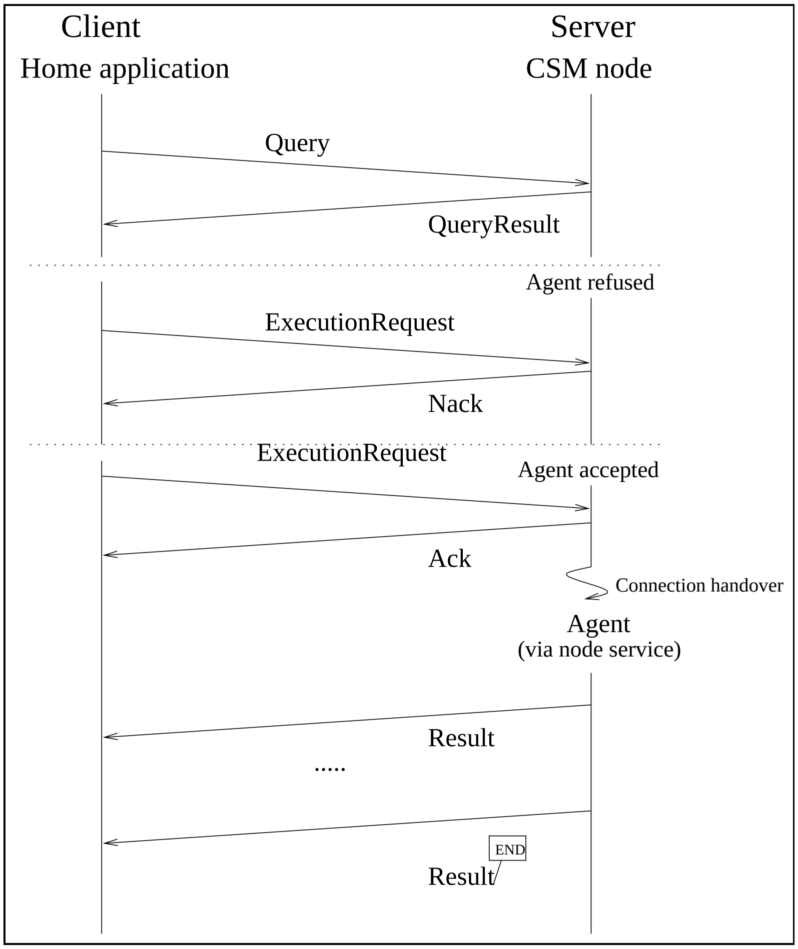


Figure 5.3: The query and the agent execution protocol.

If the agent is forwarded (a node is acting as a client - see section 4.4) the results of an agent cannot be sent along the connection. Else, a forwarding node would have to keep many connections open and route results of forwarded agents. Instead, agents close the connection with a dummy result and request a new connection from the local node. The node then sends a CallBack message object to the address and port provided by the agent. Again, the agent then sends its results along the open connection using the Result message objects in the same way as described earlier. Note that customers can easily introduce new result formats by subclassing `clientserver.Result`.

The RoutingUpdate message is no fundamental part of CSM communication. If a node learns about new neighbor nodes, it sends this message to all of its neighbors and then immediately closes the connection again. The CSM nodes use this one-way message to implement a node routing table (overlay topology), so that nodes can learn how to forward agents along a route towards a given IP address (see section 5.7).

5.2 The T-Component and the Raw Packet Protocol

The T-component is a packet copy mechanism integrated directly in the peering router or attached to the peering connection. The T-component provides the genericity to customer-based service monitoring. It does so by giving the customer access to any IP packet of an IP service associated with that customer plus the packet's position in time and space. The CSM architecture separates the T-component from the CSM node for several reasons: The T-component must be very fast and should not interfere with the normal packet forwarding of a router. Therefore, T-components depend on the specific architecture of the peering points. T-components will meet these requirements best if they are directly integrated by the network equipment manufacturer or if they are implemented in network specific measurement hardware such as protocol analyzers [CC98]. A T-component can also be used for other applications than just customer-based service monitoring (e.g. provider specific management software). So, because of the its equipment dependence and its usefulness in other contexts it makes sense to factor out the T-component into a separate entity.

This section describes what kind of T-components have been implemented, how these T-components interact with the CSM node, and what other options exist to implement a T-component.

5.2.1 T-components Implementations

The CSM implementation can use three kinds of T-components: an offline version that uses traffic traces stored in files, an online version that copies IP traffic from Ethernet cards in promiscuous mode and a version for virtual routers which is called *t-bone*.

The former two component versions are related to each other. Both are Unix shell scripts that start a C++ client to send the packet copies and use the Unix pipe and filters mechanism to feed the C++ client. Both T-components use the tcpdump program [JLM89]. Tcpdump is a network management tool that is normally used to print out the headers of packets on a network interface that match boolean expressions. It supports also binary traffic dumps of complete layer two packets. One T-component uses this mode and the boolean expression to copy IP traffic. The offline component version of the T-components uses tcpdump output that has been previously stored in a file while the online version starts tcpdump directly with the appropriate boolean expression.

The t-bone is a T-component for so-called virtual routers [BB00]. Virtual routers are emulations of IP routers that can run on one or more PCs. The routers can forward IP traffic generated from real world applications. The t-bone is written in C and also includes the client functionality to connect to the node.

5.2.2 The Interaction between the Node and the T-component

Since the T-component is device dependent and may be realized in software or hardware standardizing a communication protocol may not be useful. However, to reduce the implementation work the communication between node and the T-component is kept simple and uniform. All three T-component versions use the same protocol to send packet copies. The protocol is called the Raw Packet Protocol. However, the T-components differ in the way the node requests the copies. For script based T-components the node starts a new T-component for each request. It passes a T-component-specific filter description, an IP address and a TCP port number as arguments to the script. Once a script-based T-component runs it uses the port and address to open a TCP connection to the node. Then it starts sending the copied packets. The T-component for the virtual router is more convenient. The node simply connects to the T-component and requests the packets. The T-component then sends the packets over the already open connection.

Request for IP packet copies. The node contains an object of the class `node.T_Configurator` which is able to order packet copies from T-components or to start T-components if needed. As mentioned before two of the available T-components are scripts. The configurator starts the offline T-component with a file name as argument along with port and address for the callback. The online version also gets the boolean filter expression for the tcpdump program. The configurator calculates this expression from the filter that the node generated for the agent (see section 4.3.3). Therefore, only packets are sent that the agent has requested and that are allowed to be seen by the agent. In case the node is not located on the machine to be monitored, the script is started remotely using UNIX's `rsh` command. Note, that each agent gets its packet copies on a separate connection. This improves the CSM performance since the demultiplexing of packet copies would impose additional workload on the node which could then become a bottleneck. Also, when using scripted T-components, each agent leads to the start of a T-component. This is not the case for the t-bone, the T-component of the virtual routers. Instead, the t-bone is started as an attached program to a virtual router. The t-bone includes a TCP server that accepts requests for IP packet copies. A request consists of a human readable ASCII string terminated by the end-of-line character. The syntax and semantics is not described in detail here, because it is device specific. See this illustrating example instead which orders the next 100 packets of TCP traffic coming from the subnet 10 and going to the subnet 11.12.13:

```
gimme -number 100 -src 10.10.10.10/8 -dst 11.12.13.14/24 -proto 6
```

Note, that the t-bone's server is reentrant. It can handle several node requests at the same time.

Delivery of the IP packet copies: the raw packet protocol. All T-components send the packets on an open TCP connection according to the raw packet format. The format has a fixed header of 10 bytes followed by a variable payload part that contains a copy of one IP packet. As long as the T-component copies packets it keeps sending a header followed by a variable part. The protocol finishes when either the node or the T-component closes the TCP connection. The header uses little-endian numbers. The first two bytes encode the length of the payload in bytes. This reflects the possible length of the encapsulated IP packet. Note, that we cannot use the length field of the IP packet since the T-component may already have truncated the payload according to the filter it has got from the node. The other eight bytes of the header encode a time stamp. The timestamp stores the time that has passed between the 1.1.1970 and the arrival of the packet. The first four bytes encode the seconds the second 4 bytes encode the micro seconds.

5.2.3 Other Options for T-components

The T-component is device specific and this influences also the way the node has to request packet copies. In this section we discuss alternatives how the T-component can be implemented focusing on how the packet copies can be acquired in a non-intrusive way. We differ between an approach using additional hardware, one using additional functionality provided in network hardware and a software based approach.

Protocol analyzer hardware. As said before, the T-component may acquire the packet copies from a protocol analyzer [CC98]. Protocol analyzers are instruments dedicated to analyze a communication protocol. Protocol analyzers are used to troubleshoot network problems and to monitor network performance. The analyzer has built-in knowledge of the protocol to ease the analysis (e.g. for Ethernet or for ATM). Nevertheless, a protocol analyzer has the capability of passive traffic recording therefore it can be used as a T-component. Often traffic analyzers are portable devices with dedicated hardware and high performance. However, they are usually expensive. Also they provide far more functionality than needed for a T-component. Finally, there is no standardized interface to control protocol analyzers remotely.

Enhanced network devices. The Simple Network Management Protocol (SNMP) [CFSD90, Sta99] is an Internet standard protocol to manage and monitor nodes on a network. Network state information is structured in Management Information Bases (MIB). If the peering device fully supports the Remote Network Monitoring MIB (RMON) [Wal95, Wal97] it can act as a T-component. RMON defines objects of of a so called *filter group* that allows the CSM filtering and objects in a so called *packet capture group* which can be used as the CSM packet copy mechanism. Unfortunately most router manufacturers do not fully support the packet capture mechanism. Cisco for example only supports the capture of packet headers [Cis00a]. For testing purposes however, we used the port-redirection mechanism [Cab98] (which is a subset of the packet capture group) of Cabletron's SmartSwich to feed a T-component.

Packet capture software. Modern operating systems allow personal computers to act as routers. They also provide libraries to capture and copy routed network traffic. For example `libcap` is a packet capture library for Unix systems [MJ93]. On Win32 platforms the NDIS packet capture library is included. Developers can use these libraries to implement network measurement applications (e.g. [DS00]) and of course to implement a T-component. However, the performance of a software solution depends on the implementation of the library, the speed of the host machine and on the operating system.

5.3 The CSM Node

This section describes the CSM node implementation which is a central part of the CSM implementation. The node is divided into four functional parts: CSM communication, agent management, node topology and configuration. This chapter will not list all involved classes because a lot of that material is not relevant for CSM. Instead it will focus on the important features such as agent execution, node services and overall design.

5.3.1 Node Overview

Figure 5.4 shows a simplified object hierarchy of a running node. A node is started by creating a node object. The node object has a number of helper objects from different packages to setup and provide the node functionality. This subsection briefly explain the most important ones. The node uses helper objects from the `config` package to learn about its basic configuration such as its unique name, node resource limits (e.g. number of agent places), the location and type of T-component to be used and other configuration sources e.g. additional file paths and names. The `config` package was factored out because it can not only be used by the node but also by e.g. the home application. This is also true for the `topology` packet. This packet includes classes that can provide a name service, a neighboring service and a routing service to the node. The name service is used to map a node name to an IP address and port number. The neighboring service consults a configuration file to provide names of neighbor nodes. The routing service includes a client-server functionality (using the CSM protocol) to dynamically establish a routing table for forwarding agents from node to node. The node has a server that receives queries or agent execution requests via the CSM protocol (see section 5.1). Arriving CSM requests are delegated to appropriate handlers. Another important node object is the Registry. It registers agents and manages the available resources. The registry does the admission control. It associates agents with users and attaches individual policies to the agents. The registry deduces the policies from user profiles stored in a file. The registry also has a ResourceController object which dynamically checks the resource consumption of the agents. The registry stores handles to the running agents and to their execution environments.

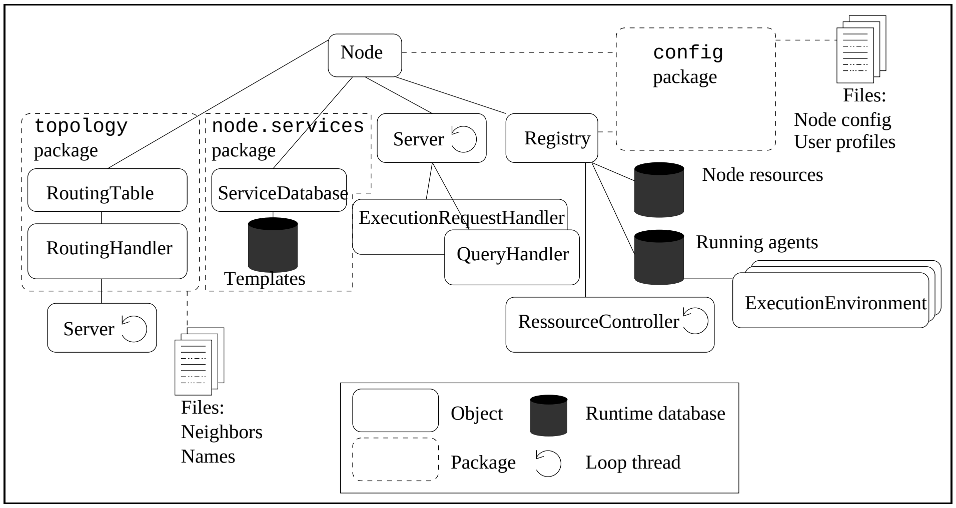


Figure 5.4: Node implementation overview.

5.3.2 Welcome Procedure for an Agent

A customer request for the execution of an agent first arrives at the server which starts a new thread to handle the request. The request then goes through the CSM protocol stack (see section 5.1.3). The stack delivers an ExecutionRequest to the ExecutionRequestHandler along with information if the agent was encrypted and successfully authenticated. The handler will now register the agent and prepare the execution environment for the agent before it finally starts the agent. Here is the procedure in more detail. Note, that each step can fail. In that case the sender of the agent gets a negative Acknowledgement message containing an error description (see section 5.1.5). The handler also resets allocations for the agent made in earlier steps.

1. The handler contacts the registry to get a policy for the agent. The registry uses the sender and the authentication information to determine the appropriate policy. It can also entirely reject the agent.
2. The handler instantiates the agent object using the AgentClassLoader. This classloader can create an Agent object from an ExecutionRequest message

(containing Java byte code).

3. The handler creates the filter to be applied to the agent by cutting the requested filter (in the ExecutionRequest object) with the filter of the policy (see section 4.3.3).
4. The handler starts preparing the execution environment for the agent. If the T-component uses a callback mechanism (see section 5.2.2), the handler allocates a port for that purpose. It also instantiates the execution environment components and queues (see section 5.3.3).
5. The handler instantiates a ExecutionEnvironment which is a container for all objects that are part of the execution environment.
6. The handler instantiates a RessourceUsage object that holds references to the ExecutionEnvironment and that is used to account the resource usage by the agent.
7. The handler registers the agent at the Registry. This may fail if e.g. a runtime resource over-usage has occurred (see section 5.5).
8. The agent is initialized to prepare it for the reception of monitored traffic.
9. The handler now starts the execution environment. First it installs the node services. Then the node service handler, the agent wrapper (that feeds the agent) and the receiver of the raw packet protocol (see section 5.2.2) is started (in this order). Each is running in a separate thread.
10. The T_configurator is started to start/connect to the T-component.
11. The forwarding of the agent is triggered.
12. The agent is acknowledged via the CSM protocol.

5.3.3 The Execution Environment

The execution environment encapsulates an agent. It protects the node from the agent, forwards the monitored traffic to the agent and serves the agent's service requests. It also accounts every operation of the agent. A specialty of the proposed CSM node architecture is that the agent does not get its own thread. Instead the agent is invoked by the environment whenever there is something to do. This approach increases security and makes resource accounting easier. Although the approach introduces a performance overhead due to thread context switches, the overhead is not a bottleneck of the CSM implementation (see chapter 7).

The execution environment mainly consists of subclasses of the abstract class `node.EnvironmentComponents`. Figure 5.5 shows the inheritance graph for the execution environment components.

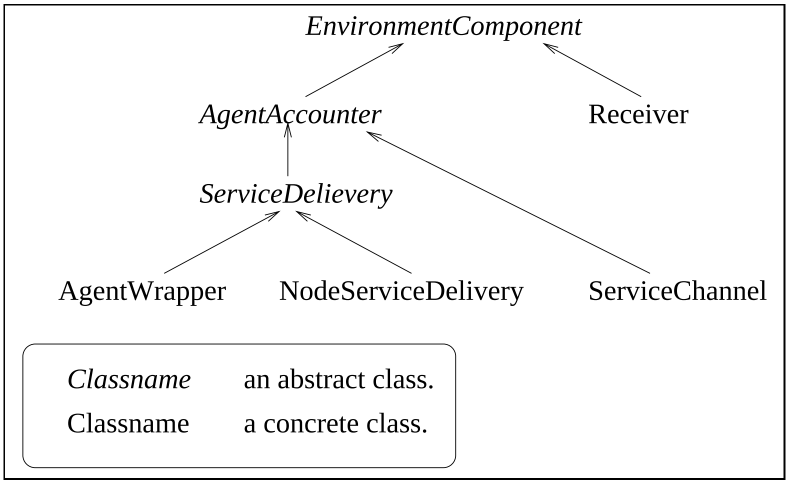


Figure 5.5: Execution environment inheritance graph.

All EnvironmentComponents encapsulate and run in their own thread. The thread management functionality is implemented in this abstract super class. The AgentAccounter contains functionality to record the running time of a single method of an agent. The ServiceChannel handles service requests of the agent (see section 5.3.4). The abstract ServiceDelivery class implements functionality to call methods of the agent, thus to start agent behavior. The objects of (sub)class ServiceDelivery are the only objects of the node that call methods of the CSM agent. Two classes use that functionality. The AgentWrapper delivers the monitored IP packets to the agent by calling a method of the agent and passing an object of class IPPacket to the method. The NodeServiceDelivery also uses a method call to the agent to deliver a result of a service that the agent has requested.

Figure 5.6 shows the internals of an execution environment. The Receiver gets the monitored IP packets from the T-component via the raw packet protocol. It creates an IPPacket object of each received packet an puts it in an ObjectQueue. The AgentWrapper (running in a separate thread) eventually grabs the packet and hands it to the agent via a method call. For accounting purposes the wrapper measures the execution time of the method call. Note, that each agent's reaction to the monitoring of an IP packet is running in the thread of the AgentWrapper. The agent can calculate its measurements on the packet, store temporary results, and request node services by putting a Service object in the ObjectQueue of the ServiceChannel. One important service of the node is to send back an agent result to the home application. Some services put a reply to the service invocation into the queue of the ServiceDelivery. The delivery of this reply proceeds similar to the delivery of monitored packets. Note, that the execution environment architecture completely separates the agent from the rest of the node. The only object reference to node objects that the agent has is to the ServiceChannel. There the only method the agent can call is the `put(Service service)` to request a node service. Furthermore, the agent can only run when it is called. Note, that the AgentWrapper and the NodeServiceDelivery are quite similar. In fact, another design alternative would only foresee a ServiceDelivery. An additional node service would then be that the agent can request monitored packets. This would simplify the design. However, the agent would have to demultiplex service replies that are monitored IP packets and other service replies. Since usually the node services are used only sparingly but monitored IP packets may come in fast, bursty, and must be handled as fast as possible I decided to provide a separate lane for the monitored packets. Also, the mentioned duplication of functionality did not result in duplicated code since the implementation factors out the common functionalities of the AgentWrapper and the NodeServiceDelivery into the common superclasses (see figure 5.5).

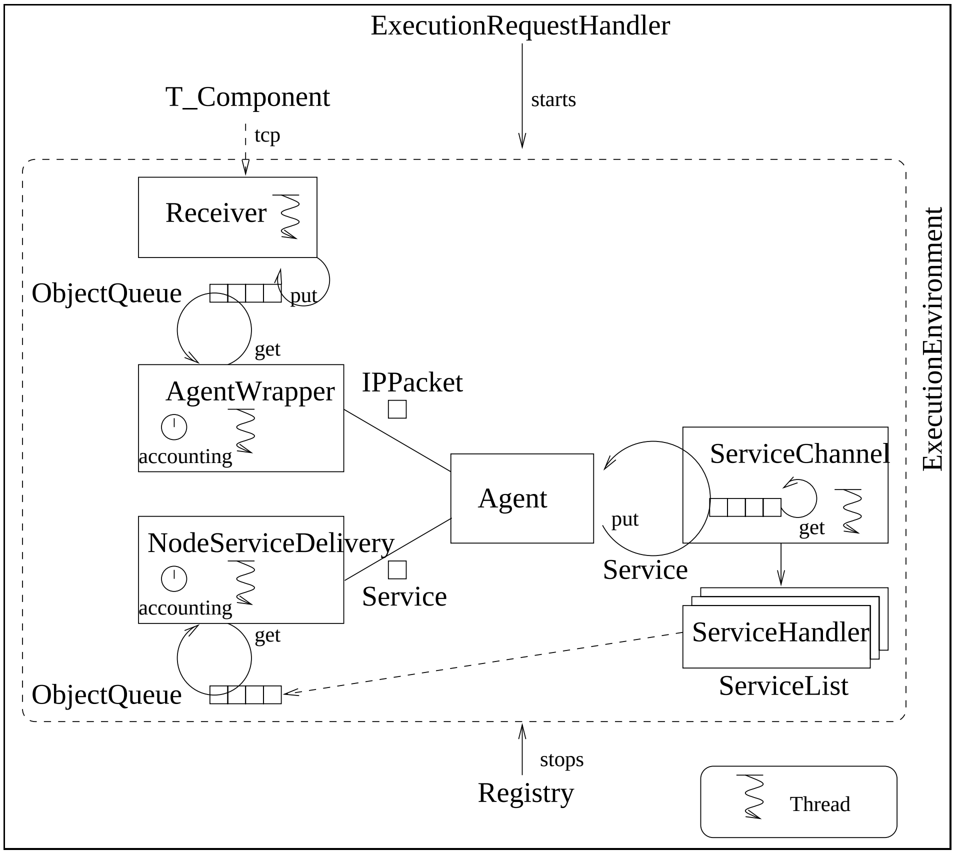


Figure 5.6: Execution environment.

5.3.4 Node Services

Running agents have only one object reference to the execution environment and this is a reference to the ServiceChannel where they can put request for node services. The classes that support node services are bundled in the a sub-package of the node named `node.services`. To request a service the Agent creates a `Service` object and puts it into the queue (see figure 5.6). Some services generate one or more replies that are delivered back to the agent by the NodeServiceDelivery object of the execution environment. Note, that the delivery is asynchronous, it takes place via a queue. The class `Service` is defined as follows:

```
public class Service {
    protected static long current=0;

    protected long number;
    protected int type;
    protected java.util.Vector args;

...
}
```

Each service request is numbered (instance variable `number`). The (static) class variable `current` helps to guarantee the uniqueness of the number. The `type` field identifies the desired service. Different services may need different kinds and numbers of arguments. The built-in Java class `java.util.Vector` is a container of an arbitrary number of arbitrary java objects. A vector is thus the ideal type for the `args` instance variable which has to store the arguments for all kinds of service requests. Replies to the service are also delivered in objects of class Service. The type and number field of these objects allow the agent to map a service reply to the request that triggered the reply. In the reply the arguments hold results or status messages of the reply.

The ServiceChannel removes service requests from the queue. It has a ServiceList that stores references to a handler for each service type. The ServiceChannel calls the appropriate handler and passes the service request to it. The ServiceHandler then executes the service operations. It also puts results (if there are some) in the reply queue. The service channel and all service handlers can terminate the agent if the agent requests services without permission or if a serious exception occurs during delivery of the service. The ServiceDatabase stores templates of service handlers. When the execution environment of an agent is constructed (see section 5.3.2) the service list for the agent is constructed from the templates in the database according to the policy that is valid for the agent in question.

Supported node services. Here is a list of the node services that the CSM node implementation supports, along with a short description of the service, its arguments and its reply behavior:

- **Self-termination.** As mentioned before, the agent has no own thread. Instead it is invoked by the execution environment every time there is something to do. If the agent wishes to stop these invocations it calls this service.

The node will then deallocate the execution environment and de-register (thus kill) the agent. The self-termination service request has no argument and will trigger no reply to the agent.

- **Result transmission.** The agent can request to send a result object along its open connection. This is the most important node service since it is the only way how the agent can deliver monitoring results to the customer. The open connection that is used for the transmission is usually the one that the agent was delivered on. The service object must contain an object of class `clientserver.Result` as argument (see CSM communication in section 5.1). CSM communication is reliable therefore the agent does not get a reply.

- **Host information.** This service provides the agent with general information about the host that executes it. Thus, forwarded agents can check themselves if they monitor traffic at interesting locations. This service request has no arguments. The reply contains three arguments. The reply includes the name (identifier) of the node, the name of the organization owning the node, and the DNS address of the node. These names are encodes as Java character strings.

- **Timer.** Since agents are only invoked when something (e.g. a monitored packet) is delivered an agent cannot perform tasks based on regular time intervals or time-outs. Consider an agent that measures the load of a service that is not used. If no packet is monitored the agent stays passive and cannot report that the service is not used. To alleviate this shortcoming the CSM nodes offer a timer service. The service delivers a reply to the agent every x jiffies[1] for n times. The agent uses two integers numbers as arguments in the request, namely x and n. Each of the n replies will 'wake up' the agent and allow it to e.g. send a report message. The replies contain an integer number that simply contains the reply number.

- **Change the connection.** This service closes the currently open connection and tries to open a new one. This service is important for forwarded agents since these do not have an open connection to their home application. The agent must provide several arguments in the request: a character string for the DNS name of the receiver, an integer number for the port, two boolean values that indicate if the node should encrypt respectively authenticate the connection and, if so, a character string with the identity of the receiving party (used for PGP cryptography). The service handler then disconnects the current connection and tries to establish the new connection. The service reply contains a boolean indicating if the connection was established. To send on the new connection the agent simply uses the 'sending' service.

---

[1] Here, a jiffy is equivalent to 100 milliseconds.

- ***Stop all agents.*** This service stops all running agents and deallocates their execution environment. It thus resets the node. This is a privileged service that only authenticated and authorized agents can execute. It takes no argument and does not invoke a reply.

- ***Stop the node.*** This service leads to the graceful termination of the complete CSM node. This is a privileged service that only authenticated and authorized agents can execute. It takes no argument and does not invoke a reply.

Note, that the first five services are considered standard and are provided to all agents. The last two service need explicit permission by the policy (see section 5.3.5). They are useful for managing the CSM nodes. Some interesting but unimplemented node services are described in section 6.5.2.

Security of node services. The node services allow the agent to perform actions that otherwise are forbidden and prevented. The agent cannot, for example, open a socket. The security manager would terminate the agent for trying this operation (see section 5.5). Node services provide access to dangerous functionality in a controlled way. Each agent is associated with a policy that exclusively describes what services are delivered to that agent (see next section). If the agent requests other services or does not provide proper arguments it is killed immediately. The node policy can also mark some services as privileged services. The node stopping service can for example only be triggered by an agent that was authenticated as being send by a root user of the node. The ServiceHandler accounts the service execution time. This helps to prevent node service based denial-of-service attacks by the agents. Furthermore, each service handler can restrict the number of consecutive service requests. The timer service can e.g. only be called once. All node services are designed to execute quickly and to use little node resources. The timer service e.g. uses a large minimum time between tow wake-ups. The change-channel and sending service enforce that only one connection can be open at any time.

Additional node services. Of course, one may imagine many more useful node services. One service for example could be the migration of an agent. An agent could request that it will be send to another node. It could also request that its state be preserved (strong migration [SBB$^+$00, BLP00]). Yet, non of the CSM applications described in chapter 6 need strong mobility. So this is not a supported feature of the CSM node implementation. Instead, agent forwarding is used (see section 4.4). However, if a new node service such as strong migration will become needed, adding a new service is no problem. The CSM node developer simply has to provide a new template for the service handler (a subclass of ServiceHandler) which implements the service and add it to the service database.

5.3.5 User Profiles and Policies

Each agent has an individual policy attached to its execution environment. The policy is individually calculated by the Registry during the welcome procedure of the agent (see section 5.3.2). While the execution environment is set up the environment components access the policy information that is relevant to them. Then the components can enforce the policy directly. Other objects such as the resource controller (see section 5.5) also access the policy throughout the lifetime of an agent.

The Policy. Policy objects represent agent resource limits and authorization during the lifetime of an agent. Here is the interface (the public methods) of the Policy class:

```
public interface Policy {
    public Filter
      getFirstMatchingFilter(filter.Filter requested);
    public boolean mustAuthenticate();
    public boolean isSuperUser();
    public long maxExecTime();
    public long maxMem();
    public int time2live();
    public short priority();
    public Vector services();
}
```

The `getFirstMatchingFilter()` method takes the filter requested by the agent and returns the filter that will finally apply to the agent. This method implements the filter policy. The registry uses this method to learn the filter to be used when installing the filtering of monitored IP packets. The `mustAuthenticate()` method implements if the agent associated with that policy must authenticate itself with cryptographic means. The `isSuperUser()` method tells if the agent associated with that policy is sent by a super user. The `maxExecTime()`,`maxMem()`, and `time2live()` methods provide policy information about limits to the runtime resource consumption. The `priority()` returns the priority of the agent. These methods are used by the resource controller. The `services()` returns a list of node service types that the agent is allowed to request.

User profile. In order to associate a policy to an agent the registry consults the user database (see figure 5.4 in section 5.3.1) to retrieve a user profile. The user profile stores a user ID (that is necessary for cryptography), network addresses administered by that user, what kind of policy is applied to the agents of that user, and the type numbers of additional node services granted to that user. Table 5.3 shows how a user profile database may look like. The first two profiles are normal customers. The third one is a super user. The last one is an anonymous user. The anonymous user is not associated with any IP subnet. The CSM node implementation stores the user profile in a file.

Table 5.3: User profiles.

Node ID	Networks	Policy group	Services
admin@iam.unibe.ch	130.92	CustomerPolicyGen	
admin@cui.unige.ch	129.194.90	CustomerPolicyGen	
root@iam.unibe.ch	130.92 129.194.90	SuperPolicyGen	555 666
anonymous		AnonymUserPolicyGen	

Policy Generators. The user profile describes what kind of policy is attached to agents of that user. The description may be complex, so it is not done in a data structure but instead it is stored in a separate class. Therefore, policies can e.g. use different procedures to calculate the filters. This would not be possible with (passive) typed data. However, introducing a policy class per customer would not be a very scalable solution. Instead, CSM uses policy generators. A policy generator abstracts a group of similar policies. At run time it generates policy objects of that group. The example profiles in table 5.3 refer to three kinds of policy generators. One functionality of the policy is that it limits the filters that an agent can request. The CustomerPolicyGenerator creates policies that use the cut mechanism (see section 4.3.3) to permit only the monitoring of traffic that originates from or goes to IP addresses associated with the customer. The SuperPolicyGen creates a policy that allows arbitrary monitoring. The AnonymousUserPolicy creates a policy that allows only monitoring of packet headers or of encrypted traffic. On the other hand the agents under the AnonymousUserPolicy policies do not have to be authenticated. Note that the introduction of new policies is simple. You only have to generate a subclass of Policy that implements e.g. the filter cut mechanism the way you want. Then, you have to create a subclass of `PolicyGenerator` that calculates and creates (possibly using the user profile) a policy object with the behavior of your choice.

Figure 5.7 shows the an overview of the use of policies, policy generators and user profiles.

5.4 Agent Interface

This section describes what the CSM node knows about the agent. It does not present the implemented agents. They will be presented in chapter 6. From what has been said in section 5.1.2 we know that the classloader needs an interface declaration or an abstract class description of the class that implements the customer agent. Note, that this is not necessary for the helper classes that the agents' byte

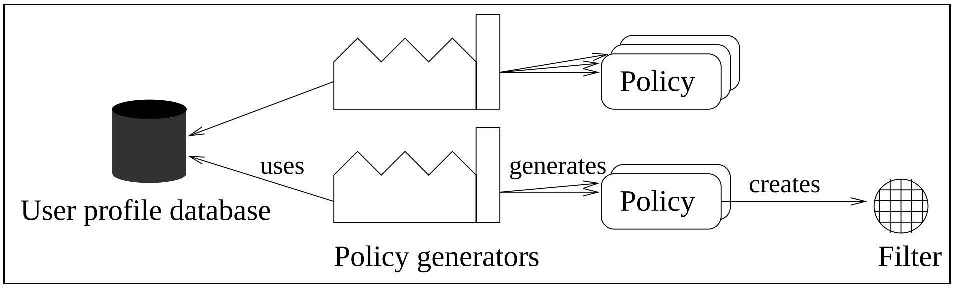


Figure 5.7: Overview of policy, policy generators and user profiles.

code may bring with it. The helper classes are only used by the agent itself, so the hosting environment (the node) has not to know about them.

CSM defines an interface that must be implemented by all CSM agents in order to be executed in CSM nodes. Here is the interface declaration of the agent.

```
(1) package capsule;
(2) public interface Agent extends java.io.Serializable {
(3)   public void handlePacket (node.IPPacket p);
(4)   public void handleService (node.services.Service s );
(5)   public void emergencyHandle(node.IPPacket p);
(6)   public boolean init(java.util.Vector initVector);
(7)   public void stop();
(8)   public void putServiceChannel(node.ServiceChannel s);}
```

The line (1) says that the agent interface declaration is located in a separate package called `capsule`. The separation is used to ease source code management at the customer side of the application, where hundreds of agents may be implemented. The name of the package comes from the active networking background of the CSM application where a capsule is an executable network packet. Line (2) starts the interface declaration. Note that for resource management the agent must be serializable (see sections 5.1.2 and 5.5). The lines (3-8) declare the public methods that an agent must implement. As mentioned in section 5.3.3 the AgentWrapper object calls the `handlePacket()` method of an agent to deliver a new monitored IP packet. The AgentWrapper gets the packets from a queue. If the queue is almost full (filled up to e.g. 80 percent) the wrapper does not call the `handlePacket()` but the `emergencyHandle()` method (line 5). The exact value of the fill level that triggers emergency handling is defined by the local node policy. The agent can should thus implement `handlePacket()` as a method for fast packet handling in case of congestion. This reduces the risk for the agent that it is killed by the node because of a full queue (see section 5.5). The `handleService` method is called by the ServiceDelivery object to deliver a reply to a node service request. The `init` method is called after the agent was instantiated but before monitored packets are delivered. Thus, the agent gets a chance to prepare itself for the packet handling. The init method uses a `java.util.Vector` object as a generic container for an arbitrary number of initialization arguments. The method returns whether the initialization was successful. If not, the agent is stopped. The `stop` method is called when the agent is stopped gracefully. This e.g. happens when the upper limit of packets to be delivered is reached. In this method the agent can for example implement the sending of a final report to the home application. The `putServiceChannel` method is only called once, during the initialization procedure of the agent, in order to connect the agent to the service channel. The service channel is the only way the agent can communicate with the node and with the rest of the world.

5.5 Security and Resource Control

5.5.1 Communication Protection

The CSM protocol implementation (see section 5.1) provides the capability to encrypt and authenticate messages using the Pretty Good Privacy program (PGP 2.6.3i). This PGP version encrypts with the International Data Encryption Algorithm (IDEA) [Lai92] using a 128 bit session key. The protection of the key exchange and the signature is supported by the RSA algorithm [RSA78] using a 1024 bit key pair. The CSM protocol supports three modes: plain text, encrypted and signed, and only signed. When the client contacts a server in one mode, the server always replies in the same mode. Thus, when the customer sends an encrypted agent also the results to be sent back are encrypted by the node. Agents that use the call-back can request the mode that the node should use. Therefore, intermediate providers cannot access encrypted results that an agent sends back to the home application unless the providers conspire. So, all CSM protocol actions (e.g. agent sending, result reception, queries etc.) can be protected if desired against man-in-the-middle attacks. Note, that currently only PGP based protection is implemented. Yet, the CSM protocol can easily be extended to other cryptography packages.

The regular IP traffic flow must be protected from the monitoring agents. The node does so by applying a policy that controls the filtering. The policy uses filters to describe what kind of traffic an agent may monitor and how much of that traffic the agent can see (see section 4.3.3). If a provider does not install the proper filtering policies the agents may get access to other customer's traffic. However, this is also the case today. The next section describes why an agent cannot circumvent the node policy mechanism such as e.g. the filtering.

5.5.2 Security Layers of the Node

The node encapsulates the running agents in sand-boxes to deprive them from any possibility of manipulating the node or other agents. The execution environment of the agent is its sandbox. It exposes only a reference to one single object namely the ServiceChannel. Java offers protection mechanisms for class methods. A method can be declared accessible by objects of that class only, by objects of subclasses only, by objects of classes in the same package or by any object. The CSM implementation isolates the agent classes in an own package and uses this mechanism to protect all methods of the ServiceChannel so that the agent only can access one method. The methods simply puts a service request into a queue (see section 5.3.4) so it cannot be misused for an attack. This one method on one object reference is the agent's only access point to the node. The agent also has no own thread. It completely depends on the computation time that of the threads of its execution environment. Note, that these threads run with a relatively low priority. The CSM node uses its own Java security manager to prevent illegal resource access by the node.

The Security Manager. Java uses a security manager to lock loaded code into a conceptual sandbox. The security manager is an integrated part of Java's class loading mechanism. The security manager keeps track of classes which are loaded from external sources (not by the default class loader). CSM agents are instantiated from external sources, namely by the AgentClassLoader that instantiates the agent from the CSM message object (see section 5.1.2). The security manager checks each invocation of a security critical method. It analyses the method call stack to see if loaded code was involved in the method call. If yes, the security manager interrupts the invocation by throwing a security exception. While Java's security managers are a nice concept the definition of a new security manager is relatively tedious. For every security critical method the developer must write a check routine. The CSM node implementation uses and extension of the `java.rmi.RMISecurityManager` class. This class defines a very restrictive security policy. No loaded code is allowed to access the file system, any thread control or the network[2].

5.5.3 Resource Control

The CSM sandbox prevents that the agent can do an illegal operation. However, the agent may excessively use legal operations to disrupt the smooth operation of the node. This is called a denial-of-service attack against the node resources. The CSM node detects these attacks with a resource controller. The controller runs in its own thread which is set to the highest priority so that it preempts any agent activity. The controller checks in regular intervals the resource consumption of all agents. If an agent launches a denial-of-service attack against a node resource the controller will detect it an can immediately terminate the agent. The controller uses the accounting information that the execution environment collects of each agent (see section 5.3.3).

Here's how the three node resources CPU time, memory and network capacity are protected.

---

[2] If an agent wants to send something over the network it needs to put a result transmission service request in the node service queue.

CPU time. The AgentAccounter components of the execution environment (see section 5.3.3) provide the resource usage statistics of each agent. The resource controller uses that data and checks for each agent if:

- The agent's maximum life time in the node has expired.
- The agent's CPU time sums up to a value greater than a maximum threshold.
- If there was a agent method invocation that did not return within an upper limit of time.

The resource controller kills the agent if any of these conditions are true. The resource controller also checks if the node is congested. It measures this by comparing how the work of each agent progresses. If one of these two conditions is met, the node is congested:

- An in-queue of an agent is full.
- In too many cases[3], an agent had to treat a monitoring packet with the emergency method (see section 5.4).

Both conditions show when at least one agent is too slow to perform its work. Then, the resource controller declares the node to be congested. During congestion, no new agent is granted admission to the node. The controller also starts the congestion resolution algorithm. The algorithm determines the agent with the lowest priority and the least effective CPU resource consumption (since the last check) and terminates it:

1. Consider only agents that have executed in this checking interval. Let their execution time in the last interval be c.
2. Consider only those agents with the lowest present priority. This avoids that many fast and low priority agents can kill one high priority agent.
3. Find among those agents the one with the least effective CPU usage. Consider therefore the number of packets n that the T-component has captured for the agent during the last checking interval. Consider the number of packets h that the agent has handled in the interval. The kill ranking r of an agent is then $r = cn/h$. If n is zero then also h is zero and the ranking is defined to be c. Note, that this can happen e.g. if the agent does not get packets but gets a reply from a node service. The agent with the highest ranking is killed.

The motivation of the definition of r is as follows: If the CPU time c is large or if an agent gets many packets (large n) it uses more resources. If it treats few packets (if h is small) the agent is working inefficient. In fact, r is the CPU time

---

[3] This is a configurable threshold of the node.

that the agent would have needed to treat all n packets that were delivered to it. So r reflects how greedy the agent is.

Note, that the thresholds and maximum values used for resource control can be configured individually by each node.

Memory protection. The agents can create and store as many helper objects as they want. An agent could use this to launch a denial-of-service attack against the memory of the host machine. The resource controller regularly checks the size of an agent. Unfortunately, the Java virtual machine does not provide a `sizeof` primitive to do so. Instead, CSM nodes use the fact that agents are serializable (see sections 5.1.2 and 5.4). The controller serializes the controlled agent into a byte stream. The size of this stream is measurable and is used as an approximation of the true memory consumption of the agent. If the size exceeds a limit, the agent is killed. The serialization is an expensive operation (see section 7.1.1), so the controller only executes this check with a configurable probability.

Network resource protection. The agents can access the network only via the node services. Therefore, there is no need to do regular checks by the resource controller. The node services can control the resource consumption directly. The service handler for the 'sending' service can e.g. include a rate control mechanism. It can impose restrictions on the rate and the size of the messages sent. These restriction may depend on whether the messages should be authenticated or encrypted. However, in the CSM implementation the excessive use of node services always lead to a poor CPU ranking and thus the CPU control mechanism already regulated the use of the node services.

5.5.4 Agent Security

In this section we discuss how the agent is protected while it resides in a node. The agent is delivered in byte code that programs any behavior desired by the user, in the user's own programming style. This obfuscates the contents of the agent but it does not protect it in a cryptographic way. The owner of the node may decompile and reverse engineer the agent to find out what the agent intends to do. The node owner can also forge agent results and send them to the home application. Section 6.4 discusses ways to make such an attack hard and to increase the chance that the attack is detected. Note, however that the node can always launch a denial-of-service attack against the agent. It can kill the agent at any time. However, the customer will find out about that. If agents of many customers do not get the service expected, some of these customers will start to prefer the services of other providers. Therefore, it is in the best interest of the provider not to attack the agents on their node platforms.

Another type of attack is when one agent tries to attack another agent. However, the same mechanisms (sand-box, resource control) that prevent the agents from attacking the node also prevents them from attacking each other. The only exception are agents with high priority. When an agent of high priority congests a node, the other agents are one by one terminated. But this behavior is intended. The agents of the regular customers should run with the same priority. Only agents from the provider itself (or maybe agents from VIP customers) should run with high priority. They can then accomplish tasks such as mission-critical troubleshooting or even node maintenance.

5.6 The Home Application

The customer uses a so called home application to access the customer-based service monitoring infrastructure. The application allows the customer to query nodes, send agents and to receive and visualize the agent results. The home application is not fully automated like the node. Instead, the user gets a tool for conveniently accessing the CSM infrastructure. While the implementation of the home application needs a less complicated internal logic it faces the problem of formating agent results for the human eye. Since CSM agents may measure all kinds of service and network parameters it is not possible to implement a solution that supports every view on results that a customer can think of. Instead, the CSM implementations allows developers to easily extend the application to other data representation models.

5.6.1 Implementation Overview

Like the node implementation the implementation of the CSM home application uses the `clientserver` package to communicate over the Internet (see section 5.1). The main parts of the home application deal with the collection of user input and the representation of agent results in graphical user interfaces. In order to be extensible the home application implementation is built around a framework of few classes. Figure 5.8 shows the framework.

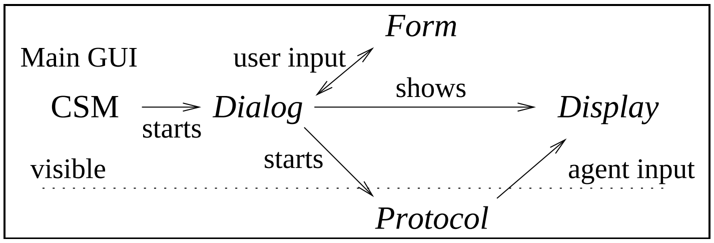


Figure 5.8: Framework of the home application.

The classes denoted as 'visual' are either extended Java abstract windowing toolkit classes or use them. The home application is started by instantiating an object of the main class `CSM`. The object displays a GUI with buttons that let the user start different `Dialog` objects e.g. for sending an agent or for sending a query. Several dialogs can run concurrently. The dialogs display forms where the user can e.g. fill in what agent or query (s)he wants to send, to what node the application should send and so on. The user can then have the dialog trigger the desired action thereby ending the dialog. When the user triggers the dialog also opens an independent `Display` object and connects it to a `ProtocolObject` that it has started in the background. The protocol object performs the CSM protocol transactions. It sends the appropriate CSM protocol request (e.g. an execution request to a node) and receives the answers. The protocol object forwards the answers to the displayer that represents them on the screen. The framework consists of abstract classes that implement basic functionalities and the cooperation between these classes. For every class there are three different subclasses that implement the three main types of control tracks: (1) The sending and receiving of a query, (2) the sending of an agent in end-to-end mode, and (3) the sending of an agent in a forwarding mode. The later two are related, but the display model is quite different. When using end-to-end sending the agent replies are delivered over the initial connection. When forwarding is used, several instances of the agent try to connect back to the home application. The display for results of forwarded agent thus is more complex and needs preliminary preparation (e.g. the starting of a server).

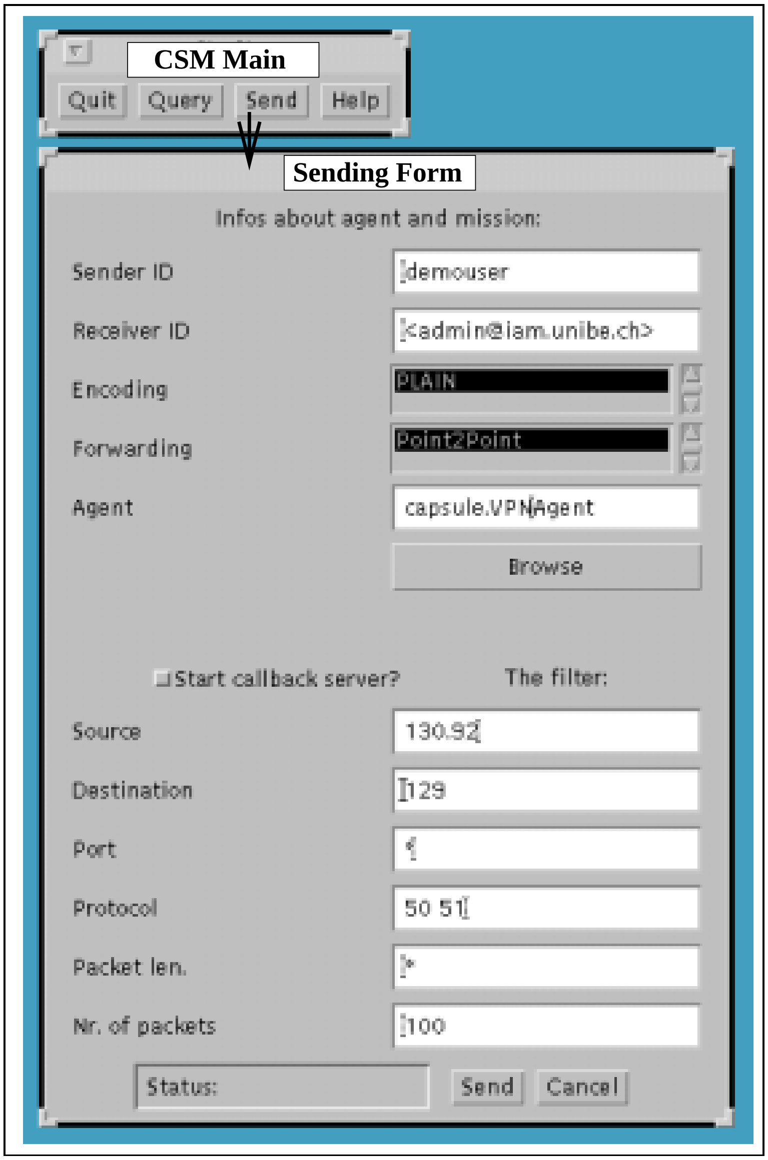
The displays use a handful of helper classes to represent e.g. an IP packet contents in different ways and to represent the network topology in case of agent forwarding.

5.6.2 The Transmission of a Request to the Node

Figure 5.9 shows the CSM main GUI and the form for sending an agent. The user has selected the *send* button of the main GUI. This has started the sending dialog that opens a form. The main GUI has a *help* and a *quit* button that provide the obvious functionalities. The *query* button starts a query dialog window. Note that for each button click a new dialog is started, so it is possible to compose and send several queries and agents at the same time. The *sending form* mainly consists of two parts: the information about the agent transmission and the filter information. Here, a customer with the customer identification *demouser* wants to send an agent to the node with the identification *admin@iam.unibe.ch*. The agent is of class `capsule.VPNAgent`. The customer can browse the file system to select available agent classes. Note, that the home application needs to know if this agent will send back the results with a separate callback. The rest of the form lets the customer specify the filter that describes the IP traffic that the agent should monitor. Here, all IPSec traffic (protocols 50 and 51) coming from the subnet 130.92.0.0/16 and going to the subnet 129.0.0.0/8 is monitored. The agent wants to examine 100 packets.

Figure 5.10 shows the form for a query message. Note the similarity to the first part of the sending form. This is because the forms share common helper classes.

When the user presses the *send* button on the sending form, the dialog validates the entries (e.g. it checks if the filter description is correct, and if the agent byte code is available), starts the appropriate display window (object of class `Display`)



Infos about agent and mission:

Sender ID	demouser
Receiver ID	<admin@iam.unibe.ch>
Encoding	PLAIN
Forwarding	Point2Point
Agent	capsule.VPNAgent

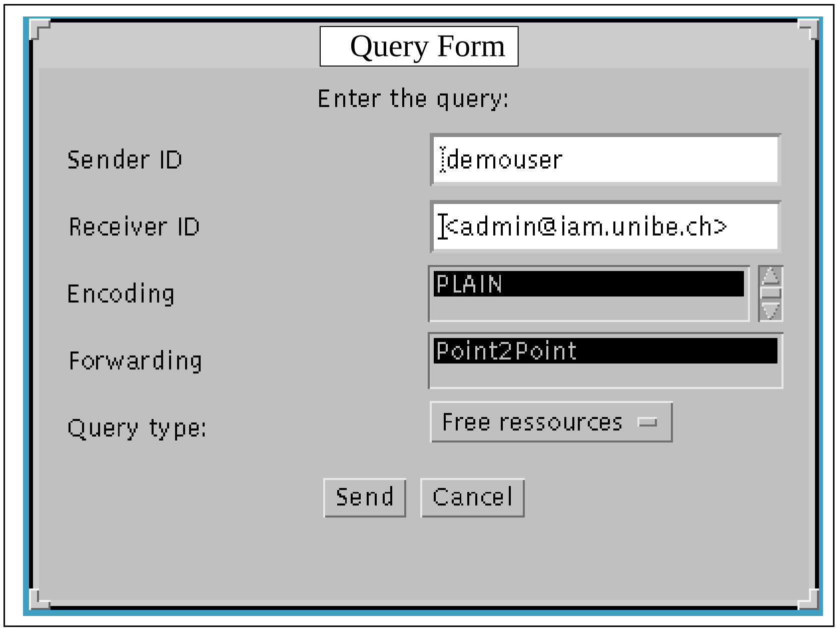
☐ Start callback server?

The filter:

Source	130.92
Destination	129
Port	*
Protocol	50 51
Packet len.	*
Nr. of packets	100

Status:

Figure 5.9: The CSM GUI and the agent sending form.



Query Form

Enter the query:

Sender ID: demouser

Receiver ID: <admin@iam.unibe.ch>

Encoding: PLAIN

Forwarding: Point2Point

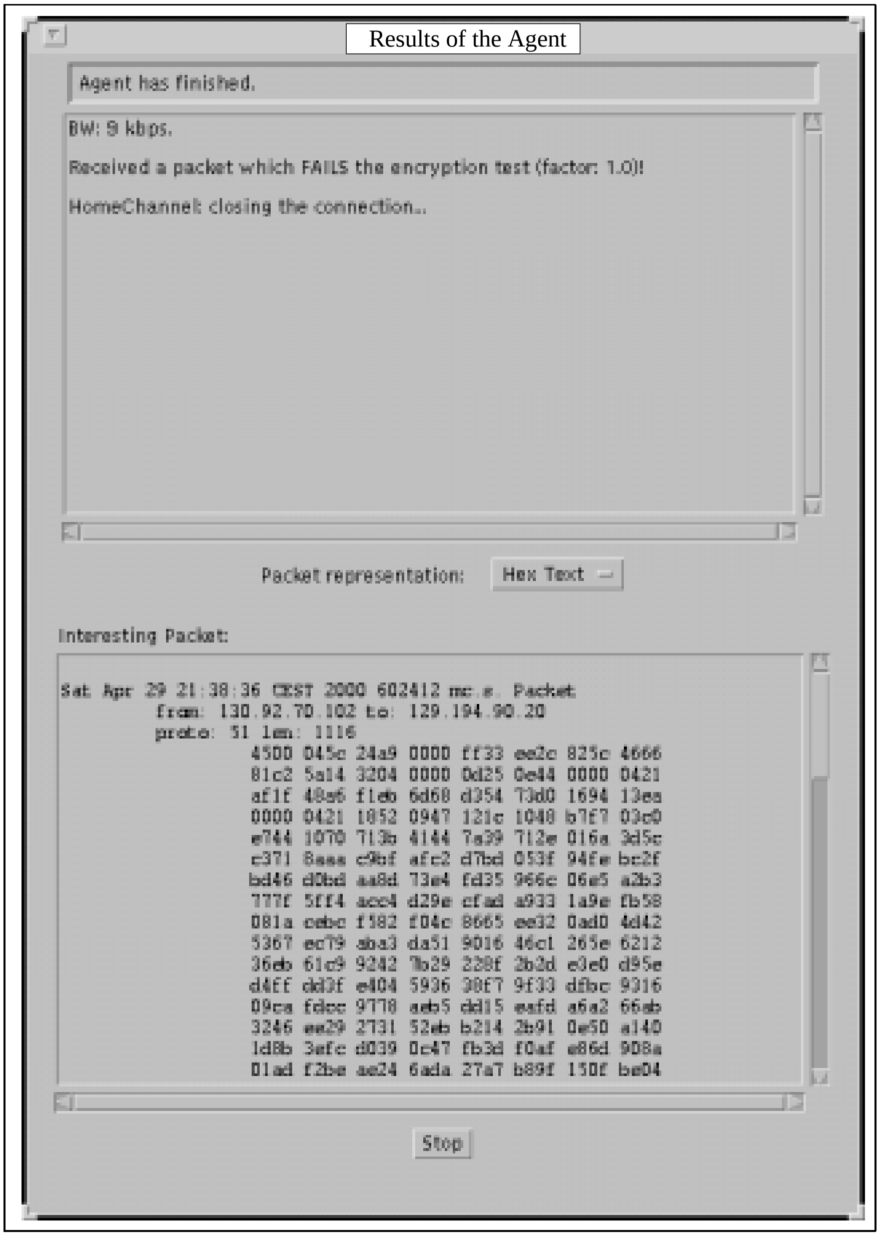
Query type: Free ressources

Figure 5.10: The query sending form.

for this kind of request, and creates a `Protocol` object. The object uses a separate thread to steers the CSM protocol interaction, thereby making use of the `clientserver` package. In case of network failure it displays warning messages. The protocol (handler) object shows an alarm if results are not encoded properly, e.g. if they are not encrypted when they should. It also forwards the node replies and the agent results to the display. The display window for an agent that was sent in end-to-end mode is depicted in figure 5.11. It has a status line on the top. Here, an agent has terminated its work at a node; the connection has been closed. Below the status line there is a scrollable text window. All result objects have a method that prints their contents to a character string. The text window uses this method to display agent results. The text window provides therefore a generic interface for the customer to inspect agent results. Here, the agent has reported the average throughput of the measured traffic (9 kilo-bits per second). It has detected a packet that does not seem to be encrypted. Note, that the result object can carry IP packets. The agent used this mechanism to send the suspicious packet back to the customer. The display provides several views to inspect the packet. Here, a header summary with a hexadecimal representation of the whole packet was chosen.

5.6.3 The Callback Displayer

When an agent is sent in end-to-end mode the home application keeps the connection open and hands it to a display. So one display shows the results of exactly one agent. When agents are forwarded to several nodes they have to explicitly contact

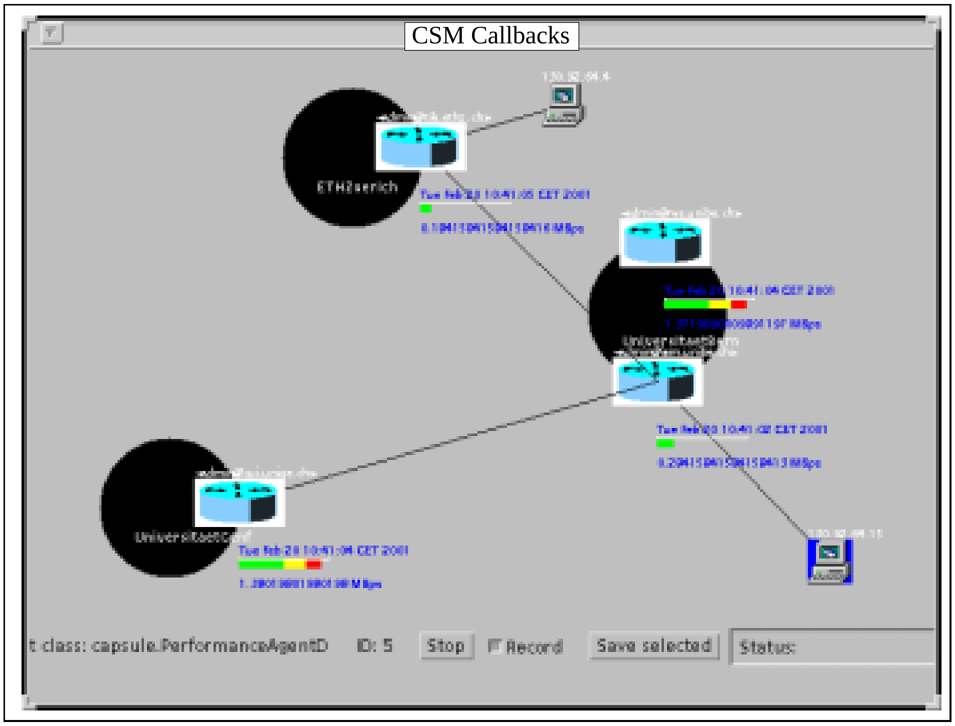


```
Agent has finished.

BW: 9 kbps.

Received a packet which FAILS the encryption test (factor: 1.0)!

HomeChannel: closing the connection..
```

```
Sat Apr 29 21:38:36 CEST 2000 602412 mc.s. Packet
         from: 130.92.70.102 to: 129.194.90.20
         proto: 51 len: 1116
                  4500 045c 24a9 0000 ff33 ee2c 825c 4666
                  81c2 5a14 3204 0000 0d25 0e44 0000 0421
                  af1f 48a6 f1eb 6d68 d354 73d0 1694 13ea
                  0000 0421 1052 0947 121c 1040 b7f7 03c0
                  e744 1070 713b 4144 7a39 712e 016a 3d5c
                  c371 8aaa c9bf afc2 d7bd 053f 94fe bc2f
                  bd46 d0bd aa8d 73e4 fd35 966c 06e5 a2b3
                  777f 5ff4 acc4 d29e cfad a933 1a9e fb58
                  081a cebc f582 f04c 8665 ee32 0ad0 4d42
                  5367 ec79 aba3 da51 9016 46c1 265e 6212
                  36eb 61c9 9242 7b29 228f 2b2d e0e0 d95e
                  d4ff dd3f e404 5936 38f7 9f33 dfbc 9316
                  09ca fdcc 9778 aeb5 dd15 eafd a6a2 66eb
                  3246 ee29 2731 52eb b214 2b91 0e50 a140
                  1d8b 3efc d039 0c47 fb3d f0af e86d 908a
                  01ad f2be ae24 6ada 27a7 b89f 150f be04
```

Figure 5.11: The agent result display window.

the home application after they start executing in the remote nodes. A special display (with the help of other objects) displays the results of several agents. Note, that the home application does not know in advance from where these answer will come and how many answers there will be. The display starts a CSM protocol server that only listens for CSM callbacks. The agents use the callback node service to contact that server (see section 5.3.4). The node service sends an initial CSM object (of class CallBack - see section 5.1.5). The message informs the home application what node is executing the agent. The display uses this information to draw the topology of the nodes that run the agent. Each agent result contains a floating point number. That number along with a time stamp is displayed close to the node where it was measured. A special value displayer performs this task. This result displayer can be extended to format the results of more specialized results in a more compact way. However, there is a danger that the callback display gets crowded very soon. It can only provide a rough overview. Therefore, all results that arrive at the home application can be stored on disk for off-line analysis with third-party tools. Figure 5.12 shows the a node topology and measurement results as presented by the display. Notice, that the display only shows the inter-provider connectivity. On the screen the internals of a single provider's network are abstracted into a filled disk.



t class: capsule.PerformanceAgentD ID: 5

Figure 5.12: The callback display window.

5.6.4 Generic Views of the Agent Results

The implemented CSM home application provides several visualizations of agent results. The visualization always use the same architectonic principle which is depicted in figure 5.13. There is a standardized result class (from the `clientserver` package). The home application introduces a number of result displayers that use a Java canvas to draw their view of the result. The canvas may be a GUI window or a GUI component provided by Java's abstract windowing toolkit. The architectonic principle allows the developer to replace a result displayer with another at run-time, so the customer can select what view of the results (s)he wants. A developer can easily introduce new subclasses of results that carry more information. (S)he can also write new displayers that can show the new aspects of the results. Nevertheless, the old displayers will also still work, because of the inheritance mechanism.

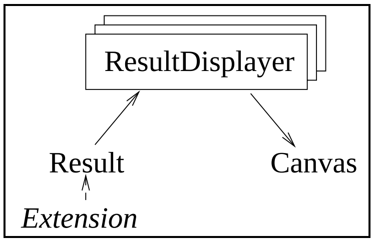
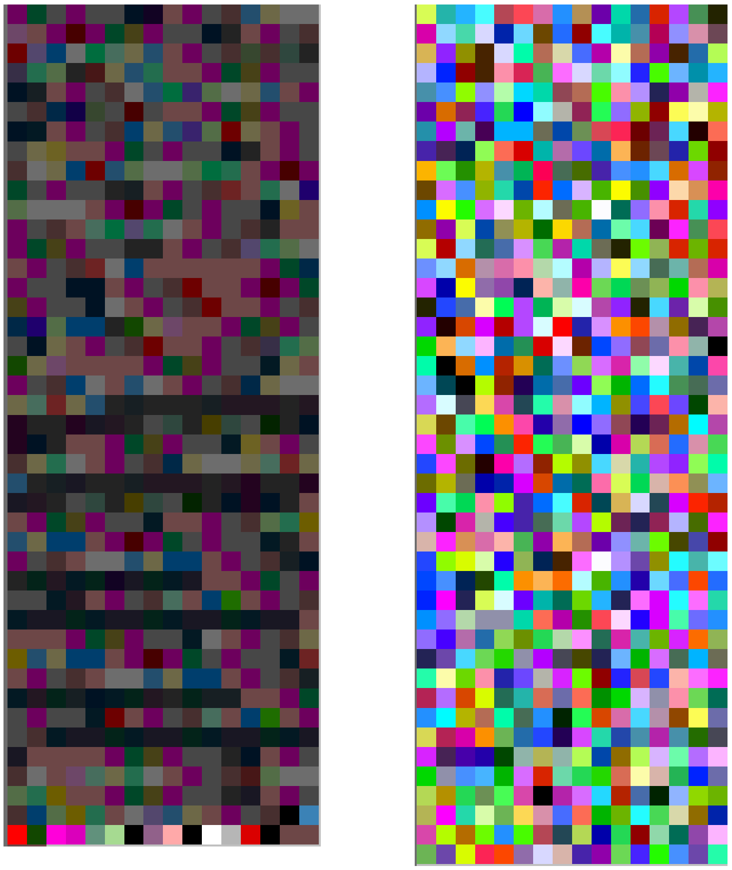


Figure 5.13: The visualisation priciple.

The home application introduces several result displayers. One uses the character string representation that each result object supports. There is also a small collection of result displayers that display the IP packet that a result object can contain. It supports a text representation that also shows the packet's payload interpreted as ASCII characters. This is useful when monitoring an ASCII character based protocol such as http. Then, there is the traditional hexadecimal representation already shown in figure 5.11. As a special feature the home application introduces displayers that represent the packet payload as a matrix of colored boxes. This can be useful to analyze encryption and to detect patterns in the traffic. Figure 5.14 shows such a graphical representation of two packets. Each colored box represents a byte value of the payload. The packet to the right is encrypted. The encryption scrambles the patterns. All colors appear with a similar probability. The packet to the left is a BSP message (see section 2.3.4). It is not human readable, but still it exposes some visible patterns. At the bottom of the packet there is a digital signature which becomes visible when displayed like that.

For agents that are forwarded and thus use the callback mechanism the CSM implementation introduces a new result class named `NumericResults` that can carry an array of floating point numbers along with an averaged number. The averaged number is then used by the value displayer to give an overview of the currently measured state (see figure 5.12). This simplifies the job for the home application, which may become a bottleneck if many agents use the callback mechanism at



Encoded packet

Encrypted packet

Figure 5.14: Graphical representations of two packets.

the same time. The agents can preprocess several results and aggregate them in a NumericResults object thus disburden the home application. The new result class and the callback result displayer are another example of the presented architectonic principle and they show how new result types and suitable result displayers can be added to the home application implementation.

5.7 CSM Internetworking Support

Section 4.5.1 identified the need of an advanced support for large scale deployment of the CSM infrastructure. The infrastructure should provide a name space, node contacting information and dynamic node topology information. Section 4.5.1 proposes to extend existing Internet protocols. For the proof-of-concept however a simpler implementation of the necessary mechanisms suffices. There, each CSM node has two special configuration files, one for providing name and contacting information and one for topology information. Note, that nodes that have access to the same file system can of course share these files. This approach is not scalable to large numbers of nodes. If there are several thousand nodes then the overlay topology may become difficult to maintain. Yet, the CSM implementation is intended as a proof of concept. The CSM experiments did at no time have access a number of monitoring points which is even near the critical size.

Nevertheless, the CSM nodes implement a dynamic routing protocol for maintaining an overlay topology, so that agents can be routed from node to node. Note also, that the interfaces between the node and the classes that provide the advanced support functionalities (that access the configuration files) are factored out in separate classes. Thus, if a solution based on existing Internet protocols will be implemented it is easy to integrate it in the existing node implementation.

5.7.1 Name and Topology Information

All node identifiers are encoded in an e-mail like naming style such as `admin@node1.iam.unibe.ch`. This is compliant with a possible future integration of node name resolution with DNS lookups. E-mail addresses also work well with the PGP encryption and authentication infrastructure. In order to have a compact solution CSM integrates the contact information of nodes with the contact information of customers. Table 5.4 shows how records of a name lookup file are structured. Each identifier is associated with an IP or DNS address where a node runs. The node listens for the CSM protocol on the given port number. The port number is not fixed so that several nodes may run on a single machine. For normal deployment of CSM there is no need to run several nodes on one machine. Yet, this feature was convenient for testing CSM nodes. The contacting information record also contains a field that names the owner organization of the node (the name of the provider). The contacting information file mixes nodes with customer identifiers. Therefore it also needs a flag that distinguishes them.

Table 5.4: The contacting information file structure

Identifier	DNS address	IP	Port	Organization	Customer
admin@node1.cui.unige.ch		129.194.71.53	1998	Uni Geneva	false
admin@sniff.iam.unibe.ch	milou.unibe.ch		1998	Uni Berne	false
mguenter@iam.unibe.ch	balu.unibe.ch	130.92.64.15	0	RVS	true

The topology lookup table allows the nodes to determine their neighbor nodes. The nodes use this information to set up routing tables that allow them to forward agents from node to node in a similar way as IP packets are forwarded in the Internet. The customer can use the CSM protocol to query the nodes about neighboring information in order to learn about new nodes. Agents that use the callback mechanism can automatically transmit neighboring information to the home application. The home application is then able to reconstruct the part of the node topology that is interesting for the customer. The node also uses the topology lookup table to store fixed IP addresses of customers. Then these customers can forward agents in the hop-by-hop mode (see section 4.4) which allows the customer to monitor a complete route. Table 5.5 shows a sample of the structure of the topology lookup file. There, two nodes are neighbors of each other and one of the node sits on an access router of a customer (mguenter@iam.unibe.ch - compare with table 5.4).

Table 5.5: The topology lookup file structure

Identifier	List of neighbors
admin@node1.cui.unige.ch	admin@sniff.iam.unibe.ch
admin@sniff.iam.unibe.ch	admin@node1.cui.unige.ch:mguenter@iam.unibe.ch

For each node, the topology file contains a list of identifiers that declare who that node's neighbors are. Note, that the nodes need the contacting information file to map node identifiers to network addresses. They also need a routing mechanism to learn more about the topology than just neighboring information.

5.7.2 Routing

At the startup of the node, the node consults the topology table to learn about its neighbors. It initializes a routing table and inserts the neighbor contacting information gained from the appropriate file. The CSM nodes implement a distance vector routing algorithm that uses the hop-count as distance metric. The routing protocol is thus similar to the RIP routing protocol of the early Internet. The routing records for the neighbor nodes thus include a hop-count value set to one. The routing mechanism of the node gets routing records from two sources. As already mentioned, at the startup of the node the topology table provides the names of the immediate neighbor nodes and neighbor customers. Other routing record candidates are received from neighbor nodes through the CSM protocol. The routing mechanism uses these candidates and enters all those records of targets that are not yet in the routing table or replaces the records of targets that have a higher hop-count in the routing table. All updated records are bundled into one CSM message, their hop-count is incremented by one and the bundle is then broadcasted to the neighbor nodes.

Here is an excerpt from the class definition of routing records:

```
public class RoutingRecord implements java.io.Serializable {
    public int IP;         // Target.
    public String nextHop; // A node identifier.
    public int hopCount=0;
...
}
```

5.8 Organization of the Source Code

The CSM Java source code is grouped into packages. This provides more modularity, safety and managability to the implementation. The CSM implementation foresees two installations: one for the customer (the home application and individual agents) and the other for the provider (the nodes). Both installations have packages that are uniquely used by them, some that they both share, and some that are only stubs. The stub packages are necessary if one installation must know some basic classes of that package but not all of them. The best example is the `capsule` package that bundles the agents. For the node installation it suffices to know the `capsule.Agent` class. The individual agent class and its helper classes are dynamically downloaded by the CSM protocol when the customer sends the agents. Here is a complete list of the packages and their purpose:

- **`application.`** This package hosts stand alone Java applications that can be used in conjunction with CSM agents. An example application is a traffic generator.

- **`capsule.`** All CSM agents are implemented in this package.

- **`clientserver.`** The CSM protocol classes and helpers are implemented here.

- **`config.`** This package groups the classes that help the node or other applications read and parse configuration information from files.

- **`filter.`** All classes related to filtering are implemented in this package.

- **`homeApplication.`** The classes that implement the home application are bundled into this package.

- **`netgui.`** This package hosts the classes that help to display a network topology and callback agent results.
- **`node.`** This package bundles most of the classes relevant for the node implementation.
- **`topology.`** Here are the classes that implement the node routing.
- **`utils.`** This package contains helper classes that are also useful in other contexts such as e.g. the PGPEncoder class that provides access to PGP encryption and authentication.

Table 5.6 shows how the installations use the packages:

Table 5.6: The use of the packages by the two installation variants.

Package	Provider installation	Customer installation
`application`	not used	exclusively used
`capsule`	stub	used
`clientserver`	shared	shared
`config`	exclusively used	not used
`filter`	shared	shared
`homeApplication`	not used	exclusively used
`netgui`	not used	exclusively used
`node`	used	stub
`topology`	used	stub
`utils`	shared	shared

Chapter 6

Applications of Service Monitoring Agents

Chapter 4 showed that the successful market introduction of new IP services will be coupled to the introduction of a customer-based service monitoring infrastructure. This chapter will give examples of new IP services and of CSM agents that are capable of monitoring them. Neither the list of services nor the collection of agents discussed here are complete. But since one key advantage of the proposed CSM infrastructure is its flexibility. For each new service a new monitoring agent can be implemented (or an old one adapted). This can be performed by customers, providers, or a third-party vendor. This chapter focuses on the IP services discussed in part I of the thesis: a virtual private network service and differentiated services for the Internet.

6.1 Monitoring a Virtual Private Network Service

Virtual Private Networks (VPN) for the Internet [FH98a, FH98b] provide a transparent and secure mechanism to interconnect remote sites with IP (see figure 1.2). IP packets are encapsulated in new IP packets when entering the Internet (tunneling). The payload of the new packet (the original packet) is encrypted. The original IP addresses may be private (not routed in the public Internet) [RMK+96] so they do not have to be world-widely unique. Thus, VPNs allow the customer to use an arbitrary number of unregistered addresses in their Intranet[1]. Virtual private networks over the Internet are a cheap and secure alternative to leased line based private corporate networks. They take advantage of the ubiquitousness of the Internet and the trend towards Intranets. The Internet Engineering Task Force (IETF) proposed the VPN standard IPSec [KA98c], which is supported by many vendors nowadays. However, VPNs and especially their cryptographic mechanisms are difficult to understand and manage [GBK99]. Therefore, service providers begin to

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[1] Intranets: Corporate networks based on IP technology.

offer VPN services where they setup and manage the tunnel end-points for their customers. However, the security is transparent to the customer. The customer believes, that all the IP traffic that is leaving the network is encrypted. But encryption is computational intensive. How can the customer be sure, that the provider is really performing the IPSec protocol properly and is not just e.g. compressing the payload? This question is not a purely academic one. In the year 2000 the question arose in two different IPSec related e-mail discussion forums [Fre00, Sec00]. There are different reasons why people need the ability to monitor a VPN service. For example, the customer's technical personnel may have to give an account of the expenses for a VPN service to the higher management of a corporation. They therefore need a way to demonstrate the gained security. The customers also need a way to examine the VPN service in order to make an informed decision whether the service is interesting to them. The customer may also have to integrate a VPN service into a corporate-wide security policy which may e.g. specify that the private address structure of the corporate Intranet shall be hidden and that all IP traffic traveling over public infrastructure is encrypted. Usually such business policies demand for processes that guarantee or enforce policy-conformance. The discussion on the expert mail lists concluded that there are two powerful ways to check conformance of IPSec VPNs: The traditional method consists of interoperability tests: if products of several vendors cooperate in a given mode, then that mode must have been implemented properly. However, most VPNs use only equipment of a single supplier in order to ease the management. Further, if a service provider operates the VPN service the customer will probably neither be able nor allowed to perform interoperability tests on the providers equipment. The second approach for monitoring a VPN service is introspection into the service traffic. Mail list authors suggest `tcpdump` for this purpose but of course this is not an option for out-sourced VPNs because of security issues. Here, the proposed customer-based service monitoring infrastructure comes to play. It provides a safe way to service inspection.

6.1.1 Functionality of a VPN Control Agent

Given an agent infrastructure as described in section 4 we have many possibilities to check whether the VPN provider implements the service as promised using specialized agents. Such a VPN monitoring agent requests (some of) the packets from the node that are exchanged between the tunnel endpoints and that belong to IPSec traffic (protocol 51 Authentication Header (AH) or 50 Encapsulating Security Payload (ESP)). The nodes of VPN providers can accept requests for monitoring ESP traffic, because the ESP payload should be encrypted, so the privacy of the sender is not compromised. For AH, the provider may enforce that only the header bytes are delivered. Paranoid providers may also limit such access to agents owned by customers that subscribe to their VPN service. The agent can thus monitor on the IPSec traffic. Here are some specific checks that can be carried out by CSM agents:

- The customer can occasionally send out agents to the egress peering points of the access network (see figure 4.1). These agents will run outside of the customer's private network and can monitor all traffic that enters form and leaves to the public Internet. The agents check for traffic that use in their header internal network addresses of the customer's network. The agents should not find any such packets because these addresses should be private. If the service is working properly the privately addressed packets are encapsulated in the payload of a packet with the public tunnel-endpoint addresses.

- The customer can send out agents that monitor the IPSec protocol activities. Agents can for example monitor the presence[2] of the key exchange protocol IKE (UDP to port 500).

- The agents can also analyze the packet structure to see if the proper tunneling modes are used. It can examine the IP `protocol` field (50 for ESP, 51 for AH) and eventually the next header field(s).

- The agents can analyze the protocol fields of the IPSec headers. For example it can use the sequence number to learn about lost packets. It can use the security parameters index to identify different tunnels.

- A VPN agent can collect statistics about the fragmentation of IPSec packets. IPSec adds additional header and eventually trailer bytes to the IP packets. This can cause packets to exceed a local MTU value and thus lead to packet fragmentation. Problem reports on e.g. the VPN mail list indicate that fragmentation is a major cause of IP-VPNs problems ranging from performance degradation to service breakdown [Bir].

- VPN monitoring agents can collect data at several points in the network. Thus an agent may monitor the traffic inside of the customer's private network (plaintext) and correlate that with data collected in the provider network (IPSec). Using this approach the customer can e.g. detect if a provider uses the same tunnel for several customers.

- The customer can test the authentication mechanism of the provider. The customer lets an agent fetch an IPSec packet in the provider network. Another agent checks for duplicated packet at the far end of the VPN tunnel. The provider retransmits that copied packet thus launching a replay-attack. IPSec should detect the attack and discard the packet. The agent can also carry out other traditional performance monitoring tasks such as recording throughput and jitter of a VPN tunnel.

- IPSec agents can be used to correlate arrival times of a given packet in order to learn e.g. the one-way delay of the transmission and the time for encryption and decryption of a packet.

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[2] The IKE protocol of IPSec is encrypted, therefore not much more than the presence can be monitored.

- The customer can use statistical tests to validate the encryption and authentication algorithms used by IPSec.

6.1.2 Statistical Tests on Cryptographic Algorithms

The VPN monitoring agent has (albeit limited) possibilities to validate the quality of the encryption and also of the authentication algorithms used for the protection of the VPN. The output of cryptographic algorithms hides the structure of the input. Value accumulations of and correlations within the input data values are washed away. The output bits look as if created by a uniformly distributed and independent source of random zeroes and ones. If a cryptographic algorithm exposes regularities, these can be used to break it. In the area of random number generators there are many statistical tests that reveal statistical irregularities. These tests can therefore be used to detect a weakness in an encryption scheme. Note, that the reverse implication is not necessary true: even if an encryption scheme is useful as a random number generator it may still be insecure. The use of statistical tests to find weaknesses in an encryption scheme is widely accepted. For example the National Institute for Standardization (NIST) used a suite of statistical tests in the evaluation process for the Advanced Encryption Standard (AES) [Sot00]. One of the AES candidate algorithms will replace the ubiquitous but used but timeworn DES encryption algorithm. Note, that several[3] candidate algorithms did not pass the statistical tests and were consequently rejected.

A statistical test suite. We implemented a statistical test suite with the programming language Java. The framework (see figure 6.1) is modular so that the input data can come from different sources and that different tests can be used. The raw data is encapsulated in singletons which format the data into numeric values or raw bytes (samples). Each singletons object represents a stream of sample values. The source of the samples may e.g. be files or user input or live encryption algorithms. The singletons thus hide the details of the source of the data. The accumulator classifies the samples delivered by the singletons object. For example it may count byte values (256 classes) or count the number of samples that have a higher value than a threshold (two classes). The accumulator has also a distribution. The distribution defines the probability for each value class that the accumulator uses. The test compares the accumulated occurrences in the value classes with the distribution. It calculates the probability that the sample values really reflect the expected probability. Of course, the expected probabilities (the distribution) depend on the classification that the accumulator uses. The test uses as hypothesis that the encrypted traffic has the same statistical properties as an uniformly distributed and independent bit stream. This leads to an expected distribution. Then the test calculates the probability that the hypothesis is true given a concrete distribution of samples. If the test result is very improbable then the encryption algorithm is prob-

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[3] 4 out of 15.

ably not safe. Note, that the test output can be used as singletons again. The test provides a probability of the form: chances that a the hypothesis is true are within 98 percent. We can then test several sets of samples and classify them into two categories: the ones within the 98 percent and the ones that are not. We know the expected distribution (0.98 for ’in’ and 0.02 for ’out’). Thus we can now calculate the probability of the hypothesis using a whole series of tests. The next paragraph shows how tests can evaluate the output of an accumulator. Most of that material originates from [Knu81] and is described in more detail there.

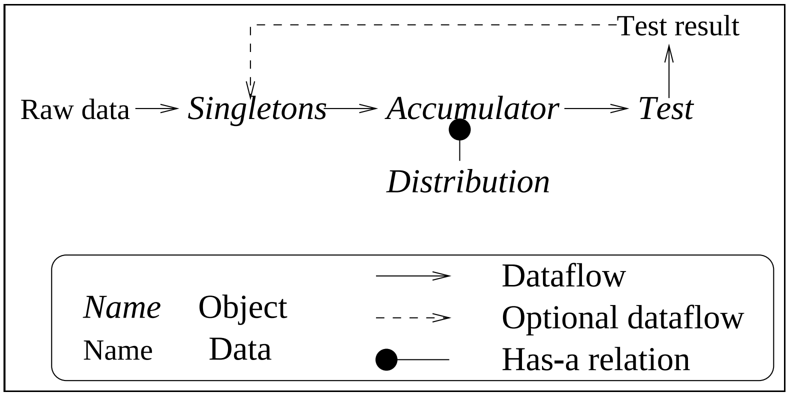

Figure 6.1: Statistical test framework.

An example of a statistical test: the byte frequency test. Here is an instance of the framework that is both illustrating and useful. The byte frequency test tests if the bytes in a bit stream are equally distributed. It interprets the input as raw bytes. The accumulator counts the occurrence of each byte value; it thus classifies the raw data into 256 categories. Note, that such an accumulation is also called a histogram. When a significant amount of bytes is counted (this depends on the test) then the test analyses how the bytes are distributed in the value space. Encrypted data should be uniformly distributed so each byte value should occur about the same number of times. However, if every byte value would occur exactly the same number of times this would be suspicious, too. Figure 6.2 shows an example histogram together with the expected distribution.

The byte frequency test uses the well-known χ^2 statistics [Knu81] to quantify the conformity of the classified values with the distribution (to evaluate the test). Assume we have k categories and Y_s samples fall into category s. Let n be the number of samples and p_s the probability that a sample falls into category s. Then the χ^2 statistics V is defined as:

$$V = \sum_{1 \le s \le k} \frac{(Y_s - np_s)^2}{np_s} \tag{6.1}$$

For each category the square of the deviation between the counted samples Y_s

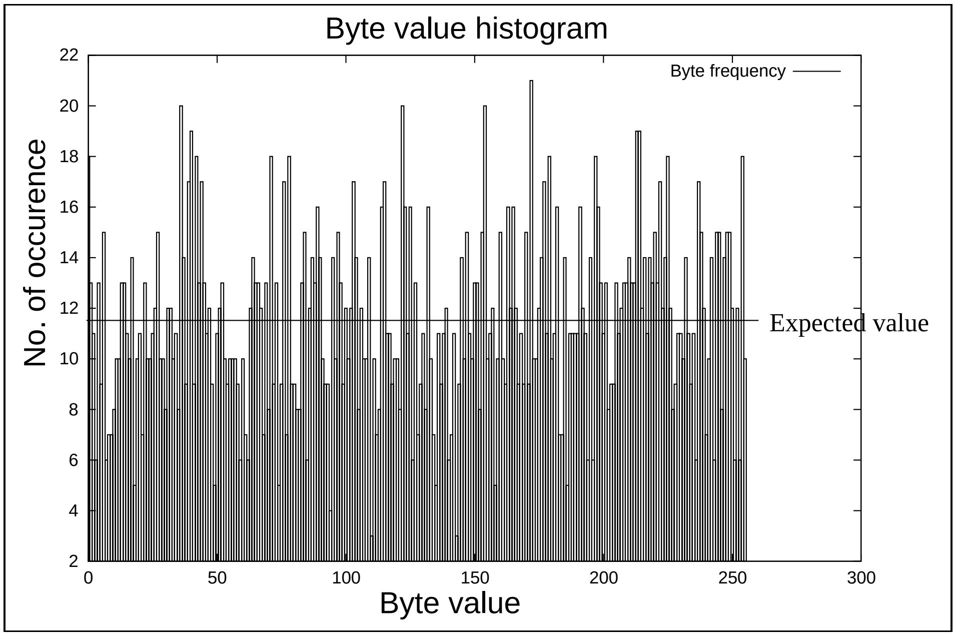

Figure 6.2: The histogram of byte values.

and the expected number of samples np_s is calculated. This deviation is put in relation to the number of expected samples and summed up over all categories. For the byte-frequency test each byte value has the same probability, thus $(p_s = 1/256) \forall s$. The nice thing about the χ^2 statistic is that it provides a single value V that can be directly mapped to a probability. The explicit formula is rather complex. In order to determine the probability of the calculated V value there are tables that map V values to probabilities [Knu81]. This mapping depends on the degree of freedom of the category classification. The degree of freedom is the number of categories minus one $(k-1)$. For the byte frequency test the degree of freedom thus is 255. The table provides information of the form: with a probability of 99 percent V should be less than 331.5. If not, the deviations between the number of occurrences and the expectations from the distribution is too large. For the byte frequency test the χ^2 distribution table also indicates that with a probability of 99 percent V should be larger than 205.5. If not, the number of occurrences in each category is *too close* to the expected value. Note that the χ^2 probability table can only be applied if a significant number of samples have been collected. The number of samples should be at least as big that the expected number for each category (np_s) is at least five. So for the byte frequency test $(n\frac{1}{256} \geq 5)$, thus at least $n = 1280$ bytes should be considered. The test for the byte distribution depicted in figure 6.2 delivers $V = 274.9$ thus the data source passes the test.

The run test. The run test is a powerful statistical test that is sensitive to correlations in consecutive data values. Instead of classifying the encrypted data by the byte values, the run test works on floating point numbers. For example, four raw data bytes are interpreted as one floating point number. The numbers are then divided in sequences of monotonically increasing numbers. E.g. the sequence $(-33.2, 104.4, -45.8, 3.0, 34.7,\ 7.1, -19.3, -93.2, 1.1)$ is interpreted as five sequences: $(-33.2, 104.4, | - 45.8, 3.0, 34.7, |7.1, | - 19.3, | - 93.2, 1.1)$. Then, the sequences are categorized according to their length. Usually, there are 6 classes: sequences of length 1, 2, 3, 4, 5, and 6 or more. The expected distribution of these sequence lengths is not trivial, because the length of a sequence depends of the length of the previous one. Therefore, the run test needs a fairly complex calculation of a statistic V in order to be conform with the χ^2 distribution table. However, with a simple trick the calculation gets much easier. You simply omit the sample right after the end of a sequence. Then, the sequences lengths are independent and the χ^2 distribution table can be used directly. When this trick is applied the probability $P(r)$ for a sequence of length r is:

$$P(r) = \frac{1}{(r-1)!(r+1)} \tag{6.2}$$

Table 6.1 shows the expected distribution of the 6 categories of the run test.

Table 6.1: Run test distribution.

Sequence length	Probability
1	$1/2$
2	$1/3$
3	$1/8$
4	$1/30$
5	$1/144$
6 and more	$1/720$

Online calculation of V. Using formula 6.1 the agents have to iterate through all categories each time they want to evaluate a test. If they perform the test to frequently then their performance may suffer (especially for the byte frequency test where there are 256 categories). However, if they perform the tests too infrequently then a statistical irregularity may be washed away by the following data. Therefore, we transformed the calculation formula, so that for each additional value in category s V can be calculated directly with constant computational complexity. Let V_n be the statistic calculated for the n-th sample value. Then:

$$V_{n+1} = \frac{n(V_n + n) + \frac{2Y_s+1}{p_s}}{n+1} - n - 1 \tag{6.3}$$

With this formula both the byte-frequency and the run-test can be executed fine-grained with and on-line.

Evaluation. The byte-frequency test and the run test both use the χ^2 distribution table to evaluate the test results. The byte-frequency test checks if the data values are equally distributed and the run-test checks if there are correlations in the data values. So both test complement each other but can share code. Therefore, the implemented VPN monitoring agent uses these two tests as encryption verification tests. Note, that there are countless other statistical tests [Knu81, Sot00]. CSM allows the customers to use the tests of their choice. The two proposed statistical tests can disclose providers that use a weak encryption scheme or that just compress the payload instead of encrypting it. Note, that IPSec is modular. IPSec can indeed use arbitrary cryptographic algorithms for the encryption and authentication. It can even use the so called null transformation that leaves the input unchanged. In [BGKL00b] we performed the presented tests (plus the Anderson-Darling test proposed in [PAMM98]) on 2 Megabytes of encrypted IPSec ESP payload and on a compressed archive of the same size. All tests were able to single out the compressed file as not encrypted. An advantage of statistical tests is that they are generic. Compare it to alternatives, e.g. an agent that scans for English words in the payload. While this may be faster and easier to implement even a simplicistic and completely insecure algorithm such as ROT13 could be used to circumvent the agent. In contrast to that, the statistic properties that the presented tests aim at are an intrinsic property that every well encrypted traffic must posses. Therefore, the statistical tests can not only be used to reveal that a provider tries to avoid the encryption work but it can also be used to detect implementation problems such as the Linux IPSec implementation problem mentioned in [Den00]. Denker points out that under certain circumstances, traffic from the private network may leak out unencrypted into the public network when the machine hosting the tunnel endpoint is restarted. Furthermore, the statistical tests can reveal if a provider uses an encryption scheme in the weak electronic code book (ECB) mode. The ECB mode does not include input form the previous block encryption into the encryption of the current data block. Thus, two equal plaintext blocks result in two equal ciphertext block. A duplicated packet of 1400 bytes size will cause the statistical tests to indicate a problem.

Nevertheless, there is also a limit in what the statistical tests can detect. First, and foremost: even if the traffic passes the encryption test it may still be encrypted with a weak algorithm. If you use e.g. the Java random number generator as input for a stream cipher then the resulting traffic will pass the tests [BGKL00b]. However, this random number generator is based on a linear congruential generator. These generators are easily broken [Sch96]. Also, the performed tests were not able to distinguish between encryption algorithms that use different key lengths. A 40-bit DES encryption passed the tests as good as a 112-bit 3DES encryption. In theory [GBB00], when testing a data amount in the same order of magnitude as the key space the statistical tests could reveal the difference. To prove that hypothesis one would have to compare at least two times 2^{40} encrypted blocks (8 byte). These are 16 Tera bytes of data and thus beyond our hardware capacity. Nevertheless, somebody may think of more intelligent tests that are e.g. tailored to an algorithm and that try to perform a cryptanalysis against it. With CSM agents the test can then easily be used by the customers. It is important to note, that traditional stationary control programs located at customer premises are not able to perform the VPN checks described in this section. They have no insight in the service as it is delivered in the provider networks. Also the functionality of the VPN agents is too complex to be implemented in traditional network monitoring application that collect information with SNMP [CFSD90] or in web-based network management entries.

Implementation. We implemented a virtual private network monitoring agent for the customer-based service monitoring platform described in chapter 5. The agent can perform either one of the two presented statistical tests to ensure that VPN traffic is encrypted and authenticated. The agent also verifies that the IPSec protocols are used in the proper modes by analyzing the packet headers. In the test layout this was AH in tunnel mode encapsulating ESP in transport mode. Further, the agent observes the throughput and packet loss of the monitored tunnel. The agent reports the measured tunnel throughput to its home application on a regular basis. It also reports special events such as packet loss, a malformed IPSec transformation or a failed encryption/authentication test. In the last case it sends back the monitored packet that caused the test to fail so that a human operator can verify the finding. Figure 5.11 showed the reports that were send by a VPN agent. The VPN agent was able to demonstrate its ability to detect unencrypted traffic on a *real* VPN tunnel. For that purpose we used our VPN management tool [KBG00] to hot-swap a properly encrypted VPN tunnel with one that does authentication only. The VPN agent immediately detects and reports this. However, performance tests indicated some limitations, since the statistical tests require computational power (much less than encryption, though). Running on a Sparc ULTRA 5 with a 269 MHz CPU, the agent could test 1.5 Mbps encrypted data with the run-test and 1 Mbps data with the byte-frequency test (for details see chapter 7). Note, that in case the agent wants to monitor a line with higher throughput, it can choose not to analyze every byte in every packet, since sample testing will also suffice to detect a VPN service misconfiguration.

6.2 Service Level Agreement Monitoring

Traditional service level agreements for Internet services are contracts that describe the business relationship between a customer and an Internet service provider (ISP). The SLA describes the nature of the service provided, its price, and clauses for special cases e.g. what happens when one of the agreement partners violates the agreement [Ver99]. A traditional IP service provides Internet connectivity. The service is relatively simple but still the ISPs try to differentiate their offerings e.g. by bundling the IP service with additional services (help-desk, web hosting, e-mail hosting etc.). We are not going to discuss the add-on services. Instead, let us focus on the pure IP service and its possible differentiations in SLAs. Even for pure connectivity there are performance metrics that are used in todays SLAs:

- **Reliability.** The reliability of the IP service is usually measured in the uptime of the network. The provider may also guarantee upper bounds for connectivity outage times or outage counts. The provider may also guarantee to solve network problems within a given time (outage resolution time). The connectivity can also be partially damaged. Reliability metrics may thus also include limits on packet loss rates and on error rates.

- **Responsiveness.** A provider may guarantee an upper bound of the IP round-trip time for certain destinations. Today, such guarantees exist but are limited to the network of the ISP. Responsiveness guarantees can also include statements about one-way delays and response times of applications (e.g. web servers).

The SLA normally also describes how the performance is measured, thus it describes the SLA monitoring. Given today's infrastructure it is the provider that measures the SLA conformance. The provider then delivers reports on a regular basis (typically each month). The customers are left with no choice than to trust the report of the provider. Further, the long reporting interval averages away the impact of network problems. For example a 99 percent uptime guarantee may look good on the SLA paper. A 7 hour connectivity outage can however cost a fortune to e-commerce company, but it is still SLA conformable if it occurs only once a month.

The proposed customer-based service monitoring infrastructure allows the customers to test conformance to the SLA metrics themselves. In the case of measuring network outages the mobile agents of CSM are particularly useful. Applications that sit in the customer network are per-definition cut-off during the outage while roaming agents reside in the Internet and can study the problem further.

With the introduction of quality-of-service (QoS) mechanisms in the Internet the provider can differentiate their Internet service offerings even more. They can offer new and more distinct guarantees defined on more fine grained performance metrics. Note, that all metrics of the pure connectivity service can be applied to a QoS enhanced Internet service. Thus, simpler variants of the QoS monitoring agents can also be used for plain IP monitoring. The guarantees that a provider offers can be quantitative (e.g. in bits per second) or qualitative (e.g. low latency). They can be absolute or relative to other service classes. Here is a list of traffic properties that may be involved in the guarantees. Different properties may be assigned to different classes of traffic, making the space of SLA diversification even bigger.

- Traffic loss (e.g. in bytes per byte).

- Erroneous packets (e.g. in packets per byte).

- Throughput (e.g. in bytes per second).
- Goodput. The goodput is the throughput of application data and thus application specific.
- One-way delay and round-trip delay (e.g. in milliseconds).
- Jitter (e.g. in milliseconds).

This diversity of metrics is a strong argument for my CSM infrastructure. CSM is generic enough to allow the customer to monitor all presented kinds of service level specifications. Therefore we are going to study CSM agents for QoS services in more detail.

6.3 Agents for Measuring QoS Parameters

This section presents quality-of-service measuring strategies using mobile CSM agents, some agents that implement the strategies, and selected results that these agents delivered in test scenarios. It follows a classification of the measurement approaches. The simplest approach is sending a single measurement agent that carries out a measurement and returns the result(s). Those are *passive* and *stand-alone* measurements. If the customer sends out several agents an compares their results this is a *distributed measurement*. If the customer uses additional applications to generate traffic and the agents use that traffic to derive results, then an *active measurement* is carried out. Some distributed measurement agents may need *synchronized* clocks. The agents will hardly be able to synchronize themselves. However, the nodes of some providers may use synchronized clocks. Their clocks may be synchronized with the Network Time Protocol (NTP) [Mil92] or with a satellite based system such as the Global Positioning System (GPS). Then, the packet time stamps that the agents use (see section 4.3.2) refer to synchronized clocks so the measurements of these agents are synchronous. If the measurement agent uses knowledge about higher-level protocols (e.g. if it knows how to collect TCP sequence numbers or how an IPSec header is structured) then the agent is referred to as *protocol dependent*. Note that measurements that rely on synchronized clocks are per definition distributed (else, the synchronization does not make sense). The following sections describe CSM based measurements on the traffic properties listed in the previous section.

6.3.1 Throughput Measurements

IP throughput measurements can be performed by simple stand-alone CSM agents. The customer sends such an agent to the desired location in the provider network. The agent is equipped with a filter that specifies what traffic flows should be measured. The customer can select to monitor everything ranging from subnet-to-subnet traffic to specific micro-flows. We implemented an agent that counts the transported bytes during a configurable interval and reports the throughput after every interval. The agent uses the `length` field of the IP packet to count bytes so the agents use filters that request only the IP headers from the node. The agent is thus very light-weighted and fast. The simple version of the IP throughput measuring agent can be improved by adding protocol knowledge. Then the agent can analyze the IP packets and extract the payload of higher layer protocols. The agent can for example subtract the bytes of IPSec headers and trailers in order to calculate the pure tunnel throughput. Furthermore, the agent can be used for distributed measurements. In general, the customer will have more information about the service state at his/her disposal when (s)he knows about the state at several locations in the network. A distributed measurement application of the simple throughput agent could be to learn about the routing of the providers. The customer sends out the agents to peering points in order to learn how much and what kind of his/her traffic passes there. The throughput agent can also for example measure the best-effort-to priority traffic ratio (e.g. for DiffServ).

Bottleneck Bandwidth Measurement. Bottleneck bandwidth is a fundamental property of a network connection [Pax97]. The bottleneck bandwidth is the upper limit of how quickly the network can deliver a sender's data to a receiver. Usually the bottleneck bandwidth is the bandwidth of the slowest link on the path. Bottleneck bandwidth is relatively easy to measure. You need a sender that sends two packet immediately after each other (also called the *packet pair* estimation). The second packet must queue behind the first until the first is completely transmitted. The delay between the two packets therefore indicates the transmission time of the first packet. Ideally, the packets travel through an uncongested network. The packets then only get further separated if the next link is slower than the slowest previous one. So the delay between the two packets indicates the bandwidth of the slowest link on the path (the bottleneck). The bottleneck bandwidth δ is thus $\delta = b_A/(t_B - t_A)$ where b_A is the size of the first packet (A) in bytes and t_A and t_B are the arrival times of the packet. One very convenient property of the bottleneck bandwidth test is that it does not require synchronized clocks. The receiver has only to compare the arrival times of two (or more) packets.

Usually the bottleneck bandwidth is determined through active measurements. A sending application sends a number of packets in a short sequence and a receiving application determines δ value before it considers this value is a maximum candidate. We implemented a *passive bottleneck measurement agent*. It calculates δ for each packet pair and selects the maximum. However, due to queuing effects caused by other traffic some δ values may be too small. The passive bottleneck agent levels this out in that a configurable number of consecutive packets must deliver the same δ. This will also prevent the problem of multi-link connections such as ISDN that cause wrong results with the packet pair method [Pax97]. Note that in the Internet the bottleneck bandwidth is not always constant. For example route changes may influence it. The implemented agent is able to cope with this by using a soft-state mechanism for the current δ. Thus, after a configurable time, the δ is reset to an initial state and the measurement restarts. Figure 6.3 shows the results delivered by a passive bottleneck bandwidth measurement agent (in *micro*seconds - μs[4].) . The agent monitors traffic on a PC that is connected to a 10 Mbit Ethernet. It filters for traffic coming from a neighbor 100 Mbit Ethernet. After about 12 seconds the agent found a bottleneck bandwidth of 1.22 MBytes which is very close to the theoretical maximum of 10 Mbits. Figure 6.3 also depicts how from time to time the agent confirms the bottleneck bandwidth. Note, that the monitoring node was not in a productive network. Therefore, the test setting included artificially generated UDP background traffic. The passive bottleneck bandwidth agent will detect the bottleneck bandwidth only if an application rapidly sends packets at least a short period of time. An FTP session transferring a file of about 100 KByte will do.

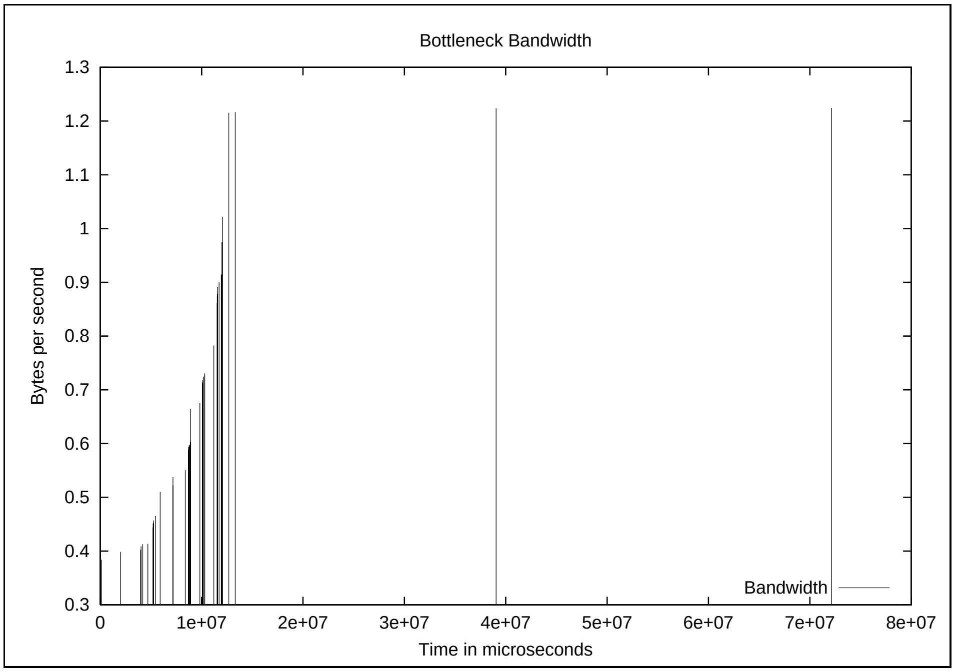

Figure 6.3: Real network bottleneck bandwidth measurement.

With the CSM infrastructure the traditional sender-receiver based bottleneck bandwidth measurement can be extended. Several intermediate agents can all measure the δ value and thus play the role of the receiver. The customer can compare the results of these agents and learn about the *location* of the bottleneck link and about local congestion. For that purpose the agents measure the delay between two (or more) selected packets and send the results to the customer application for comparison. Figure 6.4 shows a distributed measurement scenario with three provider networks (A-C) and three CSM nodes (M1-M3) on which bottleneck bandwidth

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[4] $1s = 10^6 \mu s$

agents execute. Here, the sender sends a packet pair and the agents measure the delay between the packets. First let us study the ideal case where the networks are idle. The agent at M1 can measure the delay and directly calculate the available bandwidth of provider A. The agent at M2 measures the same delay. This means that the bandwidth provided by B is at least as large as the bandwidth provided by A. If the bandwidth was smaller the delay would have been larger. The bandwidth of B could still be larger than the bottleneck but since B received the packet pair already with the given delay, the delay does not get smaller. The agent at M3 measures a larger delay. It can now calculate the bandwidth provided by C. It is the bottleneck bandwidth for the whole connection. Note, that with bidirectional traffic measurements and traffic sources using other paths the customer can eventually learn more about the unknown bottleneck bandwidth at B.

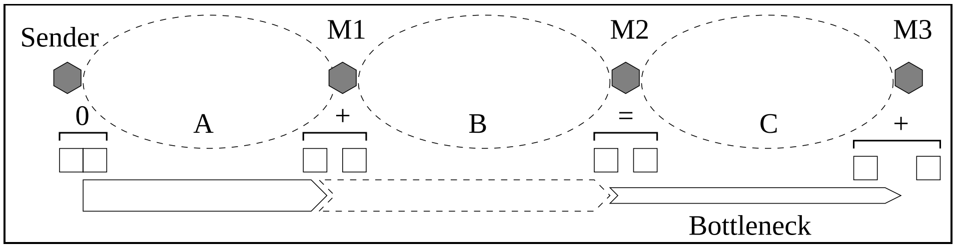

Figure 6.4: Distributed bottleneck bandwidth measurement.

Unfortunately, the networks will seldom be idle. If the packet pair waits in queues of some routers for other packets to be forwarded then this may influence the outcome of the measurement. There are two cases where queuing has an influence on the measurements. (1) If a packet of a different source interleaves between the packet pair then the delay between the packet increases and indicates a wrong bottleneck bandwidth. To avoid this we can exploit the fact that the bottleneck bandwidth measurement provides an upper bound that it is relatively constant. Therefore, the customer can carry out several measurements and compare the results. If there is an accumulation of a concrete bandwidth value then this value is probably the true bottleneck bandwidth. The other queuing influence (2) is when foreign traffic causes the packet pair to queue before a fast link. Then, once the packets are forwarded the delay between them actually decreases. While this is bad for the simple end-to-end bottleneck bandwidth measurement it is actually good for CSM based distributed measurements. CSM can use the fact that this is the only case where the delay can actually decrease. Thus, if the delay between two packets has decreased from M1 to M2 then M1 can be regarded as the sending application that sends the two packets with no delay. The measured delay then allows the customer to deduce the bandwidth provided by B.

The tests showed that by comparing the delay between consecutive packets at different daytimes the customer can use CSM agents to collect an accurate picture of where congested links and bottleneck links are located. It is, however, important that the customer compares at different measuring points the inter-packet delays that belong to the *same* packets. Therefore, the distributed agents must possess a mechanism to identify packets.

6.3.2 Coordination of Distributed Measurements

For security reasons the agent cannot read from network connections unless there is a node service for that purpose. Therefore, the home application cannot send control messages to the agent, and so the home application cannot directly synchronize the agent activities. If the node provides a synchronized clock service then the customer can program the agents to synchronize their activities with this clock. There is another option to synchronize distributed measurement agents: the monitored traffic. The agents can inspect the monitored packet and see if they are relevant to them. If all agents of a distributed measurement setting use the same criterion then their measurement is synchronized[5]. If the agents have protocol knowledge about protocols that synchronize their sender and receiver then the agents can exploit this (implicit synchronization). Protocols that built-up connections (e.g. TCP) and that use sequence numbers e.g. (ICMP) both provide information that the agents can use to synchronize their measurements. Another possibility is that they synchronize on monitored packets that match a given hash value (explicit synchronization).

The Hash Agents. We introduced a hash agent that hashes IP packets and compares them to a set of hash results. If there is a match the hash agent can react in different ways. Thus, the customer can send IP packets that trigger agent activity once the agent sees such a packet. The customer can use this mechanism to coordinate distributed measurements. If the customer wants to compare test results of agents that perform sample test it may be important that they all use the same sample. The hash function can guarantee that (with an arbitrary high probability) the same packet is studied. The previously discussed bottleneck bandwidth agent is a good example. The sender of the packet pair uses packets with a random payload. It also calculates the hash of the packet's payload. The measurement agents know the hash result that they have to look for. Thus, they can easily identify the packets to be measured. The hash agent hashes from a configurable starting point in the IP packet up to an ending point. So, for example the first 40 bytes of the UDP payload can be hashed. The customer can also configure the agent to match how many bits of the hash code must match. If for example the agent must only match 6 bits then about every 64th packet matches.

The hash function call of the hash agent is generic it can be replaced by an arbitrary hash function. Used hash functions are the IP checksum function [BBP88] and the Message Digest 5 (MD5) algorithm [Riv92]. While the former is fast the latter is secure. Using a secure hash function is interesting for agent security (see section 6.4), because even when an attacker knows what hash value the agent is

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[5] This does not mean that their clocks are synchronized, but that they perform the metrics on the same samples.

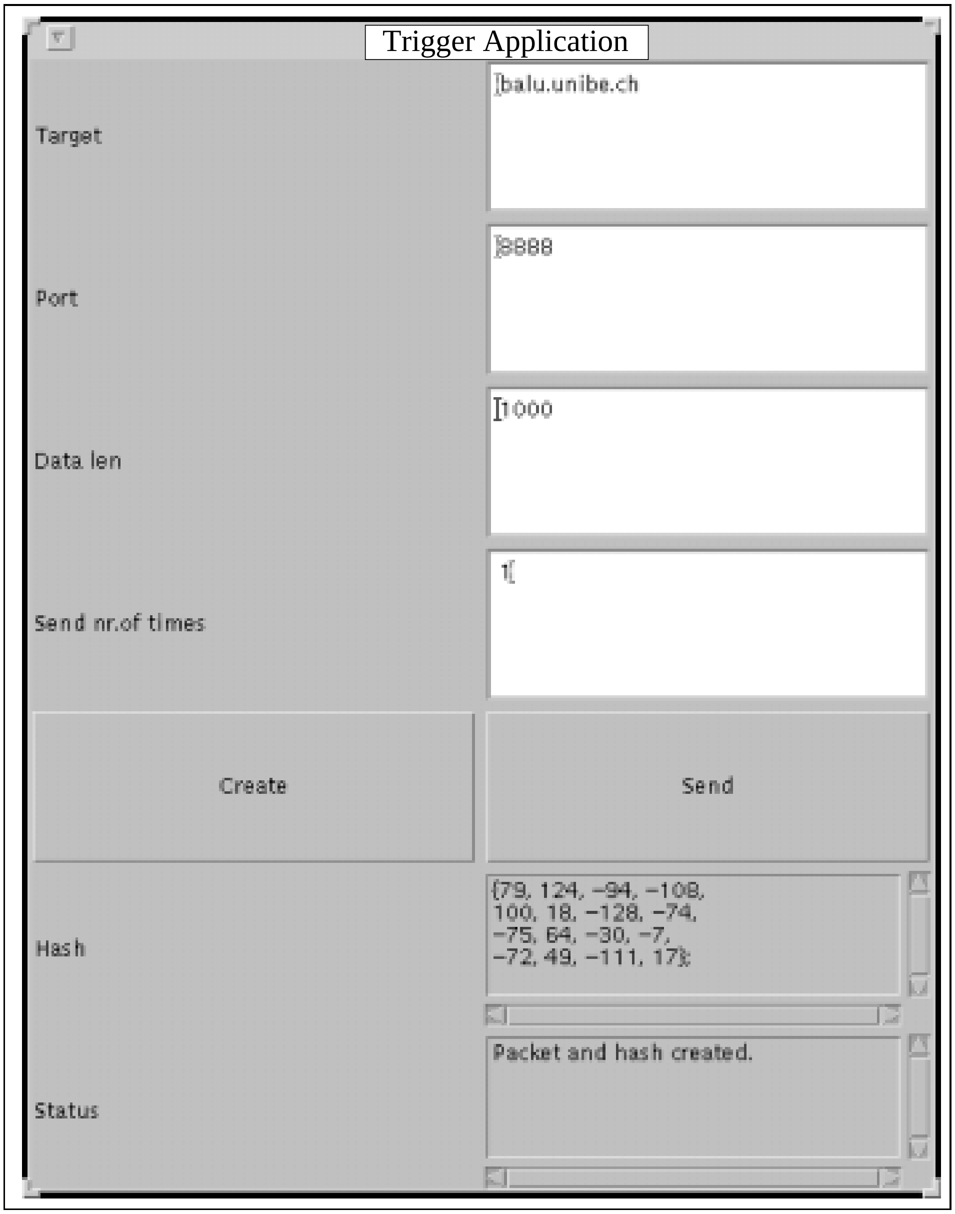
waiting for, it is practically impossible to generate a packet with that hash and thus to e.g. remotely manipulate the agent.

The Trigger Agent. The trigger agent is a subtype of the hash agent and demonstrates one way to use the hash agents. Such an application generates a packet and its hash value in advance. The agent is fed with the hash value before it is sent out. Later, the application can send the generated packet to trigger the activity of the agent. The trigger agent encapsulates an arbitrary agent of the customer. It monitors the traffic only looking for a packet that matches a hash. From the moment this packet is received the trigger agent delegates each packet or service result to the encapsulated agent. The trigger agent thus allows the customer to send an arbitrary agent and start it later by sending a special (eventually secret) start code. The trigger agent offers a generic way to add this functionality to e.g. to third-party agents.

The Trigger Application. The customer also needs a way to send packets that trigger activities of hash agents. We implemented a so called trigger application for demonstration purposes (see figure 6.5). The application can send a configurable number of UDP packets. The user has to specify the destination and the port number of the packets, as well as the packet size and the number of times the packet should be sent. There are two buttons to press. The *create* button has the application create a packet with a random payload. It also creates a MD5 hash of the created packet and displays it on the GUI. The hash is formated like a static Java array declaration so the user can cut-and-paste the hash into his/her measurement agent code. The user must then send out the agents. Finally, the user presses the *send* button for the packets to be sent. The trigger application as traffic generator for the distributed bottleneck bandwidth measurements described earlier.

6.3.3 One-Way Delay Measurements

One-way delay measurements require a synchronized clock. As mentioned before this can for example be provided by the node as a service to the agent. We implemented a one-way delay measuring agent that is suitable for distributed measurements. The agent is a sub-type of the hash agent. It records the arrival time for packets that match a hash. The hashing can be configured so that the agent performs sample tests on the background traffic, or it can be used to match only a particular packet generated by a customer application. The agent assumes the presence of synchronized clocks. Since implementing a precise clock synchronization service was out of the scope of this work we used virtual routers [BB00] to emulate a network. Note, that another possibility would have been to use clock synchronization and clock skew elimination as described in [SBBS01]. The deployed scenario is depicted in figure 6.6. The routers all run on one PC thus they have access to the same clock. So, the time-stamps on the packets monitored by



Target: balu.unibe.ch

Port: 8888

Data len: 1000

Send nr.of times: 1

Hash: {79, 124, −94, −108, 100, 18, −128, −74, −75, 64, −30, −7, −72, 49, −111, 17}

Status: Packet and hash created.

Figure 6.5: The trigger application.

the agents all refer to a single clock. The scenario includes two virtual routers interconnecting three private networks. The PC is connected to the virtual networks with two softlink devices that have the same look & feel as real network devices. Networking applications running on the PC can send real traffic through the virtual network. For each virtual router there is a CSM node that provides monitoring access to CSM agents.

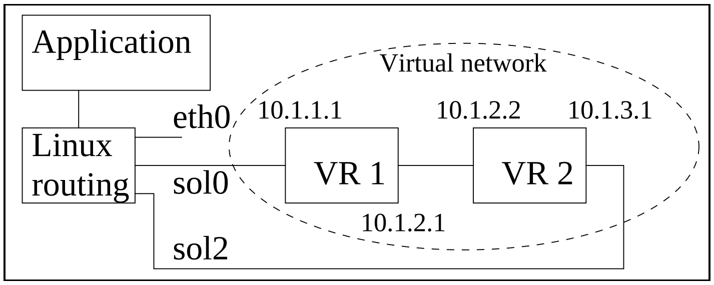


Figure 6.6: A measurement scenario with two virtual routers.

Figure 6.7 shows the one-way delay (in *micro*seconds) measured between the two virtual routers. The traffic source was a telnet session that was routed over sol0, through the virtual network and back to the host machine over sol2 (see figure 6.6). The agents use a hash that matches an average of 1 in 16 packets. I can measure that the virtual routers forward the packets fast. Every delay was clearly smaller than 0.6 milliseconds. The delay variation is quite high though. This is due to the fact that the virtual routers run in user space. Other processes may preempt the router and interrupt the forwarding. Note, that the one-way delay measurements can be easily used to calculate the delay variance (jitter) between virtual routers.

6.3.4 The Ping Measurements

As mentioned before, the agents may posses knowledge of higher layer protocols and exploit this for their measurements. The *Ping Listener* agent uses knowledge about the Internet Control Message Protocol (ICMP) echo messages [Pos81]. The agent listens for ICMP echo (request) and echo replies. One ICMP message is encapsulated in one IP packet. The structure of the ICMP echo and echo reply message is depicted in figure 6.8. The ping listener agent records the arrival times of the requests and of the corresponding replies. The agent can perform a correct mapping by using the ICMP *identifier* field to distinguish between different sessions and the *sequence number* field to map a request to a reply. Note that the agent can be used passively. It will then provide results each time somebody starts a ICMP echo session e.g. by running the ubiquitously used software tool Ping.

The ping listener agent groups the measured ICMP messages into series of configurable length (typically 10 requests and corresponding replies). For each series it reports a result statistic back to the home application. The agent can be configured to collect an arbitrary number of series. The following paragraphs outline

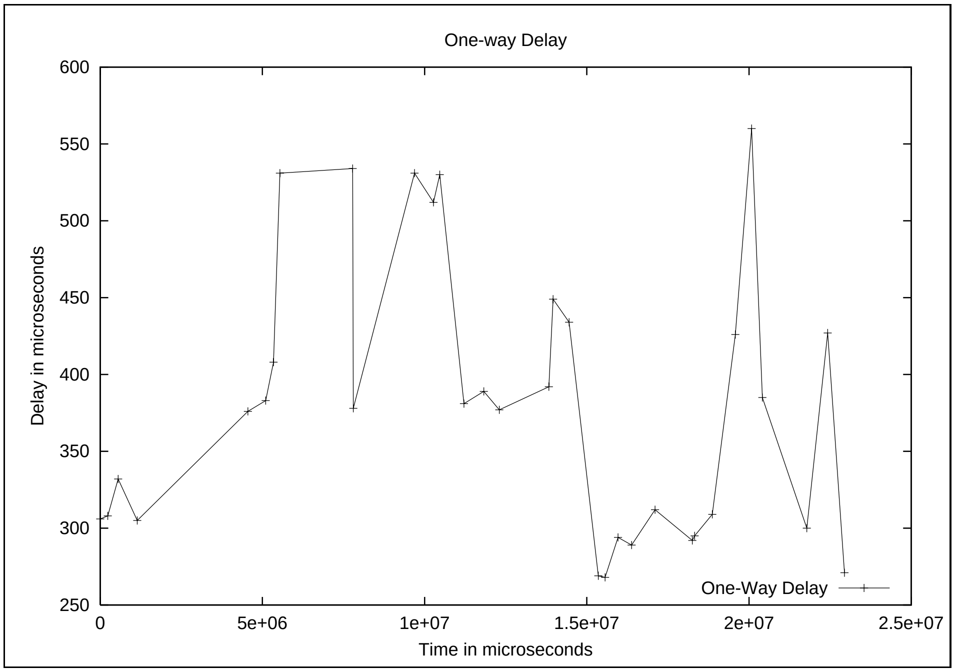


Figure 6.7: One-way delay between two virtual routers.

how the agent collects the contents of these reports: reliability measurements, jitter, and delay information. Note, that several ping listener agents can be located on a test path. Thus, more information is gained compared to a classical active measurement between a sender and a receiver. For example, if some agents see an echo message but the echo does not arrive at the sender, then the lossy part of the path can be identified. In a traditional ping based active measurement scenario (see section 8.3.3) we cannot distinguish between such an echo loss on the path and the failure of the receiving host.

8	16	32
Type	Code	Checksum
Identifier		Sequence number
Data		

Figure 6.8: The ICMP echo request/reply packet.

Reliability measurements. The ping listener agent can perform a number of reliability measurements:

- The agent calculates the checksum (if it is used) to find out about transmission errors.

- The agent can record lost request packets by examining the sequence number.
- The agent can record how many replies were lost.
- The agent detects packet duplications.
- The agent can record requests or replies that are sent in a wrong order (packet re-ordering in the network).

Jitter. The ping listener agent is able to calculate network traffic delay jitter. It can for example compare the delays between a request and a corresponding reply and calculate the standard deviation. This jitter sums up the delay variation introduced by the downstream portion of the round-trip path plus the execution time of the ICMP stack. If we assume that the ICMP echo application sends the requests in regular intervals (like e.g. PING can be told to do) then the jitter introduced between sender and the measurement point can be measured separately. For this purpose the agent compares the time between the arrival of the consecutive packets and calculates the standard deviation to report it to the home application (see section 5.6). Figure 6.9 shows the delay variations measured by the ping listener agent. The agent resides on the virtual router V1 of figure 6.6. The tests used the ping application to generate an endless sequence of ICMP echo requests targeted to the virtual router V2. The application generates one request per second in regular intervals. The agent used a series length of 10 (10 consecutive messages were treated as a group), thus per group there are 9 delays. Each delay is compared with the previous in order to measure the jitter depicted in figure 6.9. In general the jitter was very low (about 0.03 milliseconds). However, at some times there are large deviations (here about 4 milliseconds). This is the same phenomenon as already measured by the one-way delay agent (see section 6.3.3) and is due to the fact that the virtual routers run in user space.

Round-Trip Delay. If there is no synchronized clock available the ping listener agent cannot measure how much delay a single packet has gained since the last measurement. Still, the agents can provide a more fine-grained picture of where packets are delayed in the network. The agents do not need a synchronized clock to compare the time between a request and a reply. The agents on the path can thus measure *partial round-trip* times (see also figure 6.10). The difference between the partial round-trip times measured at two adjacent nodes is equal to the echo traveling time (of both the request and the reply message) in the intermediate network. While the agent cannot determine if it was the request or the reply packet that caused more delay it can figure out which provider network causes the largest part of the round-trip delay.

Figure 6.11 shows the partial round-trip times measured in the setting depicted in figure 6.10. We see that the second router causes relatively few delay with few

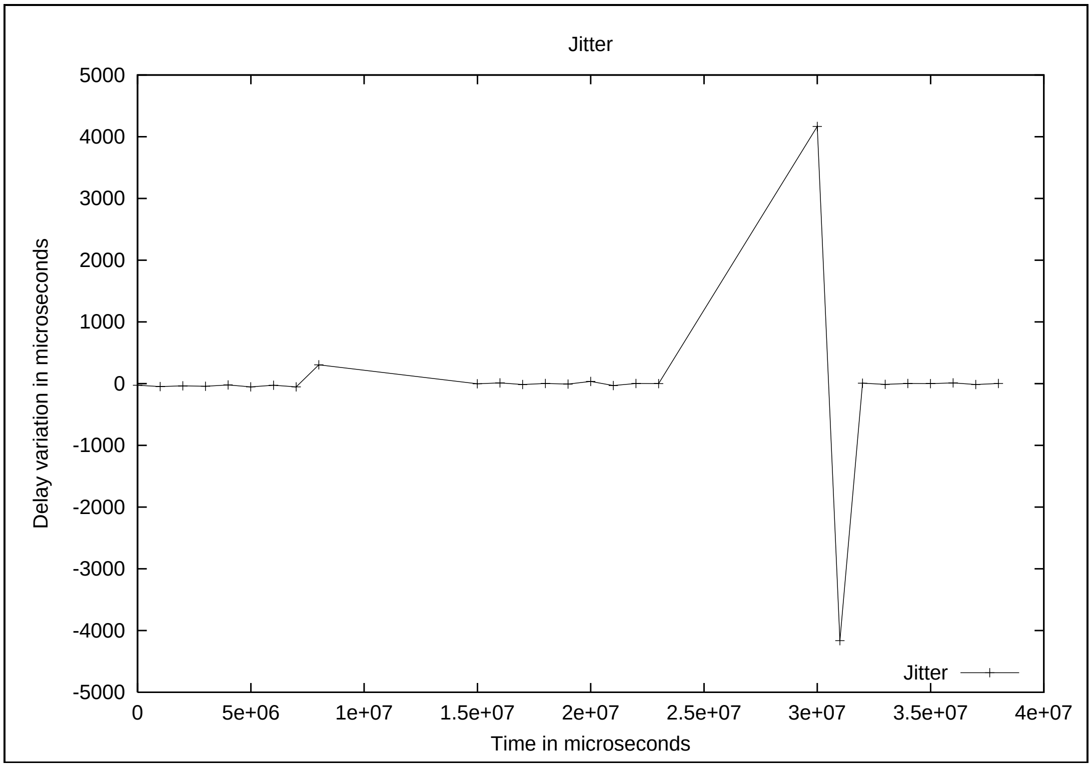


Figure 6.9: Jitter measurement in a virtual router.

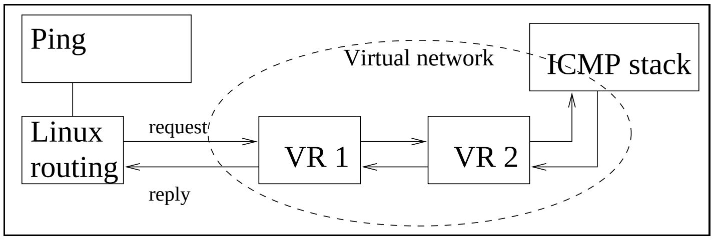


Figure 6.10: Measuring partial round-trip times.

jitter. Its ICMP stack is obviously fast. The round-trip time measured by the second router is significantly larger and the traffic suffers more delay jitter.

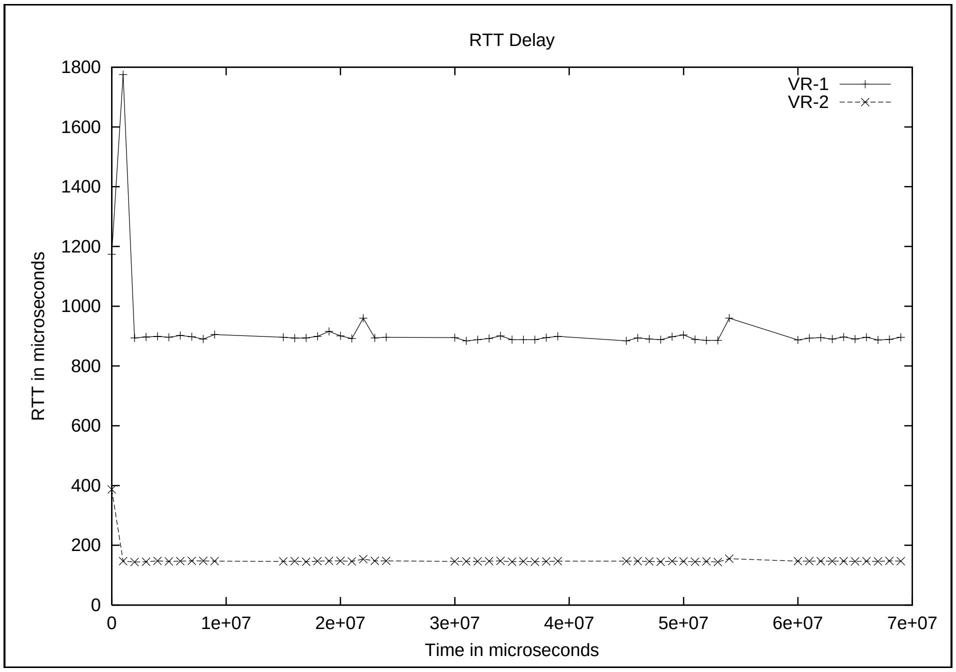


Figure 6.11: Partial round-trip times of two virtual routers.

Impact of cross traffic. The tests described here use the same scenario (figure 6.10). The tests shall prove the ability of the ping listener agent to detect the influence of cross traffic and congestion on the round-trip time and on traffic loss. This time the pings are directed to the outbound interface of V1. In order to produce congested links we used the UDP sender application presented in [SBBS01]. The link capacity of the virtual network is shaped by a token bucket filter to conform to an average of 1 Mbit per second. Figure 6.12 shows 5 series of ten round-trip times for an uncongested network. Figure 6.13 shows the round-trip times when the virtual routers have to forward a background traffic of 1 Mbit per second. Still, there is no packet loss but the delays increase heavily. Figure 6.14 shows the delays for background traffic of 3 Mbit per second. Some ICMP messages still get through but there is a heavy loss also. Note, that the loss is not explicitly depicted in the graphs but it can be seen as missing RTT bars. The heavily congested network in figure 6.14 shows only 29 out of 50 RTTs, so 21 ICMP messages were lost.

6.4 Agent Security

The CSM infrastructure protects the CSM node, the monitored device, and traffic from illegal access by the agent. Also, agents are protected from each other. This

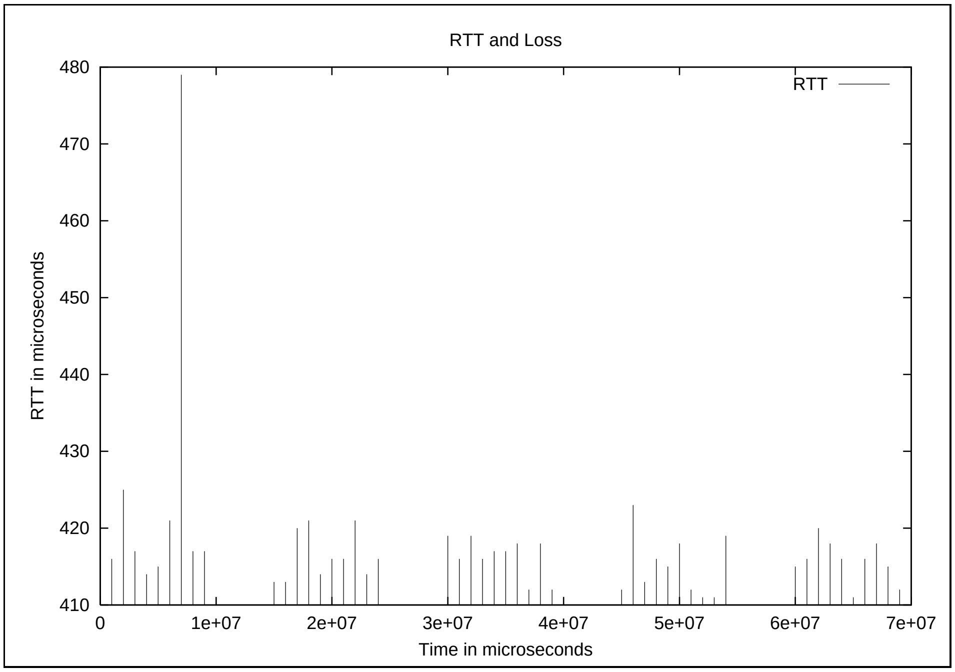


Figure 6.12: Round-trip times in uncongested network.

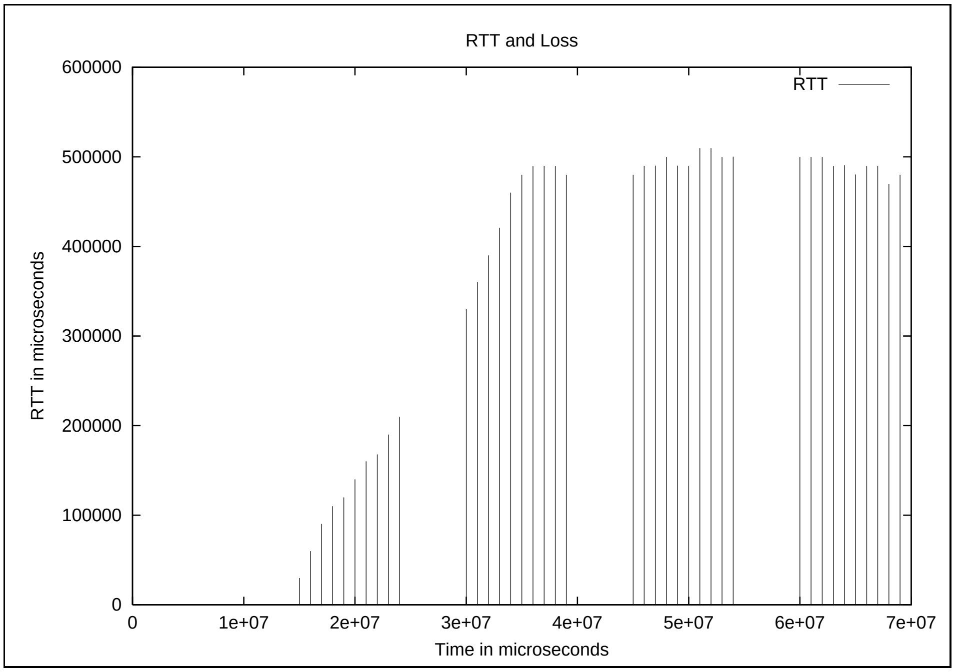


Figure 6.13: Round-trip times in mildly congested network.

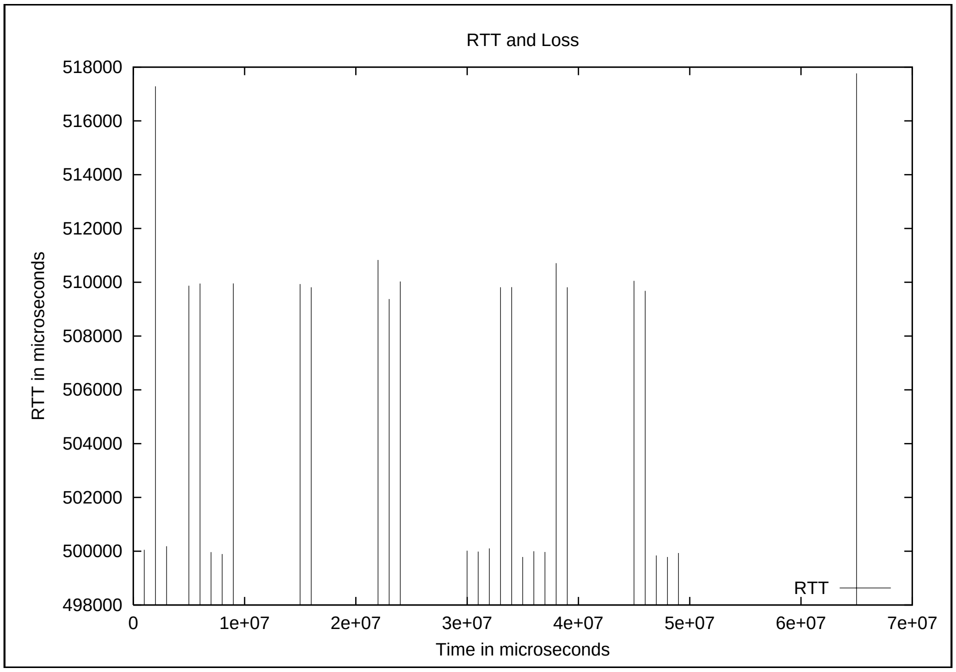


Figure 6.14: Round-trip times in heavily congested network.

section discusses attacks that are launched by the provider against an agent in one of the provider's CSM nodes.

6.4.1 Classification of Attacks

The agent is protected against exterior attacks by foreign providers or customers. Yet, the agent fully depends on the benevolence of its execution environment. The usual approach to protect the agents from the execution environment is to let the agents run in a secured box of a trusted third-party. This approach is not appropriate for CSM because the providers will probably not allow a third party to install a network measurement tool at the provider's premises without giving the provider full access. So, we have to live with the assumption that the provider has full access to the CSM node. This section is not going to discuss denial-of-service attacks launched by the execution environment. The node can for example refuse to deliver packets to the agent, refuse to execute the agent, kill the agent before its normal termination, and refuse to send results of the agent. It is the right of the execution environment to deny services. This is necessary for example in order to enforce resource control or to provide better services for agents of more important customers. Denial-of-service 'attacks' do not deceive the customers, because they are visible to them. If the customer is not satisfied with the service that his/her agents get then the customer can reconsider the business relation to the provider. This section focuses on goal driven attacks that try to manipulate the monitoring results in order to hide network problems or worse, put the blame on peering network providers. Such attacks make the customer believe that the service or the network is in a state other than the true one. A malicious provider can attack the integrity of the monitoring data at three levels: at the sending of the result (output), at the information processing of the agent, and at the input delivery to the agent (see figure 6.15). The attack may need agent specific knowledge so that the customer gets convincing results and cannot immediately see that an attack has happened. Such knowledge about the semantics of the agent can be gained through offline analysis of the agent or through online analysis of the agent and its behavior (e.g. internal dataflows). Further, the attack may be launched by a human expert or the attack may be launched automatically.

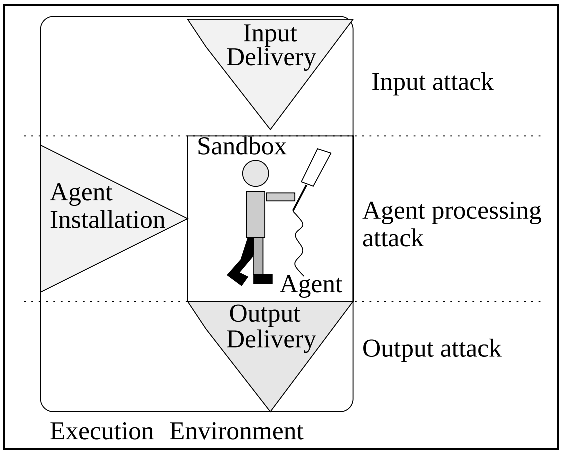


Figure 6.15: The three attacking targets.

Here are examples of these attack types:

- **Attacking the output of the agent.** The attacker may for example see that the agent sends status reports containing fields labeled with 'bytes per second' and change the value of this fields to his/her likings. In general, the attacker must know (1) what the agent measures and (2) how the results are formated and when they are due.
- **Attacking the agent processing.** The attacker may for example remove commands that trigger alarms which would inform the customer that his/her service is broken. The attacker may start a harmless version of the agent instead of the agent sent by the customer. For such an attack the attacker must have detailed knowledge about the semantics of the agent.
- **Attacking the input of the agent.** The node may for example simply not deliver those packet copies that reveal a problem. Another possibility is to manipulate the timestamp of the packet copies. The attacker may deliver packet copies that originate from other locations than the monitored network

device. This attack may also work without knowledge of the agent semantics.

Unfortunately, manipulation of the agent or its result cannot be stopped. For security reasons, agents need to be under full control of the executing node. The node environment must be able to interpret the agent's byte-code so that the agent functionality is performed correctly. Note, that some agent platforms rewrite the byte code of every agent in order to enforce resource control [BHV01, VB99]. So it is always relatively easy for the node to manipulate the agents, but we will show that the ability to program agents in a general purpose programming language is a powerful tool to sooner or later detect unannounced tampering of the agent. Our goal is to prove that the customer can write agents that are so hard to manipulate, that it is actually much easier and cost effective for the provider to (re)engineer the network to accommodate the promised service than to try to cheat.

6.4.2 The Semantics of the Agent

If the attacker wants to fake a meaningful agent result then the attacker must know the intention of the agent. For normal CSM agents this may work as follows: the attacker decompiles the agent and reverse engineers it. By analyzing the agent source code the attacker can deduce what the agent is supposed to measure. The attacker includes a cheat mode into the nodes that automatically performs a manipulation each time this agent is sent again. For example, the sending service may rewrite results or instead of the original agent a fake version is started. This is an human driven attack. Because humans are involved, the initial attack has to be off-line. It is obvious that no human can reverse engineer any agent faster than the agent is supposed to start sending results (within seconds). On one hand it is hard to protect the agents against off-line human driven attacks but on the other hand it is not necessary to provider a bullet-proof protection against such an attack since the attack effort is too high. Note, the attack-taskforce of the malicious provider would have to be ready all the time to analyze and classify every agent that every customer, peer provider or third-party vendor may send. Yet, if the attack could be automated, so that the agent is attacked on the fly then a malicious provider may profit from the deployment of such an automated attack system. Nevertheless, computing theory gives us a convincing argument that an automated attack working for all kind of agents is not feasible. As mentioned before, the attacker must know about the semantics of the agent. Yet, the agent is a complete program. It can be proven that there exists no program that is able to determine in finite time if a program stops within finite time (the infamous halting-problem [Tur36]). So from that we can extrapolate that there is no program that can extract the semantics of all other programs.

Of course, in practise things look different because the attack program does not have to work for all agents. It is enough if it works for most agents. Yet, reverse engineering is a hard problem and current tools struggle to analyze the structure of a program and do not even try to extract semantics. Thus, automatic (on-line) attacks on the CSM agents are not feasible given the state-of-the-art of artificial intelligence.

CSM agent programmers can also make the off-line analysis by humans hard. Here are some measures that can be taken that discourage the reverse-engineering:

- **Obfuscated code.** Obfuscated agents include unnecessary entities in their byte-code such as additional variables, calculations, branches, functions and classes. The agent developers should make sure that all of them are used in some cases an influence (unnecessary) parts of the result so that smart compilers cannot remove the obscure parts. The format of the result should also be obscure. For example the result may be split in parts. Numbers may be transformed with bijective functions. For example for floating point results the multiplicative inverse may be sent. The designer of obfuscated agents can exploit the expressive power of a full-fledge programming language to create endless variations of an agent.

- **Non-trivial filters.** Obfuscated agents should use filters that match more packets than actually needed and re-filter the packets internally. Otherwise, the attacker may guess the intent of the agent based on the requested monitoring traffic.

- **Obfuscated boolean expressions.** Internal filters can be protected, too, by using obfuscated boolean expressions. Here's a generic way to do so: (1) Use a tautology generator to create an arbitrary number of tautologies T_i out of many variables of the agent. A tautology T is a boolean expression that always evaluates to true no matter what the values of the involved attributes are. Tautologies can be created in linear time. (2) Use a generator that analogously creates boolean expressions that are always false F_i. (3) Obfuscate the filter expression B by generating an equivalent expression through random iterations of the following rules: replace B with $T_i \wedge B$ or $B \wedge T_i$ or $F_i \vee B$ or $B \vee F_i$. The resulting expression is equivalent and much more complex than the starting expression.

- **Send meaningless agents.** Instead of including meaningless functionality the customer can sent entire agents that do not calculate anything useful. If such an agent starts sending useful results then this is a good sign that some tampering has happened.

- **Using the input.** The agents may use the packet copies to dynamically change their behavior. A simple instance of this approach is the trigger agent (see section 6.3.2). The agent may apply an arbitrary (possibly secure) hash function to each packet and treat only those packets that match a certain hash value. The customer may extrapolate the service state from the state of that particular subset of the traffic. For itself, the trigger agents are relatively easy to reverse-engineer. Yet, the hash mechanism may be used to construct a meaner obfuscated agent: Such agents *interpret* the payload of packets that match the hash functions. The data in these packets may describe a permutation of input variables. Before the permutation is known, the attacker cannot analyze the calculations that base on these input variables. Even better, the agents can interpret parts of the payload of these packets as commands. Imagine an agent that implements a stack machine. It puts its input variables on a stack according to an order described in a matching packet's payload. It interprets further parts of the payload as operations such as addition, multiplication, division etc. The attacker would need to break the hash function in order to see what kind of packets match and thus trigger the calculation. Instead of a stack machine, the agent may itself be a virtual machine. This idea is used in [Tsc99] to securely end distributed services in an active network. The agent validates the packet with the secure hash function. It then executes the contents of the packet as commands.

- **Mobile Cryptography.** Mobile cryptography is defined as the study of mathematical techniques related to aspects of information security of mobile executable code in a network [ST98]. The basic idea is to encrypt executable code in a way that the code can still be executed. More specific the agents use *encrypted functions*. Be f a function with $f(x) = y$ then we denote $E_f(x)$ as the encrypted function of f. E_f shall have the following properties: (1) it is computationally hard to find the function f given E_f. (2) $E_f(x) = E(y)$ thus the encrypted function delivers the encrypted result of the function f. Say that the customer wants to execute the function $f(x)$ remotely and obtain the result y. The remote execution environment shall neither be able to understand the function f nor to see the result y. Given encrypted functions, the customer calculates E_f and generates an agent $A(E_f)$ that implements the encrypted function. The customer sends the agent which is then executed in the node. The node executes $A(E_f)(x)$ and delivers the result $E(y)$. The customer then decryptes $E(y)$ and thus gets the desired result y. The node only sees the encrypted function and the encrypted result. Therefore, mobile cryptography could completely conceal the semantics of the agent. Unfortunately, until today no algorithm to generate generic encrypted functions exists, and it is not proven that a secure algorithm exists at all. [ST98] proposes an encryption method E and an algorithm that can compute $E(x + y)$ from $E(x)$ and $E(y)$ without revealing x or y. Further, they propose an algorithm to calculate $E(xy)$ from $E(x)$ and y without revealing x. The algorithm allows the agent designer to create encrypted functions for polynomial functions. Yet, the proposed encryption scheme E has been successfully attacked.

6.4.3 Attacks on the Input of the Agent

If the malicious provider knows about a network problem then the provider may use attacks on the input of the agent to hide the problem. The nice thing about this attack is that it does not necessarily require knowledge about the semantics of the agent.

In the situation depicted in figure 6.16 the provider B has a provisioning problem and loses reserved traffic within B's network. The agent measurement results (the height of the bars show the throughput) clearly indicate the location of the problem. If B is malicious, aware of the problem, and has a clever intervention infrastructure on his/her CSM T-components then B could launch the following attacks on the agent input: either it sends packet copies seen at B1 to B2 or it vice versa. The two variants and the subsequent measurements are depicted in figure 6.17. The black bars indicate the measurements based on the manipulated input. Variant 1 makes the customer believe that the traffic was lost on the link between A and B. Variant 2 makes the customer believe that the traffic was lost on the link between B and C.

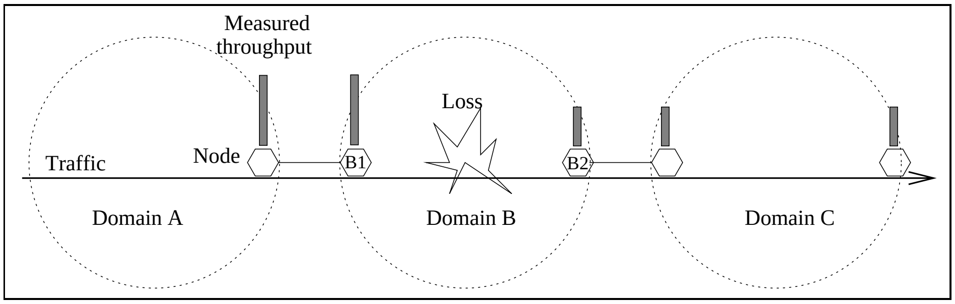


Figure 6.16: A loss situation measured at honest provider sites.

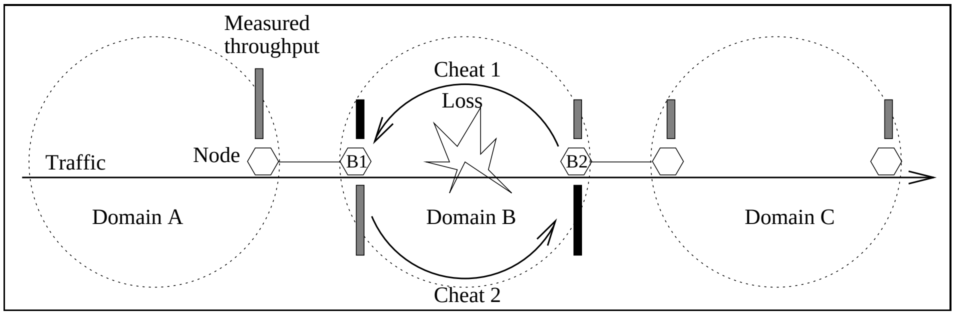


Figure 6.17: Two agent input attack variants performed by provider B.

The mobility and the programmability of the CSM agents provide means to unveil the malicious scheme. The main problem for the provider is to keep the input to the agent consistent. The timestamps on the packet copy are already problematic. If the provider delivers the packets seen at B2 to B1 then the timestamp must be set back to an earlier time. But then, the agent may see that it took the T-component much longer than usual to deliver the packets. The analogous problem may reveal the cheat when the provider delivers the packets from B1 to B2.

If the provider manages to calculate credible timestamps then the customer has further means to unveil the cheat. Assume the cheat 1 variant of figure 6.17. For the customer it may be undecidable whether A has applied the cheat variant 2 or B has applied the cheat variant 1. The customer could then assign ’penalty points’ to both providers. If later a similar situation occurs between provider B and C, then B would already have two penalty points which would indicate that B is probably cheating and neither A nor C. The customer can also send further agents that surround the cheat candidates. Measuring traffic delays and also delays within the CSM nodes (in similar ways as for the performance tests in chapter 7) generate further clues who is cheating. Finally, the customer can perform active tests. The customer may for example generate and measure bidirectional traffic, or traffic from sources, so that the traffic crosses only one of the cheating candidates. In case nearby CSM nodes provide a sending service without destination restriction then the customer can send agents to exploit this service to test particular distrusted nodes.

6.4.4 Evaluation of the Threat Situation

From the discussion in this section it should be clear that today there is no bulletproof solution that protects mobile agents from a malicious execution environment. Yet, it should also have become clear that the more effort the CSM agent developer puts into obfuscating of their agents, the more resources the attacker needs to find out about the intend of the agent. Compared to stationary approaches such as SNMP this is a major improvement. There, the provider formats the results according to globally known semantics (MIBs). If the customer requests information from the provider (for example an SNMP get message) then it is immediately clear what the customer is looking for. Further, in static systems the customer can investigate the problem literally only from one side. With programmable and mobile agents malicious providers get involved in a ‘race of arms’ against the collective body of the customers. The malicious provider must always be aware of new agents that may reveal the cheat.

The following reasons underline the claim that in the long term no provider will profit from attacks against CSM agents:

- The agent developers can make it arbitrarily hard for the attacker to reveal the intend of the agent.

- The provider must allocate considerable resources and manpower for attacks against agents. The provider will profit more if this manpower is invested in the service provisioning.

- The more different agents perform tests the more difficult it gets to manipulate these agents without running into consistency problems.
- The attacker must possess accurate knowledge about the state of the provider network in order to hide problems.
- A malicious provider is outnumbered by the customers. The provider faces the collective creativity of the customers, of peering providers and of third-party agent developers.
- There is always a chance that the cheat is revealed. If so the provider will probably face the full range of retaliation. Because of the aforementioned difficulties of launching an attack it is then obvious that the provider did it with malicious intend and not because of errors.

6.5 Extended Application Scenarios

The CSM infrastructure provides a generic interface for service monitoring. The metrics used by the agent depend on the service, on the customers' interests and on the service level agreement between customer and provider. This section presents some more ideas for useful CSM agents and for new node services that enable the agents to examine the new IP services more thoroughly.

6.5.1 Further Applications Independent of New Node Services

Customizable event notifications. One important aspect of network monitoring is the notification of an authority (e.g. the system administrator) when exceptional networking conditions are measured. Today, event notification is often done manually (sometimes also referred to as trouble-ticketing). There, a formal way exists for the network users to report observed network problems. Automatic systems often use a threshold mechanism (e.g. SNMP traps) for event notification. If a network parameter is above or below a threshold, then a notification is sent. This model is useful but simplistic. If for example the network parameter stays very close to the threshold for a longer time or if it rapidly approaches the threshold then issuing a notification or a warning may also make sense. However, traditional stationary network monitoring infrastructures use a hard-coded notification mechanism (typically threshold based). The CSM agents can decide themselves when to notify and to whom to report. The agents can for example implement a heuristic model that notifies with a probability proportional to the proximity of the value to a threshold. They may thus implement a 'random-early notification' scheme. The agents can also use estimation functions that try to estimate the future (expected) measurement value based on the extrapolation of actual measurements [GB01]. Such a function may allow the agent to warn the customer early about problems that are brewing. CSM enables the customers to use the estimation function they think will serve their purpose best.

Trace-back of denial-of-service attacks. Distributed Denial-of-Service (DoS) attacks [CER99, Fer00] are able to knock-out the network connectivity of even large e-commerce corporations. For launching a distributed service attack the hackers infiltrate a large number of systems that are weakly protected (e.g. because they belong to an open academic environment or because there is nothing interesting to be found on them). The hackers install software that allows them to direct traffic at the victim host. Because of the large number of traffic sources, the host under attack will be cut off from the regular traffic and may even crash. If the host provides critical network services such as domain-name lookup or proxy services then an entire customer-premises network may be affected by the attack. The DoS software sends IP packets with a forged IP source addresses. The victim is thus not able to trace the source of the attack and the hacker can use the installed DoS software as often as desired. A measure to prevent these kind of attacks is described in [FS00]. At the network ingress points all traffic should be filtered. By consulting the routing tables the devices are able to detect packets with spoofed IP source addresses that are about to enter the Internet. Unfortunately, the deployment of such filtering rules may take a long time and there will probably always be sites that do not follow the rules. CSM agents are not intrusive so they cannot prevent distributed DoS attacks. However, they may detect the sources of the attack. Identifying the sources is very important since then the DoS software can be removed from infected systems and there is a chance that the hackers that installed the software can be located. The customer runs DoS detection agents which are sparsely distributed in the Internet. The agent performs sample testing of traffic destined for the customer network. If the agent has access to the node's routing (a node service) then it can detect spoofed IP addresses. If not, it can keep logs. Since not all DoS traffic is routed the same way the agent is not affected by an attack. It can keep a log of unusual high incoming traffic. After an attack, the logs can be used to identify the path of the attack. The agent can also check back with the home application if there really is an ongoing attack. If so, the agent migrates to the next hop node over the interface from where the DoS traffic is coming. It then starts monitoring there, looking for traffic directed at the attacked host. Eventually the node will migrate to the node nearest to the DoS attack source. Thus, even when the IP source address in the DoS traffic is spoofed the agents can track down the source of the attack.

6.5.2 Future CSM Extensions

The expressive power of the proposed CSM architecture combined with the implemented node services is sufficient to perform the service monitoring tasks which are necessary for the proof of concept and for the ANAISOFT project goals (see beginning of chapter 4.1). This section presents some extensions that open even more possibilities.

Extended Node Services

Communication services. The communication support available for a running agent is relatively restricted. Here are some additional communication services that the node may provide:

- **Injection of test traffic.** The agent may want to generate test traffic for active measurements. Some of the presented tests used specialized applications on the customer's premises for example to generate traffic. If the agents can play this role, then the measurements are not restricted to end-to-end active measurements thus they allow the customer to derive a more fine-grained picture of the service. In some situation it may even be useful that the agents insert traffic with spoofed IP addresses that appear to be coming from the customer's network so that downstream providers cannot distinguish between active measurements and 'productive' network traffic.

- **Reception of control traffic.** The control of agents may be simplified if they can use a node service to wait for commands from the home application. We can substitute this service by techniques like the ones described in section 6.3.2.

- **Agent-to-agent communication.** For the presented CSM applications there is no necessity that the agents can communicate with each other. However, when agents are deployed in large scales, then an agent hierarchy may become a necessity. Thus, some manager agents have a way to control their subordinate agents (see also chapter 8.6).

When these communication services are implemented as node services then the node should apply security measures. The traffic can for example be filtered in similar ways as the monitored traffic. The node can also enforce the traffic rates by applying e.g. a token bucket filter.

Log file access. Most providers keep log files about events that are relevant to the services provided. These log files represent aggregated information about the state of the service. For example, a VPN tunnel endpoint host may log the failed authentications or replay attacks. Introspection into these log files may save the customer a lot of monitoring work. The precondition is that the customer trusts these logs. The CSM agent infrastructure may be used to perform sample tests to verify the log files. If the CSM nodes provide a log files access service then the agents can do this locally. Here is an example: the VPN implementation of Windows 2000 did under certain circumstances use the relatively weak DES encryption even though it was configured to solely use the stronger Triple-DES encryption. This flawed behavior was visible in the log files [Vaa00, W2K00]. However, securing the log-file access may be more difficult than securing the traffic monitoring. The node needs policies that include knowledge about the semantics of the log files in order to decide whether an agent is allowed to browse certain log entries.

A session key service. Section 6.1.2 showed that the quality of the provider's cryptographic algorithm may be examined by the VPN agents, but that there are limitations. By only examining encrypted traffic the agents cannot deduce which algorithm was used and with what key length unless it launches a brute-force attack. The nodes of VPN providers may thus offer a session key service. Only CSM agents that have proven through strong authentication that they were sent by a VPN customer may request the service. The node then delivers the currently used session key along with information about the applied encryption algorithm. The agent can now decrypt samples of the VPN traffic to check whether the decryption delivers a plausible result. For that purpose the agent may use knowledge about the sent plaintext or it may for example recalculate checksums of higher layer protocols that were encapsulated. With such a session key service the agent can therefore prove that the cryptographic algorithm in use is indeed the one specified and which key length was used. Note however that the node must be able to extract the session key from the current IPSec security association. This may introduce a security hole into the IPSec implementation.

Management information base access. Many network devices support simple network management information bases. Similar to the log file access the Simple Network Management Protocol (SNMP) allows the agent to collect information that is already condensed and thus more compact. For example for measuring the network load the agent does not have to request copies of all packets. It might simply request the appropriate SNMP variable from time to time. Thus, it may be useful to introduce an SNMP management information base access service that offers support for (restricted) SNMP access to the monitored router. Handling (repetitive) monitoring tasks with local SNMP requests saves bandwidth and reduces latency. This has also been recognized by the IETF therefore they developed an experimental standard for local management scripts [SQ99].

Model Extension

The customer-based service monitoring model described in chapter 4 is non-intrusive. In order to widen the application area it can be useful to invalidate this property. Instead of requesting packet *copies* from the node, the agent may order the packets *themselves*. The agent could then play a role in the forwarding process. The node would also offer a forwarding service and access to the routing table. Agents on such a node platform can obviously do more than just monitoring. It can shape traffic, implement a firewall mechanism and influence the route that packets take. They can also 'consume' certain packets, interpret the packet contents as commands, and eventually replace them with others. The CSM architecture would then become an full-fledged *active networking* platform (see section 4.2). The CSM protocol (see section 5.1) would then be the management plane of this active networking platform. This extension opens up new application areas that go beyond the customer-based service monitoring. However, the extended version of the CSM infrastructure is much harder to deploy because it is intrusive. This introduces new security problems and (probably even worse) it introduces performance problems. Note, that the node environment cannot be physically separated from the router like proposed for CSM (see section 4.3.2). But even if the node environment is integrated in the routers, the Java agents are not able to perform forwarding at backbone link speeds.

Chapter 7

Performance Evaluation

This chapter provides an overview of the performance of the implemented customer-based service monitoring components. The focus is on the performance of the node environment but also the performance of relevant agents, the end-to-end performance and the T-component are discussed.

Methodology. The node environment runs (if not mentioned otherwise) on a Sparc ULTRA 5 with a 269 MHz CPU connected to a 100 Mbit Fast Ethernet. If the T-component is the subject of the test then it runs on an IBM Thinkpad 380 ED with a Pentium(r) processor and performs live packet capturing. The Thinkpad is connected to a 10 Mbit Ethernet. If the T-component performance is not the subject of the test I used a T-component dummy that artificially generates monitored traffic and sends it to the node. Time is measured using Java's `System.currentTimeMillis()` system calls at appropriate locations in the code. If not mentioned otherwise the time is taken at a single machine. Therefore, no clock synchronization is necessary. The time is represented in milliseconds. Bandwidth consumption and throughput is usually represented in bytes, kilo-bytes (KB), and mega-bytes (MB) per second. Note, that we interpret kilo as 1000 and mega as a million (not 2^{10} and 2^{20}). In order to have a benchmark time, I implemented the *FastestAgent* which is an agent with empty method bodies. Thus, the agent does not perform any work. It is therefore the fastest possible agent.

7.1 Performance of the Node Environment

Each agent is isolated in a separate execution environment which 'feeds' the agent with monitored packets (see section 5.3.3, especially figure 5.6). A receiver puts the packets coming from the T-component into a queue. The agent wrapper takes the packet out of the queue and hands it over to the agent. The wrapper runs in a special execution thread. This separation brings security but it may also impose performance penalties because of the context switch between threads. Therefore, we wanted to measure the speed of the packet hand-over. We replaced the receiver with a packet generator with parameterizable speed. The generator runs in its own thread and fills the queue with packets. After a fixed number of packets n, the thread yields its execution so that the agent can process the packets. In the following results this is referred to as the number of consumers to producers ($1/n$). The test agents include the aforementioned FastestAgent and a throughput measuring agent. The later uses the IP packet length field to measure the throughput over one-second intervals. For each interval the agent sends a result message back to the home application. Here are the results of some relevant test runs.

7.1.1 Throughput of the Execution Environment

The packet generator generates packets of selectable size at a selectable speed. The throughput of the execution environment is measured in bytes per time unit and in packets per time unit.

The throughput measurements are influenced by the rate at which the receiver generates packets. In this setting the packets are generated as fast as possible. Yet, always after a certain number of packets the generator yields the CPU `Thread.yield()`. In order to determine the weight of this influence we conducted the following measurements: We vary the aforementioned rate at which the agent (FastestAgent) is given the CPU to process the packets from 1 (once for each generated packet) to 1/40 (once for forty generated packets). Note, that the a smaller rate than this does not make sense, because the queue can only hold 40 packets. Thus, after the receiver has generated 40 packets it blocks anyways. The packet size here is 1500 bytes. The test result is shown in the graph of figure 7.1. Rate 1 is not optimal. The high number of context switches between the threads slows down the execution environment. The rest of the rates (between 0.5 and 0.025) do not cause significantly different performances. In the tests of the rest of this section the rate is set to 0.1 where not mentioned otherwise.

The speed of packet processing of the execution environment is also influenced by the packet size. Figure 7.2 shows the throughput in packets per milliseconds (for both presented agents) in relation to the packet size. The upper performance limit is 13 packets per millisecond (for 40 byte packets). The aforementioned throughput measuring agent (an agent performing real work) comes close to 12 packets per millisecond. Naturally, the packet throughput decreases for bigger packets. For maximum sized packets (65535 bytes - not depicted in the graph) the maximum throughput is 2.55 packets per milliseconds.

Figure 7.3 visualizes the same measurement data, but now we compare how many bytes per second are delivered. From this point of view, the execution environment performs better for large packets. For the maximum sized packets the throughput reaches more than 167 MB per second. For small packets (40 bytes) the throughput measured is 516 KB per second. Note, that these numbers represent absolute upper limits.

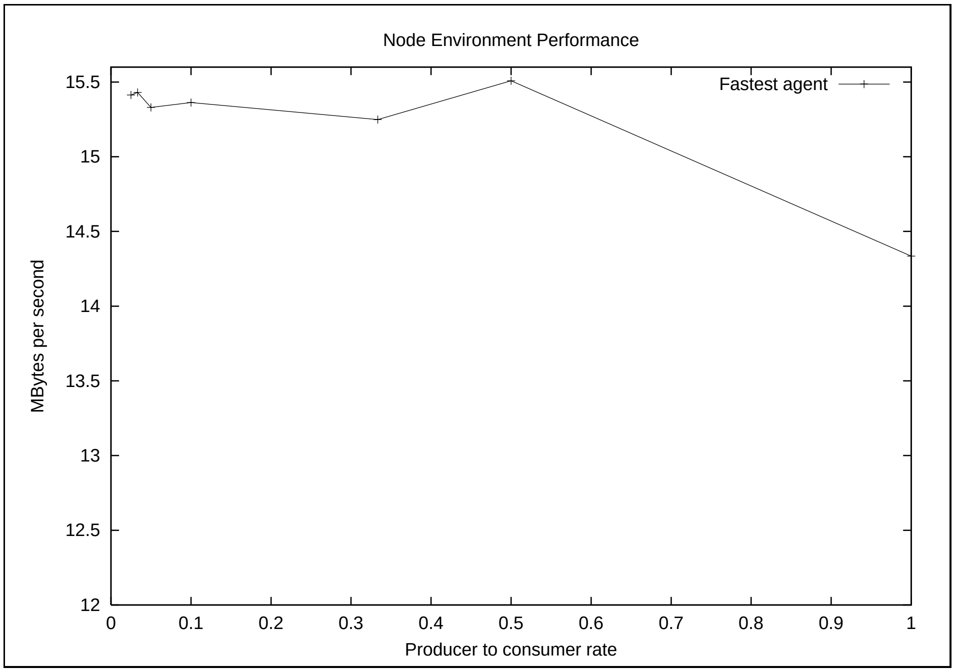


Figure 7.1: Influence of the packet generation rate.

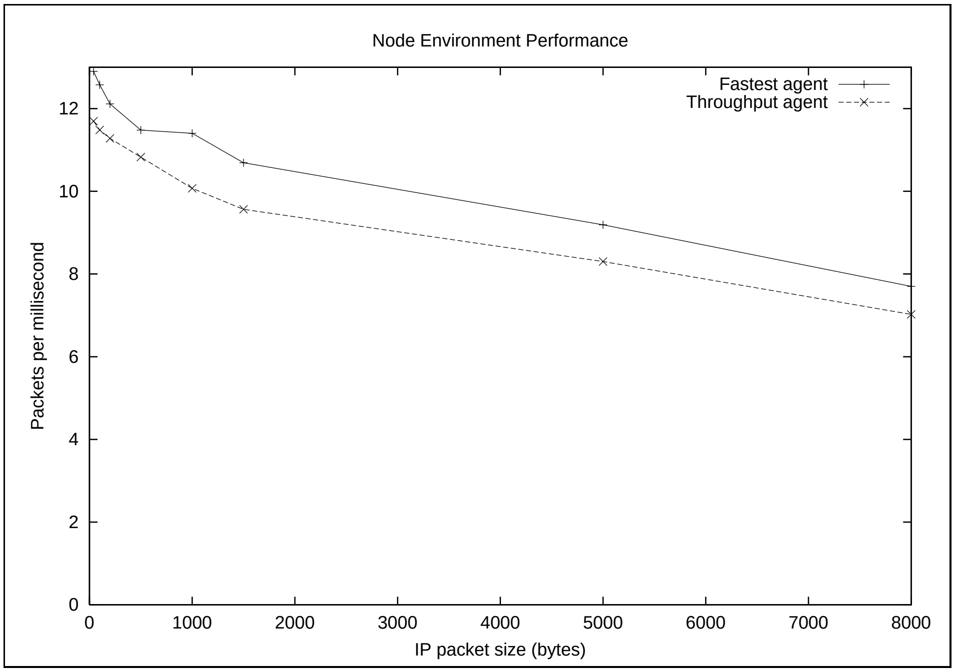


Figure 7.2: Packet throughput of the execution environment.

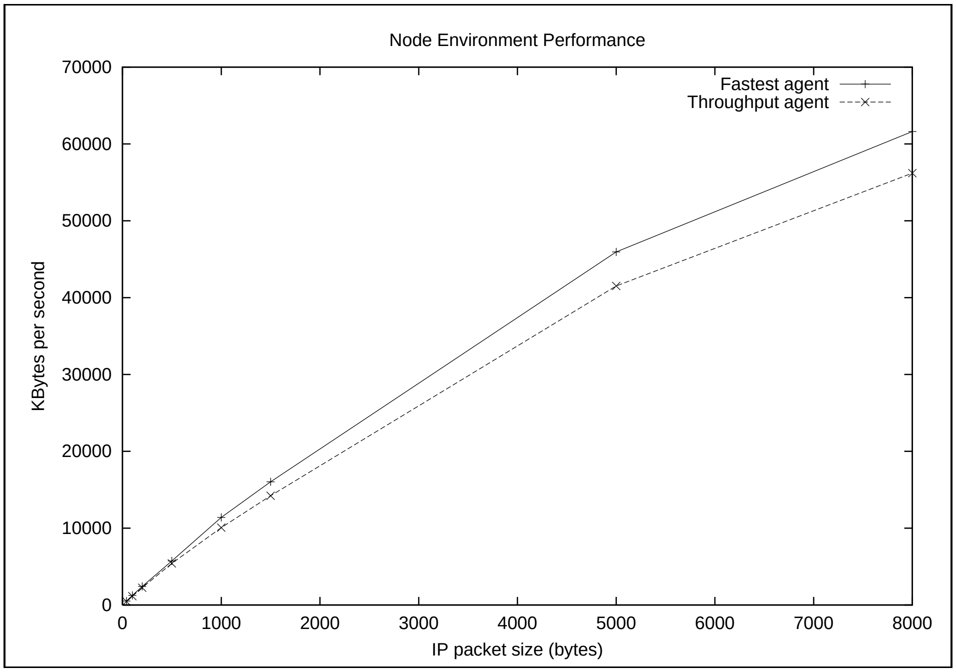


Figure 7.3: Packet throughput of the execution environment.

Influence of the resource control. During their execution all agents are subject to resource usage control (see section 5.5.3). Once a second a resource controller checks the CPU and memory usage of the agents. This work may slow down the node. By comparing the performance of the FastestAgent with and without resource control one can measure the impact of the resource control. The test run measured the time the execution environment needs to treat 100’000 packets with a size of 1500 bytes. The result is depicted in the graph of figure 7.4. Since the benchmark agent does not add overhead for agent specific computing, the impact of the resource control must stand out in this setting. Yet, as the figure suggests the impact of the resource control is only minor (about 5%).

For regular agents that perform some work the relative impact is even much smaller. One exception is the memory usage control. The used mechanism (object serialization - see section 5.5.3) is relatively slow. Its effort grows with the size of the agent to be tested. We implemented a test agent that slowly grows in size. The CPU time used to determine its size during a resource check is shown in figure 7.5. The memory check duration is more or less linear to the size of the agent. Check times of larger agents tend to fluctuate more. Note, that the graph ends at agent sizes of 40 KB because the node policy declares this to be the maximum tolerable size. The 300 milliseconds checktime for agents of about 40 KB size is large (about 30 percent of the interval time). Therefore, memory checks are not carried out at every check interval but only after a random number of intervals (again see section 5.5.3). This is justifiable because experiments showed that rapidly growing agents

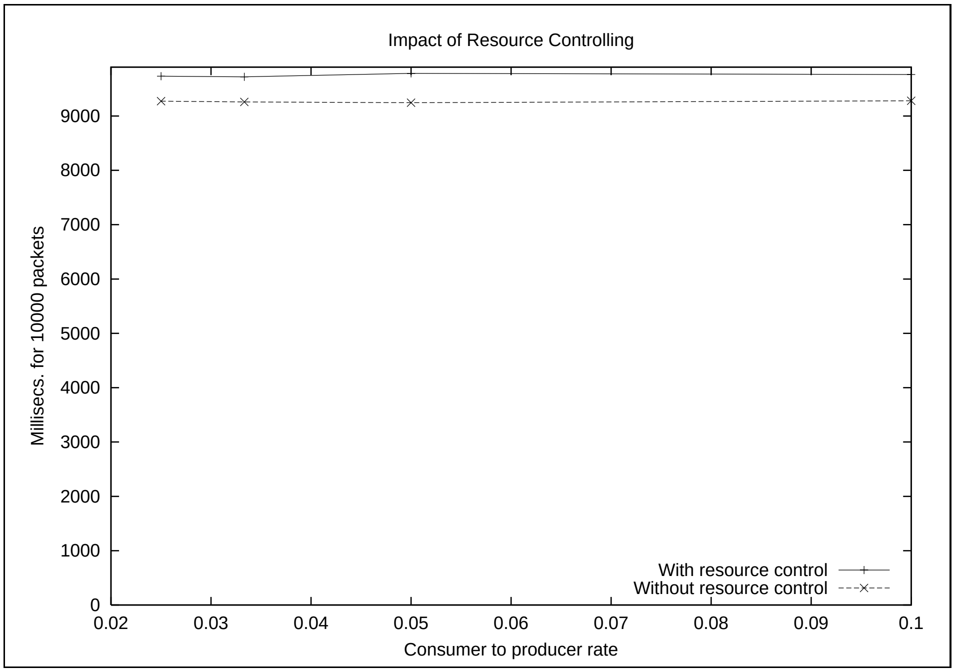


Figure 7.4: Influence of the resource control.

are usually eliminated by the CPU control mechanism.

7.1.2 Node Throughput Including the TCP Receiver

In the previous experiments the receiver component of the execution environment generated artificial packets and injected them directly into the execution environment's in-queue. Here, a separate thread is used to emulate an external T-component. Thus, the monitored IP packets are still artificial, but they enter the receiver through a TCP connection. Again, the FastestAgent is a benchmark. In this measurement we vary the packet size to measure the impact on the packet throughput. Figure 7.6 shows the results. Again, the throughput is higher when the packets are bigger. The achieved throughput is now considerably smaller (about 5 times) than when the receiver generates the packets directly. This implies that the Java TCP/IP sockets are a potential bottleneck of the execution environment. For larger packets the packet per millisecond rate decreases yet only slowly. However, for packets smaller than 200 bytes there is an anomaly where small packets experience a smaller packet rate. This can have several reasons for example that the Java socket implementation for either sending or receiving is less effective for small packet. Yet, we could not clearly locate the cause.

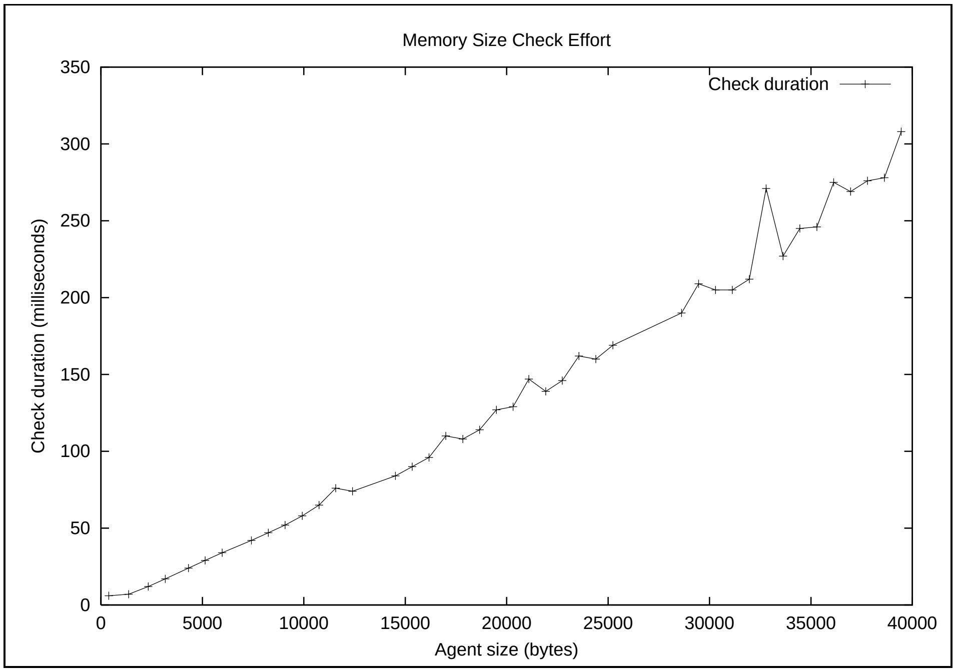


Figure 7.5: Size dependency of the memory control duration.

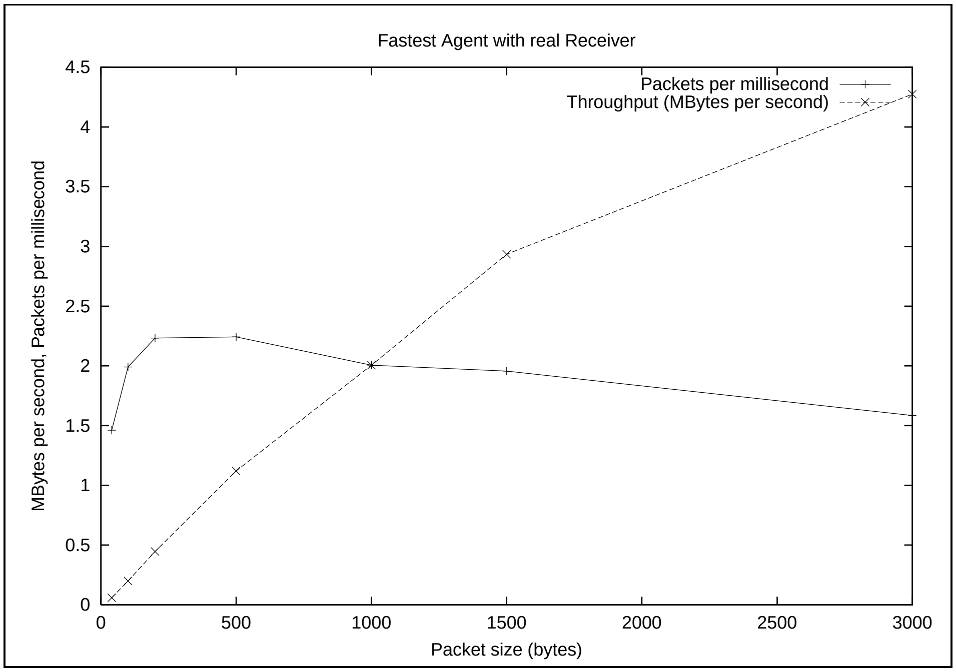


Figure 7.6: Throughput of the execution environment including the TCP receiver.

7.2 Agent Performance

The previous sections already presented the performance of the fastest agent possible and the performance of a throughput agent. The later did perform close to the benchmark. It represents those agents that do only little work per monitored packet, such as for example agents for delay, jitter and loss measurements. This section discusses the performance of the VPN agent presented in section 6.1. The agent calculates a statistic of the complete payload of the monitored packets. The VPN agent is therefore a performance 'heavy-weight'. The VPN agent can perform two kinds of statistical tests: the byte-frequency test and the run-length test. The byte-frequency test involves more computation because it works on 256 value classes whereas in the run-test only uses six classes (see section 6.1.2).

Each agent has an emergency method to treat packets if the in-queue is running full (see section 5.4). Usually, this method just discards the packet[1]. This is also the case for the VPN agent and thus such packets are referred to as ‘lost’ packets. The mechanism allows agents to treat packet bursts and continue their work even if the load of incoming packets is higher than the agents’ packet handling capacity. This emergency mechanism is nevertheless limited. If the agent handles too many packets as emergency then the node interprets this as a sign of a congestion and starts killing low priority agents (see section 5.5.3). Figure 7.7 shows the performance of the VPN agent. Here, the receiver acts as a packet generator with a varying rate (see section 7.1.1). A smaller rate means that more packets are produced before the agent is given a chance to consume them. The results show that the throughput stays relatively constant when less than 20 packets are produced before the agent gets a chance to consume them. After that point the agent starts to drop packets. It can thus handle more packets and the throughput increases. The node limits the loss rate to 40 percent (0.4 in the graph). The VPN agent using the byte-frequency test is unable to support a consumer-producer rate of 0.025. Such a rate leads to a loss rate which is too high and the agent is killed. The VPN agent using the run-test has a significantly higher throughput and can also support the generated traffic up to the maximum rate of 0.025. With a packet size of 1500 bytes, it can handle monitored traffic of up to 0.36 MByte (approximately 3 Mbit per second) without loosing packets. This is also the maximum speed at which software devices can perform encryption. With a reasonable loss (less than 40 percent) the agent can support speeds of over 0.6 MBps (approximately 5 Mbit per second).

7.3 Communication Performance of the CSM System

From the perspective of the user the response time to an agent execution request is relevant. This is the time that elapses between the moment that the user sends the agent and the moment when the user receives the acknowledgment that the agent is running. Note, that the CSM protocol acknowledges the agent only after the exe-

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[1] The agent may also count these lost packets or perform a simplified test on them.

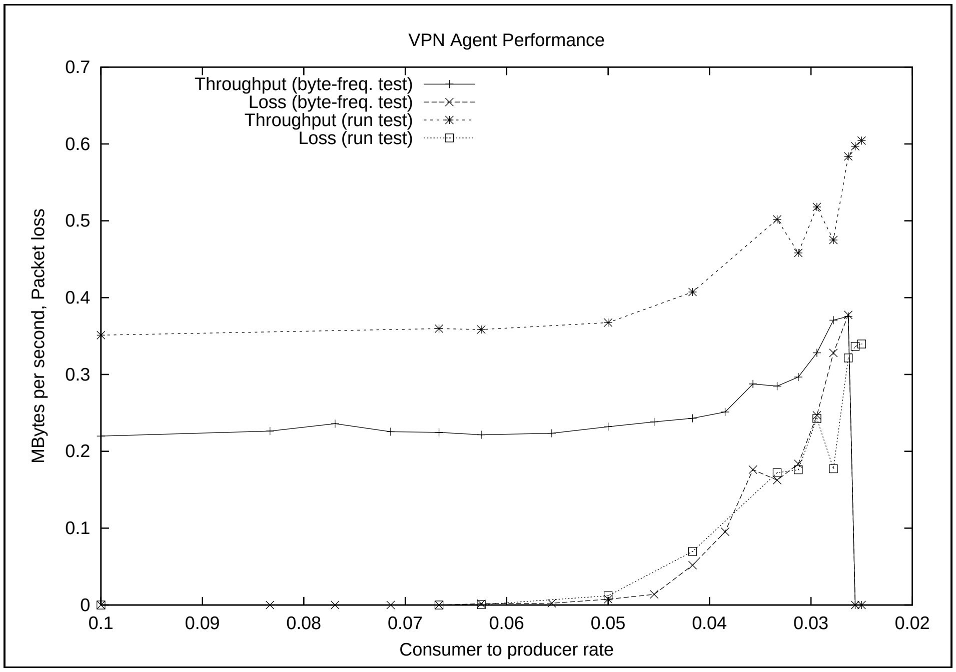

Figure 7.7: Performance of the VPN agent.

cution environment is set up and the agent is started successfully. In the following test setting the CSM customer application runs on the same machine as the node environment. The requests are sent through the local TCP/IP stack. The response time is influenced by a number of factors: the size of the agent, the encoding of the message and security overhead. We conducted a series of tests with ten samples each. The results for the benchmark agent (FastestAgent) are depicted in table 7.1. The first (minimal) option uses a receiver that generates packets and a node without resource control. The next option adds the resource control. The next series adds a real receiver with a TCP connection to a T-component dummy. This may impose some overhead because a server socket must be started for the communication with the T-component. The next step is to use PGP authentication for the CSM execution request messages. Finally, the response time for PGP authenticated and encrypted the messages is measured.

From table 7.2 we can see that the resource control does not have a negative impact on the response time. The start of a server socket for the T-component communication however has a small negative impact. Encryption and authentication add a large delay. Note, that the node always answers in the same encoding as the request. So, not only the request is encrypted and decrypted (authenticated) but also the acknowledgment. Using the external PGP implementation has the advantage that the implementation is tested by many security experts and thus has become trustworthy and stable. Further, the computationally expensive cryptographic operations can be performed in native code instead of Java byte-code. Yet,

Table 7.1: Response times of the FastestAgent

Option	Average (ms)	Standard deviation (ms)
Minimal	129.0	9.2
Plus resource control	126.2	7.8
Plus receiver	156.8	45.7
Plus authentication	1990.3	171.2
Plus encryption	3357.0	276.6

as table 7.1 showed, the speed of the script-based PGP access (see section 5.5) is limited. Instead of a script-based approach, the Java Native Interface (JNI) can be used to access external PGP functionality [Jam01]. This improves the cryptographic performance. Yet, the speedup is not breath-taking. For small agents (1 KB) the speedup factor is 1.71, for medium sized agents it is 1.24 and for large agents (500 KB) there is no improvement.

The size of the agent has also an impact on the response time. The benchmark agent size is 692 bytes. The message of the execution request (which carries the agent and other information e.g. the requested filter) is 2154 bytes. The acknowledgment message size is 190 bytes. The VPN Agent execution request size is 29'238 Bytes. Table 7.2 shows the response time for a VPN agent execution request. The normal setting is with a real receiver and with resource control.

Table 7.2: Response times of the VPN agent

Option	Average (ms)	Standard deviation (ms)
Normal	179.9	64.5
Plus authentication	2864.8	267.7
Plus encryption	4505.4	193.4

Latency until the reception of the first result. The previously presented response times represent the time between the customer initiates the transmission of an agent and the time the acknowledgment of the agent execution returns (see also section 5.1.6). It is also interesting to see how long it takes for an agent to send its first result. The sending of results is a node service so it may be subject to additional latency (see section 5.3.4). To test this we implemented an agent that carries a payload of variable size. As soon as it starts executing it sends this payload back to the home application. The agent performance can be compared to agents of other mobile agent platforms. We have chosen the NOMADS platform for comparison [SBB$^+$00]. Table 7.3 shows that the CSM platform outperforms NOMADS. This is mainly due to the fact that NOMADS uses a more fine-grained resource control mechanism and supports strong mobility. On the other hand NOMADS does not face the overhead of the T-component communication. Note, that the execution platforms and test layout were not exactly the same so the results are only approximative. Yet, the tests showed that the performance of the CSM implementation does not significantly fall behind state-of-the art agent systems.

Table 7.3: Response times

Payload	NOMADS response (ms)	CSM response (ms)
0 KB	333.5	198.2
16 KB	337.4	273.4
64 KB	341.6	280.7

Latency within the CSM platform. The time between the generation of a packet at the T-component dummy and the notification of that packet at the home application is of interest because this is the minimum time that it takes an alarm to reach the customer. Figure 7.8 shows the latency measured. The scenario consists of one node which uses a dummy T-component that generates and sends artificial packets. The home application is running on the same machine. The time between the interception of the packet and the delivery of the packet to the agent is very short (usually smaller than 1 millisecond). The sending and reception of the CSM message (including object de-/serialization) takes about 55 milliseconds). This includes also the time that the agent's request for sending waits in the service channel (see section 5.3.3).

Forwarding Latency. The customer can request that the CSM agent be forwarded from one node to another (see section 4.4). For security reasons a node forwards only authenticated agents and only after the node could successfully start the agent. Therefore, the propagation of the agent will be relatively slow. A throughput measuring agent was used in the forwarding latency measurement setting. Figure 7.9 shows the test setting. There are four CSM nodes running in three machines on two different subnets. The CSM home application is also running on the machine named balu. The figure shows how the nodes are interconnected.

The first test run sent the agent to the node named IAM. The agent requested to be broadcast. Table 7.4 shows the resulting latency times. The numbers represent the time that has passed between the initial transmission of the initial until the callback of the agent instance at that location. First the agent starts at the IAM node. After the execution this node sequentially forwards the agent to the RVS node then the CUI node then the TIK node.

The second test sent the agent to the RVS node. The agent requested the node to broadcast it from there. The result is shown in table 7.5. Apparently, if a node

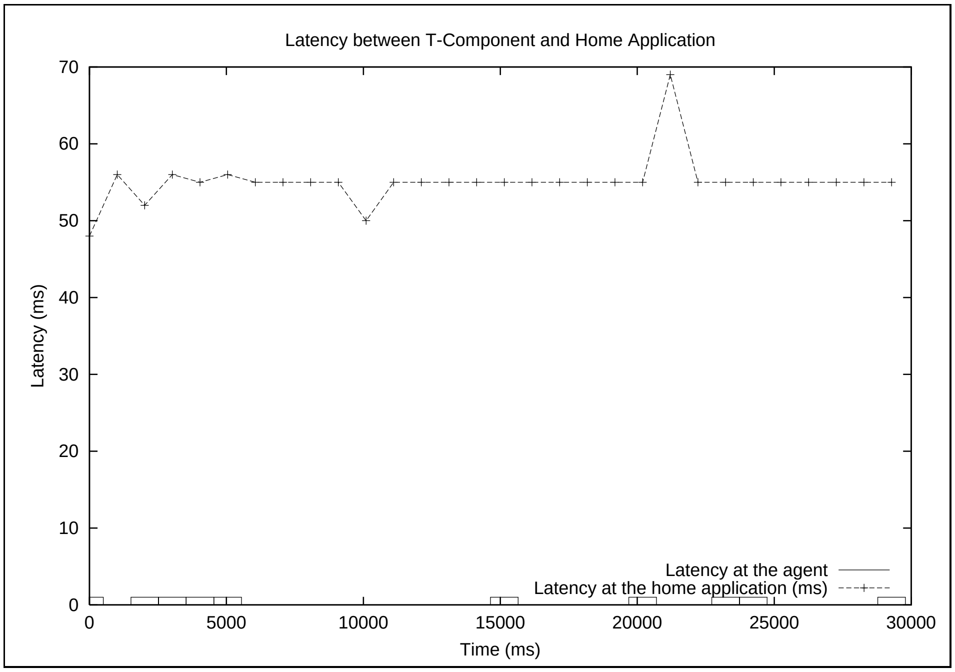

Figure 7.8: Latency between the generation of a packet, its delivery to the agent, and customer notification.

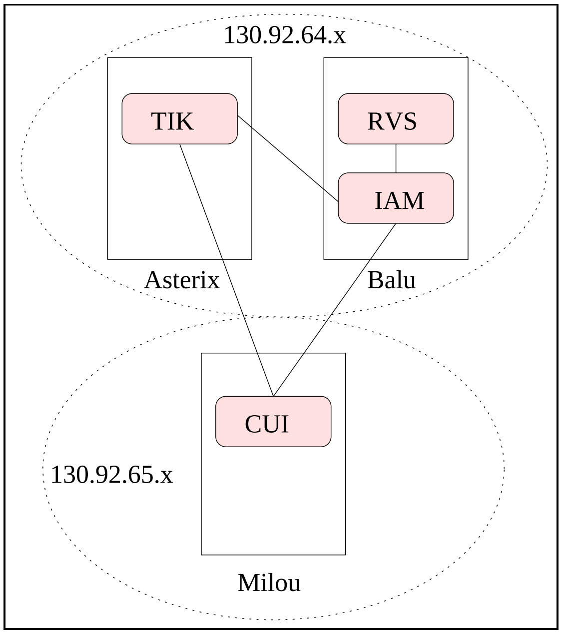

Figure 7.9: The forwarding latency test setting.

Table 7.4: Forwarding latency over IAM

Node	Latency (ms)
IAM	1520
RVS	2170
CUI	3827
TIK	5298

has to forward the agent to several neighbors this slows down the forwarding. This is because the forwarding happens sequential. So, the node forwards the agent and waits for the acknowledgment before it forwards the agent to the next neighbor node. Furthermore, the node has to perform excessive cryptographic work when it has to authenticate the forwarding acknowledgments. An easy and effective optimization would be that the node forwards the agents in concurrent execution threads.

Table 7.5: Forwarding latency over RVS

Node	Latency (ms)
RVS	1515
IAM	2159
CUI	2778
TIK	4129

7.4 The T-Component

The previous performance measurements often used a T-component dummy to artificially create measured packets. This is to isolate the measured subjects (agents, the node and the communication) from the influence of the T-component implementation. Now the focus is on the performance of the T-component that is capable of monitoring a real network device. The T-component implements the fast packet copy mechanism that delivers the input on which the CSM agents carry out their measurement. Thus, the T-component has to work at (a potentially very high) line speed. The task of the T-component is relatively simple. Therefore, the best solution would be to implement the T-component in hardware. Scripting was used to start the Tcpdump tool and a C++ program to send the output to the CSM node (see section 5.2). The T-component ran in a laptop with a 10 Mbit Ethernet interface. Using a laptop has the advantage that the network can easily be tapped at different locations but the disadvantage is that the laptop is relatively slow. The first version of the T-component was only able to forward traffic at a speed of about 0.75 Mbps. The main problems were that the C++ program parsed human readable Tcpdump output and that it sent the result in small chunks. The second version of the T-component uses the (undocumented) raw-format of Tcpdump and sends the copied packets in large chunks (ideally one packet per packet). In order to analyze the capacity of the new T-components we used a UDP sender and receiver tool. The receiver is located in the same machine as the T-component. The receiver measures how much traffic arrives at the laptop. The t-component copies the packets and sends them to the CSM node. The test scenario is shown in figure 7.10.

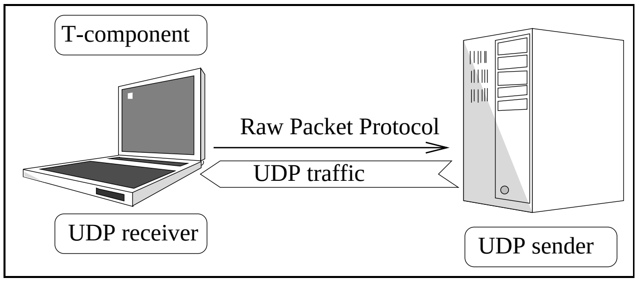

Figure 7.10: T-component performance test scenario.

For the test packets of 1KB size were used. We compared the measurements of a throughput measuring agent with the results of the UDP receiver. Furthermore, we analyzed the CPU consumption of the T-component (the sender of the packet copies) and of the underlying Tcpdump program. Table 7.6 summarizes the results. For speeds up to 4 Mbps the T-component did deliver all packets and the agent computed the correct throughput. Note that for 4 Mbps the CPU consumption of the T-component is already very high. At higher sending rates, Tcpdump consumes considerably more CPU time than before. The main problem is however the transmission of the T-component. The 10 Mbit Ethernet connection starts getting congested. The T-component sends back packet copies. It sends them wrapped in TCP packets which are wrapped in IP packets. So in theory the T-component more than doubles the traffic load on the Ethernet. As a consequence the TCP connection between the T-component and the CSM node (the raw packet protocol) suffers. The agent does not get all packets and measures a wrong throughput. Because the raw packet protocol backs-off the T-component blocks and yields the CPU so the T-component uses less CPU in the congestion case. Tcpdump is able to cope with the traffic upcome, but it has to consume more CPU.

Nevertheless, the agent can request that the T-component only sends a part of the packet. When the agent requests only the first 40 bytes of each packet, then the T-component can support up to 6 Mbps without getting congested. For 7 Mbps the T-component is congested again. About 13 percent of the packets do not reach the agent. If packets are smaller than 1 KB then the upper limit of supported traffic load is lower.

It is a UNIX pipe that delivers the dumped packets to the T-component. Thus,

Table 7.6: T-component load

Sent	Received	Measured	T-component CPU	Tcpdump CPU
2 Mbps	1.95 Mbps	1.95 Mbps	<40%	< 5%
3 Mbps	2.92 Mbps	2.92 Mbps	<50%	< 6%
4 Mbps	3.85 Mbps	3.85 Mbps	<55%	< 20%
5 Mbps	4.70 Mbps	*3.20 Mbps*	<40%	< 25%
6 Mbps	5.60 Mbps	*2.00 Mbps*	<20%	< 30%

the packets travel a relatively long way until they are finally delivered to the agent. Figure 7.11 shows this delivery time for the same scenario. The packet size is 1 KB and the T-component delivers a full packet copy. The UDP traffic load is 0.5 Mbps. The results show that there is a significant latency of about 300 milliseconds. Note, that this latency does not influence the agents ability to measure correctly. The agent measure based on the timestamp provided by the T-component and not on the time when the agents first see the packet.

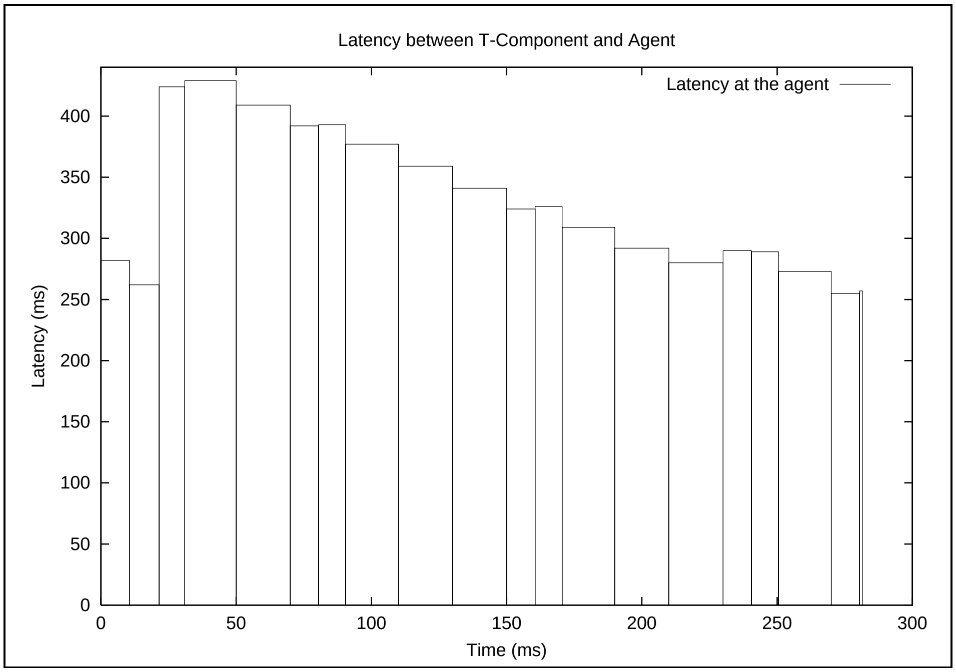

Figure 7.11: Latency of the Tcpdump based T-component.

7.5 Discussion and Improvements

The intent of the customer-based service monitoring architecture is to provide a facility for customers to measure the service level they get. All implemented components (node environment, agents, and T-component) support a data rate of at least 1.5 Mbps. Thus, the presented implementation can support customers with Frame Relay and T1 Internet connectivity. Yet, there are some shortcomings where the CSM implementation should be improved in order to accommodate higher speeds. Here is a summary of those and suggestions for improvements.

- Instead of piping the Tcpdump output into another program the implementation of the T-components should directly access the packet capturing libraries. This will reduce the latency between the T-component and the agent. Backbone T-components should be implemented in hardware or at least directly in the monitored device to support higher network loads.
- The TCP/IP communication between the the T-component and the node is a bottleneck. A UDP based protocol with a checksum may be helpful.
- Small packets introduce significant overhead in both the T-component and the node environment. The problem occurs if the small packets are sent at a high rate. In that case, the raw packet protocol and also the agent execution environment should bundle several small packets into one packet/object.
- The cryptographic mechanisms are very time consuming. Built-in cryptographic libraries may alleviate the problem.
- The object serialization mechanism is relatively slow. The byte stream it produces contains much redundancy. CSM uses the mechanism for the message protocol and for the memory consumption control.

Nevertheless, the performance measurements have shown that a CSM implementation is feasible in pure software and with off-the shelf and portable technology. The implementation cannot support backbone speed service monitoring. Yet, even with security features included (authentication, encryption, resource control) the software implementation is capable of monitoring at WAN access speed.

Chapter 8

Comparison with Related Work

8.1 The Internet2 Initiative and the QBone

In 1996 several American universities started the Internet2 initiative [Rab98, Uni]. The Internet2 should recreate the partnership among academia, industry and government that fostered today's Internet in its infancy. The partnership aims to initiate the next evolutionary step of the Internet. Today, the Internet2 is a non-profit consortium, led by over 180 US universities and over 60 companies, developing and deploying advanced network applications and technology, thus accelerating the creation of tomorrow's Internet. The primary goals of Internet2 are to:

- Create a leading edge network capability for the American research community.
- Enable revolutionary Internet applications.
- Ensure the rapid transfer of new network services and applications to the broader Internet community.

The Internet2 is not a separate stand-alone network but it takes advantage of new high performance IP networks such as the vBNS and Abilene. Abilene [ABI] is a US high speed network spanning the USA with Sonet optical carriers OC-48 links (2404Mbps). The Abilene is interconnected with CA*net 3 of Canarie [CAN], the Canadian counterpart of the Internet2, with the European research network TEN-155 [DAN] and other research networks around the globe. Abilene also peers with the very high performance backbone network service (vBNS) [vBN] of MCI. MCI runs the vBNS for the US National Science Foundation (NSF) until 2004.

The Internet2 members collaborate in working groups on advanced applications, middleware, advanced network infrastructure and new networking capabilities. The last issue concerns the developing and testing of new IP network services and is therefore relevant to this thesis. In particular the QBone working group

[Int99, THD^{+}99] addresses problems related to this thesis. QBone is an inter-domain testbed for differentiated services. QBone seeks to provide the Internet2 with end-to-end services in support of emerging/advanced networked applications. QoS support is implemented with DiffServ. The following subsections discuss the QBone work on goals that interleave with the goals of this thesis: (1) inter-domain DiffServ services, (2) DiffServ signaling and (3) network measurements.

8.1.1 QBone Architecture

Consistent with the Differentiated Services architecture, each network participating in the QBone [Tei99] will be considered a *DS domain* and the union of these networks - the QBone itself - a *DS region*. QBone participants must cooperate to provide one or more inter-domain services besides the default, traditional best effort IP service model. The first such service to be implemented is a leased line like service called the QBone Premium Service (QPS). Every QBone DS domain must support the Expedited Forwarding (EF) Per-Hop Behavior (PHB) and configure its traffic classifiers and conditioners (meters, markers, shapers, and droppers) to provide a QPS service to EF aggregates. Between each QBone DS domain there are Service Level Specifications (SLS) that characterize aggregate traffic profiles and per-hop behaviors to be applied to each aggregate. The SLS is bilateral. Currently the QBone focuses on SLS for the QBone premium service and refers to it as a globally well-known service. This simplifies the concatenation of bilateral SLS into an inter-domain end-to-end service because the SLS can be designed so that they ‘fit’ the QPS.

The end users request the QPS service by sending a reservation of the form: *source, dest, route, startTime, endTime, peakRate, MTU, jitter*. So, the user requests the QPS service starting at *startTime* and ending at *endTime* across the chain of DS-domains *route* between source *source* and destination *dest* (may both be IP hosts or network addresses) for EF traffic ingressing at *source* and conforming to a traffic profile parameterized by a token bucket profiler with token rate equal to *peakRate* bytes per second and bucket depth equal to *MTU* bytes. Out-of-profile packets are dropped. The QPS service shall offer the following guarantees: low loss, low latency and low jitter (an upper delay variation bound). There shall be virtually no loss, delay or jitter due to queuing effects.

The user sends service requests to the first hop bandwidth broker. The broker maps the request to local resources and to SLS with neighbor DS domains to check if it can be accommodated. In the first deployment phase of the QBone project the broker only performs local admission control. In the next phase the brokers will signal these requests to ensure end-to-end quality. Finally, in the third phase the broker is able to change SLS dynamically in order to accommodate the user requests (see next section).

Figure 8.1 shows the functional decomposition of the Bandwidth Broker (BB) as proposed by the QBone. The BB communicates with three key protocols: The *user/application protocol* is an interface provided for resource allocation requests from customers. The *intra-domain protocol* has the purpose to communicate BB decisions to routers within the bandwidth broker's domain. The *inter-domain protocol* provides a mechanism for peering BBs to ask for and answer with admission control decisions for aggregates and exchange traffic. The proposed bandwidth broker also has an interface to a policy management system (PM iface) and an interface to the network management system (NMS iface).

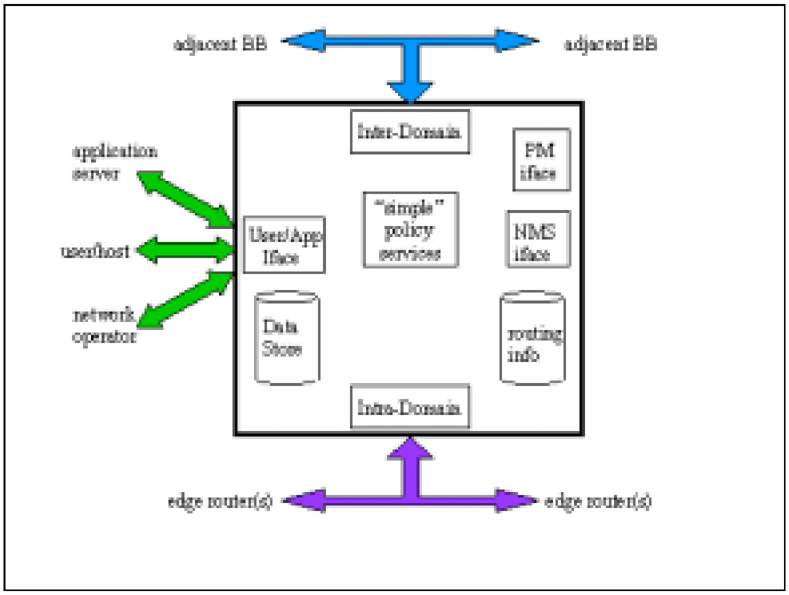

Figure 8.1: QBone bandwidth broker model.

The bandwidth brokers need access to interior and exterior routing information. Furthermore, the different components of the broker share a common data repository which stores the following information:

- Service mappings/DSCP mappings.
- Policy information.
- SLS information for all ingress/egress routers.
- Current reservations/resource allocations.
- Configurations of routers.
- Network management information.
- Authorization and authentication databases (for users and peers).
- Monitoring information from routers.

8.1.2 Architectural Comparison of the QBone

The service broker architecture that proposed in chapter 2 and the QBone architecture were both developed independently at about the same time. They are both inspired by the DiffServ architecture and by the bandwidth broker idea from [NJZ99]. Both architectures are very similar. Yet, the service broker architecture is not DiffServ specific, because it is designed to also cover VPN management. The QBone architecture on the other hand makes a more sharp distinction between the technical description of the service (SLS) and the business contract (SLA). The QBone brokers only deal with SLSs not with SLAs. QBone omits the business aspects and factors them out into SLAs which are not further studied. This makes sense for the QBone since it is an academic initiative and the QBone DiffServ region is open to all partners. The SLAs as used in the first part of this thesis include a business part and a technical descriptive part (SLS). The way this thesis uses the term SLA best corresponds to the SLS definition of the phase three of the QBone plus some charging and billing aspects.

When our internal and external service broker (see figures 2.4 and 2.5) are combined to one entity then this is basically the same as the QBone BB node depicted in figure 8.1. Our 'master interface' corresponds to the network management interface. Our peer ESB interface corresponds to the inter-domain interface. Our slave interface corresponds to the intra-domain interface. Our service broker architecture's customer server corresponds to the user/application interface. Note, that the QBone architecture does not cope with service bundling since if focuses on on specific DiffServ service. The coordinator component together with the autonomous behavior corresponds to the central 'policy services' component of the QBone architecture. The SLA- and service configurations repositories of the service broker architecture correspond to the data store. Both architectures provide an interface to an external policy management mechanism. The external policy query interface of our architecture is amongst other things intended to collect routing information.

The basic difference between the two architectures is that the service broker architecture tries to decompose the central broker entity according to the two-tiers Internet model. Thus, there is an internal broker that hides the particularities of the local DiffServ domain. The external broker can be fully standardized. Also, this thesis models the configuration of heterogeneous devices as element managing agents. The idea is that device specific configurations can be optimized by specialized intelligent agents (the EMs). So, the service broker architecture has a higher degree of functional decomposition. It proposes a set of service agents with specific functionalities instead of one central BB that is supposed to be a generic problem solver.

8.1.3 QBone Signaling

The QBone has formed a signaling design team in 1999 which develops the Simple Inter-domain Bandwidth Broker Signaling protocol (SIBBS). The work is still in progress, a draft document can be found at [QAr]. The design team points out that the DiffServ signaling should not destroy the key advantages of DiffServ which are based on 1) aggregation of traffic into a small number of behavior aggregates, 2) requiring only bilateral service level agreements and 3) allowing for maximal flexibility in local resource management decisions. The design group is looking for a simple and robust protocol. However, it should also be extendible and leave room for future growth.

The current work of the QBone working group assumes that SLS are already in place. An SLS represents a *potential* for reservation. The provider of the SLS guarantees to accept reservations up to a limit described in the SLS. The QBone signaling describes the communication to reserve and release these resources. As said before, in phase 2 of the QBone deployment the reservations may also lead to dynamic SLS updates. But the QBone working group does not specify that process up to now. In [THD+99] Teitelbaum et al. describe the following signaling options:

1. **No signaling.** There are three options to mark the packets: the layer 2 markings are used, the host marks the packets, or the network edge marks the packets. From then on all packets in a DS class are treated the same. Inter-domain resources are statically allocated and there is no signaling between the domains.

2. **Local signaling.** A host application dynamically signals for resources. Yet, only the local DiffServ domain knows about the dynamic resource requests. A bandwidth broker keeps track of intra-domain commitments. Links across DiffServ domain boundaries are statically provisioned. This approach requires careful monitoring of the links towards destination domains.

3. **Signaling with Inter-broker communication.** Inter-domain communication allows for dynamic adjustment of the commitments made across the domain boundaries. The communication protocol must at least include information about resource allocation changes on the peering link. If destination-network information is also included then this can be used to propagate the resource request further. However, Teitelbaum et al. note that this increases the signaling complexity and may thus have a negative effect on the scalability of the approach. The flow of end-to-end signaling is shown in figure 8.2. An alternative is the immediate response signaling depicted in figure 8.3. There, each bandwidth broker immediately answers to the request. Then, the source can start sending while the request is propagated through the domains. Yet, this approach only allows for better than best effort service because end-to-end resources are not reserved immediately. Immediate response signaling is considered as not well-suited for premium-style services like the QPS.

The QBone signaling design team is about to specify the Simple Inter-domain Bandwidth Broker Signaling (SIBBS) protocol [sdt01]. The protocol shall be used

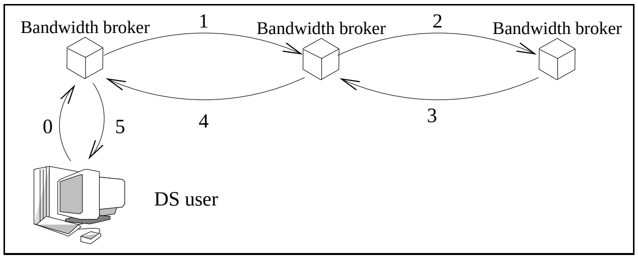

Figure 8.2: End-to-end broker signaling.

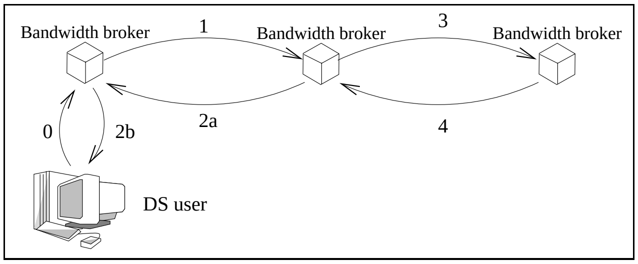

Figure 8.3: Immediate response broker signaling.

in phase 1 of the QBone deployment in order to signal reservation related information between bandwidth brokers. Signaling follows an end-to-end model as depicted in figure 8.2. A special case are the so called *core tunnels*[1]. This is a reservation between two end domains instead of a reservation between two hosts. The bandwidth broker of the source domain can aggregate local requests and map them to the 'tunnel'. Therefore, individual reservation requests do not have to be processed in intermediary domains. SIBBS foresees that the source domain broker must signal a new reservation request only to the destination domain broker, so that both brokers can participate in the admission control decision. The SIBBS specification includes message format descriptions for the following messages:

- **Resource Allocation Request (RAR).**
- **Resource Allocation Answer (RAA).**
- **Cancel.** For tearing down a reservation before it expires.
- **Cancel acknowledgment.**

The messages contain a number of fields such as a protocol version number, a unique message ID, the sender ID, and the signature of the sender. The RAR and the RAA message also contain a *Service Parameterization Object* (SPO). This object describes the service specific parameters that the DS user requests. For the QBone premium service this consists of the route, the peak rate the MTU and the

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[1] Despite the name, there is no tunneling mechanism used here.

jitter bound. The RAA includes a reason code that contains information allowing the receiver to diagnose the rejection. For each new service these objects must be redefined. Then, there is a core tunnel voucher which is used in the core tunnel case. When a source domain bandwidth broker maps a local request to a core tunnel, it asks permission of the destination broker thereby referring to the core tunnel voucher which it has received when the tunnel was set up.

Comparison to this Thesis

The QBone is about to be deployed in a research network. The design thus started bottom-up in three deployment phases. The design includes the end-user procedures and the provisioning of the ’last mile’. The approach of this thesis started top down from the interactions between the bandwidth brokers and directly tried to evaluate dynamic SLAs. SLAs are established between service brokers. This thesis considers the end-user procedures only as a special case of an SLA establishment. A customer either runs a local service broker or has a tool to send BSP messages to a service broker (like the GUI described in section 2.4.1). Another option, which is described in [BBG00], is that service brokers of the access networks are able to to map resource allocation signals of the applications (e.g. RSVP) to broker signaling requests.

The QBone documents and this thesis identified similar design goals (scalability and flexibility), trade-offs (end-to-end guarantees versus scalability and utilization versus signaling complexity) and problems (missing destination information). The SIBBS protocol specification could be implemented with the flexible protocol that is proposed in section 2.3.4. The end-to-end signaling described in section 3.5 corresponds closely to the SIBBS signaling, but it also includes the notion of SLA updates. Thus, chapter 3 discusses the design trade-offs of the QBone phase 2 which is yet to come. Since QBone is intended as a testbed for DS signaling, the QBone may at some time in the future use and verify the results of chapter 3.

8.1.4 QBone Measurements

QBone participants must collect and disseminate a basic set of QoS measurements. Since the QBone is a test environment it is important to posses complete measurement information in order to debug, audit and study QBone services. The QBone measurement infrastructure is thus necessary to study and validate the operation of new DiffServ services and the application of these services. An important aspect of the measurements is to verify that DiffServ traffic is indeed protected from other traffic according to the SLSs, in an end-to-end fashion.

The QBone participants must instrument each edge router of a QBone domain to serve as a QBone measurement node (probe). Measurements are collected in three ways: active, passive, and polling of static data.

- For active measurements the probe generates as small amount of test traffic and sends it to other nodes. Measured metrics are: one-way packet loss and delay variation. Also, complete traceroutes are collected to test path stability.

- Passive measurements are used to derive the following metrics: traffic load in packets per second and bits per second.
- Polling of static data provides the following information which is used to interpret the other measurement data: link bandwidth, EF commitment (SLS[2]) and EF reservation load.

All metrics should be measured for all existing behavior aggregates. The metrics must be applied simultaneously to the aggregates so that the results can be compared and correlated. This is important in the QBone context because one goal is to verify that the QPS traffic is successfully isolated from best-effort traffic. Therefore, a situation must be examined where the best-effort traffic suffers due to queuing-effects (e.g. loss or delay) but the QPS traffic is unaffected at the same time.

A large part of the QBone architecture describes the metrics and how the measurement data must be formated (e.g. in HTML) so that all QBone participants have access to a uniform database.

Comparison to this Thesis

The uniform measurement interfaces provided by the QBone could be used to implement the adaptive reservation scenario that section 3.3 describes. However, trust issues are not addressed at all. It is unrealistic that a commercial domain will make its complete measurement data available. On the other hand, reservations will cost and thus the available measurements must somehow also become trusted. Furthermore, the QBone working group spent a lot of time and effort to specify the uniform measurement interface and measurement metrics. Still, they say that new measurement metrics will be added with experience. Standardizing and deploying new metrics into all QBone measurement nodes is not a simple task. If the QBone would deploy a customer-based service monitoring system as described in part II of this thesis then these problems can be addressed. A new measurement metric does not require a standardization process of the working group and a subsequent deployment of an updated QBone measurement node. The implementation and broadcast of a new measurement agent is all that would have to be done. In the initial QBone phases CSM measurement nodes could be open to anyone. Later, the security mechanisms of the CSM node (see section 5.5) can be used to restrict access to trusted parties. Finally, the mobile agent approach helps the domains to build trust into the measurements.

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[2] In the current planning of the QBone SLS are static.

8.2 Further IP Service Related Initiatives

8.2.1 The IEEE P1520 Project for Programmable Networks

Several companies are collaborating on the IEEE standards development project IEEE P1520 [BLH+98, P15]. This project envisions tomorrow's telecommunications network as a giant computer - a fully programmable machine - that delivers advanced voice, data, and video services globally. In today's intelligent network paradigm, the key intelligence of the network, which lies in the signaling network, is built with a few fixed algorithms or programs known as standard signaling protocols and control programs. Development of richer signaling protocols and control programs has been a slow and arduous process. This is because the signaling standards for the modern telecommunications industry have become very complex and require consensus from all manufacturers and operators of switching equipment. In contrast to that the world wide web allowed third party application service providers to rapidly deploy a vast array of new application services. The goal of the IEEE P1520 is to standardize programmable interfaces to the networks (both circuit switched networks like ATM or packet networks like IP) so that new services can emerge at the same pace as they do in the Web.

The IEEE P1520 project introduces the reference model shown in figure 8.4 (July 1998). There are four levels in the model:

- **The value-added service level.** This level is end-to-end oriented. Entities located here combine services of the underlying levels and of third-parties. The composite service server of our broker architecture maps to this level.
- **The generic service level.** The entities at this level deal primarily with the functioning of the network. Routing engines and also for example Differentiated Services scheduling are located here. The service brokers of our architecture map to this level.
- **The virtual network device level.** The entities of this level represent logical network devices and their abstract state. The element managing agent of our architecture maps to this level.
- **The physical element level.** Routers, switches and so on.

The IEEE P1520 project focuses on providing standardized and orthogonal programming interfaces between these levels.

- **The V-interface.** A variety of user level programming interfaces provide access to the value-added services. These are collectively called V-interface. The V-interface shall enable developers to write highly personalized end user software.
- **The U-interface.** Programming interfaces between the value-added services level and network generic services level are collectively called the upper

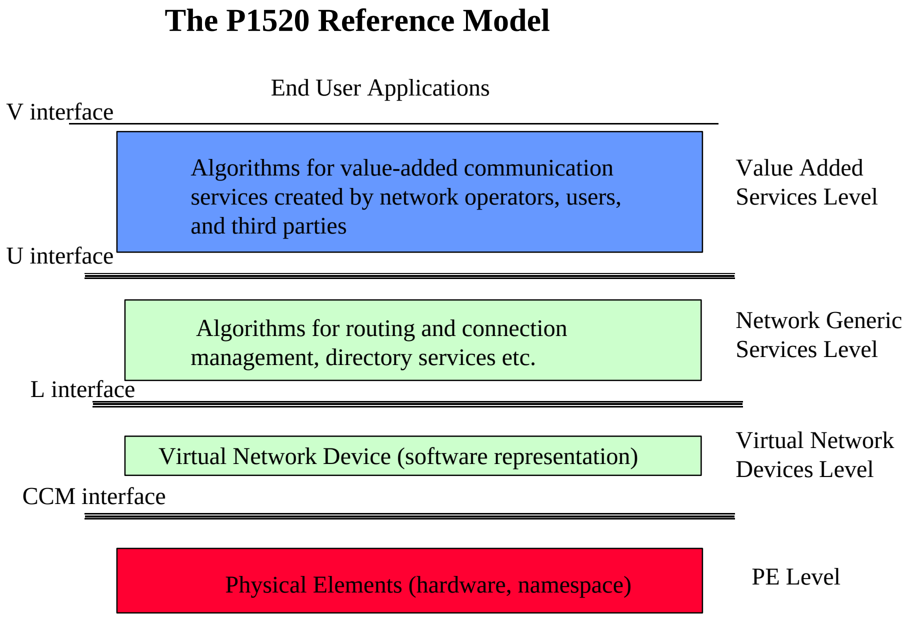

Figure 8.4: IEEE P1520 reference model.

interface (U-interface). The interface allows its user to make requests for service enhanced connections (e.g. for a VPN tunnel).

- **The L-interface.** The programming interfaces between the network generic services level and the virtual network devices level are collectively called the lower interface (L-interface). The L-interface enables the upper levels to directly access and manipulate local network resource states.

- **The CCM-interface.** These are open protocols to access the state of physical devices. The Connection Control and Management (CCM) interface is not a programming interface like the others but a collection of protocols (for example SNMP or telnet) to access network devices.

Originally, the IEEE P1520 project focused on ATM networks. Yet, recently more attention is payed on the programming interfaces for IP routers and switches (CCM- and L-interface) and on programming interfaces for IP networks (L- and U-interface). Draft documents are publicly available but they are in an early stage (architectural assumptions, digest of state-of-the-art).

8.2.2 EURESCOM Project P1008-PF: Inter-operator Interfaces for Ensuring End-to-End IP QoS

The European Institute for Research and Strategic Studies in Telecommunications (EURESCOM) [EUR] is the (self-declared) leading institute for collaborative research and development in telecommunications. EURESCOM is a virtual company. All major European telecommunication providers participate. The EURESCOM P1008 project [Brü] intends to support European operator's interests in managed interconnection in IP based networks and services, especially with respect to QoS issues. The work takes into account initiatives of other forums including the IETF QoS architectures (DiffServ, IntServ) and traffic engineering architectures, like MPLS. Another input source is the Telecommunications Management Forum (TMF), which is considering what needs to be done to offer a commercial, telco-quality IP service.

The P1008-PF project explicitly addresses inter-provider issues. Customer perceived QoS is an end-to-end concept. If the service is offered across several domains then the operators of those domains will need to cooperate to ensure customer requirements are met. Inter-domain management processes, interfaces and models are needed to support that cooperation.

The main objectives of the P1008 are to:

1. Understand the new inter-domain management requirements presented by end-to-end IP services and to relate those new requirements to existing standards and work.

2. Produce implementation independent specifications of the extra management processes, models and interfaces required to support end-to-end IP QoS service assurance.

3. Capture requirements for network performance monitoring and service parameter measurements needed to support those processes, interfaces and models. Here the CSM architecture of part II of this thesis can support this task.

4. Disseminate these specifications to EURESCOM shareholder organizations (the participating telecoms) and relevant standardization and industry bodies.

5. Coordinate this work with other related activities in EURESCOM, and external activities (e.g. IETF, TMF, TINA, QoS-Forum, EU projects) and public information provided by IP technology vendors.

The details of how IP QoS will be provided and assured, together with the choices of the underlying network technology to support the IP layer remain open to further development. The inter-domain management implications of different options need to be understood and solutions proposed. The project is currently about to complete the number one of the presented goals: The first deliverable (found at [Brü]) contains a comprehensive survey of relevant technology and specifications for IP QoS. Currently, no further and concrete research results are publicly available.

8.3 Network Measurements and Monitoring

In this section we focus on related work in the are of network measurements and network monitoring. In contrast to network monitoring there is also application monitoring. There, applications incorporate measurement code to monitor application specific behavior like for example hit counts of documents on a web server. Another example is the response time of a distributed system. The Application Response Management (ARM) API [ARM96] is an open standard for application monitoring. Yet, this section is going to focus on network management and on network related metrics because this is related more closely to the customer-based service monitoring infrastructure presented in part II of this thesis.

8.3.1 IP Measurement Methodology

Network measurement is by its nature a distributed task. Even the old but nevertheless useful `ping` tool needs a source and a destination (to reflect the ICMP message).

Here are distinctions of measurement approaches:

- **Active vs. passive measurements.** For active measurements additional traffic with known characteristics is injected into the network. Passive measurements work non-intrusive on the existing traffic.
- **End-to-end measurements vs. network element based measurements.** End-to-end measurements are carried out by the communication end points (sending and receiving hosts). Network element based measurements are also carried out within the network.

IP Performance Metrics

A network performance *metric* is a carefully specified quantity that is relevant to the performance and reliability of the network. The IP Performance Metrics (IPPM) Working Group has developed a set of standard metrics that can be applied to the quality, performance, and reliability of Internet services by networks operators, service providers, and other independent testing groups. [PAMM98] classifies metrics, specifies methodologies to collect statistics of the metrics and describes problems of measurement approaches (e.g. clock skew and unintentionally synchronized measurements). The performance metrics defined by this IPPM working group include: one-way packet loss across Internet paths (RFC 2680), one-way delay (RFC 2679), connectivity measures between two nodes (RFC 2678), and other second-order measures of packet loss and delay (RFC 2681).

Traffic Flow Measurement Architecture

The Real-time Traffic Flow Measurement (RTFM) Working Group has produced a measurement architecture to provide a well-defined method for gathering traffic flow information from networks and internetworks [BMR99]. This architecture can be applied to any protocol/application at any network layer. The proposed model is based on the concepts of *meters* and *traffic flow*. Meters observe packets as they pass by a measurement point on their way through the network and classify them into certain groups. For each such group a meter will accumulate certain attributes (such as number of packets and bytes). These metered traffic groups may correspond to a user, a host system, a network, a particular transport address (e.g., an IP port). Meters are placed at measurement points and selectively record network activity as directed by its configuration settings. Meters can also aggregate, transform and further process the recorded activity before the data is stored. A traffic flow is a logical entity equivalent to a call or connection. A flow is a portion of traffic, delimited by a start and a stop time, that belongs to one of the metered traffic groups mentioned above. Attribute values (source/destination addresses, packet counts.) associated with a flow are aggregate quantities reflecting events which take place between the start and the stop times. Flows are stored in the meter's flow table. Since for connectionless network protocols such as IP, there is no way to tell whether a packet with a particular source/destination is part of a stream packets or not, each packet is completely independent.

A traffic meter has a set of rules which specify the flows of interest. Classifying packets into ’flows’ provides a practical way to measure network traffic. Appendix C in [BMR99] provides a list of the flow attributes. Yet, there is no QoS related attribute specified.

Besides of flows and meters, the traffic model measurement includes managers (to configure and control meters), meter readers (to transport recorded data from meter to analysis applications), and analysis applications (to process the data from meters readings so as to produce whatever reports are required). Since there has been considerable interest from users in allowing a meter to report on an increased number of flow-related measurements, the RTFM WG has produced a new document [HSBR99] specifying such measurements (the ’new’ attributes). Some of the proposed extensions include QoS attributes such as the DSCP to support DiffServ. Possible uses of DSCP attribute include meters that aggregate flows using the same code points, and that separate flows having the same end-point addresses but using different code points. The new document also includes QoS parameters for Integrated Services based QoS support.

8.3.2 The Simple Network Management Architecture

To support and automate IP network management the IETF standardized the Simple Network Management architecture (SNMP) [CFSD90, Sta99]. SNMP allows the monitoring of network elements and the pushing of configuration information into all kinds of IP based networking devices. SNMP versions 1 to 3 exist. The older versions were mainly used for monitoring and less for configurations. The SNMP model foresees an *SNMP manager* which is a management application that is running on a dedicated *management station* and operated by the human network administrator. The manager communicates with *SNMP agents*. Each SNMP agent represents a local and permanent management process in a managed device. Thus, usually the network device implements the SNMP agent. The relevant device state is represented as SNMP objects (also referred to as variables). These objects are stored in a Management Information Base (MIB). MIBs have to be standardized in order to manage devices of different vendors. The language used to describe a MIB is called Structure of Management Information (SMI). It is a modified version of the Abstract Syntax Notation 1 (ASN.1) of the ISO OSI standard. The time between the specification of a MIB, its standardization, and finally the implementation of the MIB support in the devices is long (several years). MIB specifications for DiffServ and IPSec are underway. Yet, today only a (limited) and proprietary implementation for a DiffServ capable MIB exists.

The SNMP manager communicates with the SNMP agent through the SNMP protocol. The protocol supports three messages: (1) *get* with which the manager gets the scalar value of an object, (2) *put* with which the manager sets such a value, and (3) *trap*. The trap is not solicited by the agent and is triggered in case a previously declared network event has happened at the device of the agent.

The Remote Monitoring (RMON) MIB

While the standard MIBs include objects to reflect the performance of networking interfaces (such as a byte counter, a lost packet counter etc.) the RMON MIB [Wal95] defines management objects so that an agent can monitor the networking activity of a complete IP subnet. The RMON objects are arranged into the following groups:

The Ethernet Statistics Group. The Ethernet statistics group contains statistics measured by the probe for each monitored Ethernet interface on this device. In the future other groups will be defined for other media types including Token Ring and FDDI. These groups should follow the same model as the Ethernet statistics group.

The History Control Group. The history control group controls the periodic statistical sampling of data from various types of networks.

The Ethernet History Group. The Ethernet history group records periodic statistical samples from an Ethernet network and stores them for later retrieval. In the future, other groups will be defined for other media types including Token Ring and FDDI.

The Alarm Group. The alarm group periodically takes statistical samples from variables in the probe and compares them to previously configured thresholds. If the monitored variable crosses a threshold, an event is generated. A hysteresis mechanism is implemented to limit the generation of alarms. This group requires the implementation of the event group.

The Host Group. The host group contains statistics associated with each host discovered on the network. This group discovers hosts on the network by keeping a list of source and destination MAC Addresses seen in good packets promiscuously received from the network.

The HostTopN Group. The hostTopN group is used to prepare reports that describe the hosts that top a list ordered by one of their statistics. The available statistics are samples of one of their base statistics over an interval specified by the SNMP management station. Thus, these statistics are rate based. The management station also selects how many such hosts are reported. This group requires the implementation of the host group.

The Matrix Group. The matrix group stores statistics for conversations between sets of two addresses. As the device detects a new conversation, it creates a new entry in its tables.

The Filter Group The filter group allows packets to be matched by a filter equation. These matched packets form a data stream that may be captured or may generate events.

The Packet Capture Group. The Packet Capture group allows packets to be captured after they flow through a channel. This group requires the implementation of the filter group.

The Event Group. The event group controls the generation and notification of events from this device.

The first version of RMON has some shortcomings. For example the filtering can not describe filters based on higher level protocols. So, it was for example not possible to distinguish between different TCP flows in order to derive statistics on the usage of web related protocols. Therefore, two years after RMON, RMON version 2 was standardized [Wal97] which can distinguish also between the application layer headers. Nevertheless, most devices do not even support the full RMON version 1 MIB. This is a good example of the lack of flexibility of SNMP compared to CSM.

Comparison to this Thesis

Concerning the first part of this thesis, the SNMP protocol is one possible choice to implement the communication between the element managing agent of the service broker architecture and the networking devices. If all networking devices support MIBs to configure the desired network service then the the SNMP agent can play the role of the element managing agent proposed by the architecture. The internal service broker then plays the role of the SNMP manager.

SNMP is also related to the CSM system since it provides network monitoring functionality. The RMON filtering and packet capture group could be used to implement a CSM T-component, since it provides the needed filtering and packet copy mechanism. Yet, most networking devices do not implement the RMON packet capture group. Traditional SNMP is not preferable as a customer-based service monitoring infrastructure. The mobile agent based CSM infrastructure has the following advantages over traditional SNMP:

1. SNMP is not flexible enough for customer-based service monitoring. Such monitoring must be tailored to each new IP service that a provider offers. Not all customers will be interested in the same measurement metrics. Therefore, huge MIB definitions would have to be specified. By the time the devices implement these MIBs and the provider has deployed these devices the service may be out of date and the customer may have switched to another provider. With the CSM system either the provider, the customer or a third party supplier can rapidly develop a new measurement agent and distribute it.

2. The SNMP manager gets the network monitoring information through polling of all the SNMP agents. Since SNMP agents cannot preprocess the data,

the monitoring data will use up significant bandwidth resources when transmitted to the manager. Furthermore, the manager that finally analyses the measurement data may become a bottleneck. CSM agents can preprocess the monitoring data thus putting it in a more compact form which only contains the information that is of interest. The CSM agent only informs the home application in case there is something relevant. SNMP can also emulate this behavior by using traps. However, traps are based on a simple threshold mechanism. Advanced schemes such as random early notification (see section 6.5.1) cannot be implemented in SNMP.

3. The intent of SNMP is to provide a tool to the network operator of a domain. Therefore, fine-grained and user-based access control schemes are hard to implement in SNMP. Either the customer has no access to the desired SNMP objects or the customer has access to SNMP objects that (s)he should better not have. The CSM infrastructure has a customer oriented security scheme.

4. SNMP does not provide topology support to the customer. While CSM agents can use routing and forwarding services of the CSM nodes no such thing exists for SNMP. Therefore, each customer needs to find out on his/her own where the relevant SNMP agents are located.

8.3.3 Measurement Testbeds

Today, most large-scale network providers perform network measurements and monitoring, usually as part of a proprietary network management system (e.g. Cisco's Netflow [Cis00b]). Often, providers hesitate to make any results of these measurements publicly available, because they fear to offer attacking points to their competitors. This section presents two public and large-scale Internet measurements initiatives.

The NLANR Network Analysis Infrastructure

The National Laboratory for Applied Network Research (NLANR) is developing a Network Analysis Infrastructure (NAI) to support research on high performance Internet networks [MBB00]. The main focus is on passive collection of header traces, active measurements (based on ICMP), SNMP derived data, and Border Gateway Protocol (BGP) derived data. NLANR collects raw measurement data from the high-performance connection community in the United States. Various partners develop off-line analysis tools for the data. Tools for the presentation and visualization of the data are also of interest.

OCXmon is the passive measurement sub-project of NLANR. Currently, 11 OC3/ATM monitors are deployed. An OCXmon monitor is a rack-mountable PC running the FreeBSD or Linux operating system. An optical splitter is used to connect the monitor cards of the PC to an OC3 or OC12 link. This is exactly the setting that the CSM T-component would need in order to accommodate backbone network speed. OCXmon thus shows that CSM T-components are even feasible without extension of router hardware. Further information on the OCXmon equipment is available at [NLA]. NLANR measurement data is available on the world wide web at [DAT].

The PingER Project

The PingER project [MC00] performs active Internet performance monitoring for the HENP community. HENP (high energy nuclear and particle) physics experiments generate huge amounts[3] of data. The Internet is used to disseminate this data to universities all over the world. In order to assess the feasibility of the HENP networking goals, a large end-to-end performance monitoring infrastructure is being set in place. The infrastructure consists of an network probing system along with a set of tools for analyzing the data. The architecture has become known as PingER, for Ping (see section 6.3.4) end-to-end reporting. In regular intervals each site uses the Ping utility to send ICMP echo requests (pings) to a configured set of destinations. First, it sends 11 pings (of which the first is ignored) with a 100 byte payload, at 1 second intervals, followed by 10 pings with a 1000 byte payload also at 1 second intervals. In September 1999 511 nodes in 54 countries participated in the measurements. The PingER analysis defines five metrics: packet loss, round-trip time, unreachability, quiescence, and unpredictability. The packet loss and round-trip time metrics are self-explanatory. The other three metrics need some further discussion. If no reply is received from all 10 ping packet then the remote host is considered *unreachable*. For PingER it is extremely difficult to program analysis code to tell the difference between network related unreachability an a crashed end host. If the CSM infrastructure was used then intermediary agents could help to locate the problem (see section 6.3.4).

If all 10 ping echoes return then the network is considered *quiescent* or non-busy. The frequency of this zero packet loss event may give clues of network usage patterns.

The unpredictability metric is derived from a calculation based on the variability of packet loss and round-trip time. If a path loses much more packets at one time than at other times or if the round-trip time fluctuates heavily between two measurements then the calculation yields a high unpredictability value for this path. The unpredictability metric is a useful innovation of the PingER project.

The PingER methodology has some shortcomings. The measurements happen at regular intervals instead of Poisson distributed intervals. The PingER results may therefore be biased due to synchronization effects (see [PAMM98]). Furthermore, some routers treat ICMP packets different than regular traffic. This may also bias the measurements since this means that the pingER measurements are not representative for regular traffic. Nevertheless, the collected data is useful for recognizing short and long term networking trends and identify network problems.

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[3] During the whole lifetime of the project the expected data volume is somewhere between 10^{15} and 10^{18} bytes.

For, example the deployment of the the TEN network (see section 8.1) had a measurable positive impact on the packet loss rate measured by European HEMP partners. Also, university holidays have a measurable impact. Note, that given the CSM infrastructure the ping listener agent (see section 6.3.4) can easily be adapted to provide a superset of the PingER measurements.

Comparison to this Thesis

In academically influenced networks of the presented projects, network measurement data is often available for via the Web or FTP. However, such data is too aggregated for customer-based service monitoring. It may only be useful as a CSM node service that provides access to aggregated measurement data. Then, an agent can for example compare the throughput of the customer's traffic compared to the aggregated throughput of the whole network traffic. Architectures for fine-grained (per-packet) traffic data repositories have been proposed [KMKA99]. However, they do not collect the data on a per-service and per-customer basis. All collected data enters the same database. Therefore, they need to scramble the origin of the data for privacy reasons. This will also render the data useless for some customer-based service monitoring applications.

8.4 Mobile Agents for Network Management and Monitoring

This section discusses work that is closely related to the customer-based service monitoring infrastructure. In that work mobile code (mobile agents or active networking) is used for network management management in general or for network monitoring (a subtask of network management).

8.4.1 Network Management with Mobile Agents

The work in [BPW98] proposes mobile agents for various network management tasks and contains a detailed description of the advantages that the mobile agent paradigm offers:

- **Efficiency savings.** CPU consumption is limited, because a mobile agent execute only on one node at a time. Other nodes do not run an agent until needed.
- **Space savings.** Resource consumption is limited, because a mobile agent resides only on one node at a time and carries the required functionality with it. In contrast, static multiple servers require duplication of functionality at every location.
- **Reduction in network traffic.** Code is very often smaller than the data that it processes, so the transfer of mobile agents to the sources of data creates

less traffic than transferring the data. This is particularly true for CSM. All presented agents are relatively small compared the monitored data stream. The largest and slowest agent is the VPN agent. It can monitor 3 Mbit per second and is about 30 KByte large (see section 7.2). Thus, the migration of the agent pays of after 0.08 seconds of monitoring at top speed. For smaller and faster agents the time to pay-off is even shorter.

- **Asynchronous autonomous interaction.** Mobile agents can be delegated to perform certain tasks even if the delegating entity does not remain active. For CSM this is interesting because a monitoring agent can still collect measurements when the home network is unreachable due to some network problems.

- **Interaction with real-time systems.** Installing a mobile agent close to a real-time system may prevent delays caused by network congestion.

- **Robustness and fault tolerance.** If a distributed system starts to malfunction, then mobile agents can be used to increase availability of certain services in the concerned areas. For example, the density of fault detecting or repairing agents can be increased. In the case of CSM this could be applied when the customer suspects that an agent or its results have been manipulated by a provider.

- **Support for heterogeneous environments.** Mobile agents are separated from the hosts by the mobility framework. If the framework is in place, agents can target any system. The costs of running for example a Java Virtual Machine (JVM) on a device are decreasing.

- **Online extensibility of services.** Mobile agents can be used to extend capabilities of applications, for example, providing services. This allows for building systems that are extremely flexible.

- **Convenient development.** Creating distributed systems based on mobile agents is paradigm relatively easy. The difficult part is the mobility framework, but when it is in place, then creating applications is facilitated.

- **Easy software upgrades.** A mobile agent can be exchanged virtually at will. In contrast, swapping functionality of servers is complicated. For CSM this is the often cited flexibility that the user has in deploying service tests.

8.4.2 The Script MIB

The IETF Distributed Management (DISMAN) working group recently standardized definitions of managed objects for the delegation of management scripts (the Script MIB) [LS99]. The script MIB shall solve two pending problems of SNMP: (1) The processing and communication load on the central management station and

(2) the overhead due to polling over distance. The script MIB allows the SNMP manager to send management scripts to devices that support the script MIB. The script MIB is programming language independent; any kind of executable code can be considered a script. The script MIB defines variables that encode the language support of the managed device. The Script MIB Extensibility protocol (SMX) [SQ99] can be used to separate language specific runtime systems (which execute the scripts) from the runtime system independent Script MIB implementations. A Java runtime system [SQK00] and a Perl runtime system [BG00] for the Script MIB exist. Both were used to address selected network management problems.

The Script MIB defines objects that allow the manager to carry out the following tasks using the SNMP protocol:

- Transfer of management scripts.
- Initializing, suspending, resuming and termination management scripts.
- Transfer of arguments for management scripts.
- Monitoring and control of running management scripts.
- Transfer of results produced by management scripts.

Typically, a manager uses an SNMP *put* message to push a the script to a device that implements the script MIB. An alternative is to put a URL into a dedicated variable which causes the SNMP agent to fetch the script itself. The manager uses the *put* message to set the command line arguments of the script. Later, the manager may use the *put* message to trigger the execution of the script as many times as desired. The script writes its results or termination code into appropriate SNMP variables. The SNMP agent can notify the manager that the script has produced a result by using SNMP traps. The manager can then use the SNMP *get* message to query the state and the result of the script.

In [QK99] the authors discuss applications of the Script MIB. They identify amongst other things that customers of QoS enhanced network services may want to measure and supervise the service level *themselves*. This is an important argument for CSM. The authors of the article used a Java script runtime system and their scripts were Java byte-code. They identified two shortcomings of the Script MIB: (1) The Java management 'scripts' are supposed to perform the SNMP interactions with the local devices. Therefore, the Java byte-code needs to carry an implementation of the SNMP protocol routines. This made the management scripts too large (about 500 KB). (2) The communication facilities of the Script MIB are very limited. Basically, the script can write one result into the appropriate SNMP variable[4].

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[4] The script can actually write several results but each new result overwrites the old one.

Comparison to this Thesis

The proposed customer-based service monitoring infrastructure can be built almost completely based on SNMP mechanisms. As mentioned in section 8.3.2, a device supporting the RMON MIB can play the role of the T-component. The node environment can be implemented as a Java runtime system attached to a Script MIB enabled device. An SNMP manager application can play the role of the CSM home application. Yet, such a solution has some shortcomings compared to a pure Java-based approach: (1) the aforementioned insufficient communication infrastructure offered to the management scripts. The CSM agents can communicate with the home application at will. The data format of CSM messages is not limited. (2) The transmission between the monitored device and the management script is a bottleneck. In an SNMP-based solution the management scripts must send SNMP *get* messages to fetch packets (polling). This is a critical overhead compared to the raw packet protocol (see section 5.2.2) which sends packets as soon as they are copied by the T-component. (3) SNMP does not provide topology support to the customer. The agents cannot be forwarded from one Script MIB to another.

8.4.3 Network Management with Active Networks

Active networks are a set of interconnected network nodes that not only forward data packets, but also interpret a subset of these packets as executable code and subsequently execute them.

In [RS00] the authors propose a non-intrusive active networking approach for efficient distributed network management. Active packets (capsules) are send over ANEP compliant UDP packets. ANEP [ANE] specifies a mechanism for encapsulating active network capsules for transmission over different media (here IP). In the proposed active networking based network management approach the routers run a *diverter* which extracts ANEP packets and forwards them to the dedicated machine that provides an active engine (execution environment) to the capsules. The architecture is similar to the CSM infrastructure because it is non-intrusive and uses a dedicated machine to host the mobile code (capsules). Several capsules may belong to one distributed task (called a session). The capsules can either be sent directly to the router or they can be send in a 'blind' way towards a destination address. Then, the first diverter on the way will reflect the capsule to its active engine. This is similar to the hop-by-hop forwarding in the CSM infrastructure (see section 4.4). The executing capsules contact the SNMP agent of the router to gather monitoring information or to reconfigure the router. The executable capsule contents consist of Java byte code. Security is achieved through the separation of the active engine from the router, through the Java security manager and through network utilization restrictions imposed on the sessions. Capsule authentication is also foreseen but not implemented.

The proposed active networking infrastructure can be used to implement a customer-based service monitoring system if the managed router implements an

SNMP based T-component (e.g. the full RMON MIB - see section 8.3.2).

Yet, the same drawbacks as described for the Script-MIB apply then: (1) Dependency of the available SNMP MIBs and (2) Inefficient packet copy forwarding (see 8.4.2). Furthermore, the topology support is limited. There is no such concept as the node services here. So the capsule can not, for example, acquire topology information about the overlay network (where other active engines are located and to whom they belong). Another problem of the presented active networking approach is that large management programs may have to be split into several capsules. The rearrangement of these capsules has to be done by the active engine and is limited to 256 packets per session. Such a problem does not occur with CSM since the agents are transported on a TCP connection.

Nevertheless, the discussed work shows that a CSM infrastructure could also be deployed on a non-intrusive ANEP-based active network.

8.5 Pitfalls of Agent Based Software Engineering

Software agents as a self-contained problem-solving systems capable of autonomous, reactive, proactive, and social behavior, represent yet another tool for software engineering to develop increasingly complex and distributed systems (see section 1.3). However, there are a number of pitfalls that the developer of an agent based solution faces. The article [WJ99] presents a comprehensive list of these problems. This section is going to address this list in order to show that service brokers (as software agents) and customer-based service monitoring agents avoid these pitfalls. The following list is labeled with the same terms as it was labeled in the original work[5].

8.5.1 Political Pitfalls

- **You oversell agents.** There are many tasks that go beyond the scope of automation and need traditional techniques. Further, software agents are not generic problem solvers. Their intelligence is restricted to the state of the art of artificial intelligence research. The service brokers only automate the repetitious tasks of the service operation (see section 1.4). They are driven by human provided policies that provide the rules for the automation. Typical CSM agents possess only little intelligence which concerns one specific monitoring goal and on how to squeeze the desired information out of the measurement data. So both approaches do not oversell agents.

- **You get dogmatic about agents.** Agents are not a universal solution. Conventional software development paradigms are often more appropriate. Another form of dogma that causes trouble is that agent developers have their

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[5] The management pitfalls are omitted because these apply to commercial software development projects and not to research in the context of a PhD thesis.

own opinion on exactly what constitutes an agent. The service broker architecture is compliant and interoperates with state-of-the art network technology. Referring to the service brokers as intelligent agents conforms to the widely used definition of software agents (see section 1.3). The only agents of the CSM infrastructure are the measurement agents. These agents are mobile. This thesis proposes a mobile agent based approach not because of a dogma but because of reasonable arguments (see section 4.2.2 and 8.4.1).

8.5.2 Conceptual Pitfalls

- **You believe in silver bullets.** A ’silver bullet’ is a technique that will provide an order-of-magnitude improvement in software development. Neither the broker architecture nor the CSM infrastructure are agent based because of software development reasons but because of existing constraints in IP networks and because of upcoming needs of IP service customers and providers.

- **You forget agents are software.** Traditional software engineering processes such as requirements analysis, specifications, design, verification and testing should not be neglected when developing agent based solutions. For our implementations in the area of the service brokers and for the CSM implementation we used object-oriented engineering processes ([Bud91, BL94]).

- **You forget agents are multi-threaded software.** The problems inherent in developing multi-threaded systems (synchronization, mutual exclusion for shared resources, deadlock, and livelock) cannot be considered solved. Both the service broker architecture and the CSM infrastructure use the well-understood client-server communication model. This simple but effective communication pattern helps avoid coordination problems. The service broker prototype and the CSM node implementation are servers that extensively use multi-threading. Considerable care has been taken to use the specialized Java synchronization mechanisms (see also section 5.1.2) in order to avoid multi-threading related problems.

8.5.3 Analysis and Design Pitfalls

- **You ignore related technology.** This thesis studies related technologies (as discussed in this chapter). The service broker architecture is derived from the existing bandwidth broker concept. For agent implementation we used the Java programming language which has become dominant for agent systems and applications (compare for example the approaches listed in [Hoh]). Distributed computing platforms (middleware - e.g. Corba [OMG]) can provide many of the necessary agent functionalities. Yet, middleware is traditionally used exclusively to coordinate applications of one administrative domain and is therefore no alternative for solving inter-domain collaboration problems.

- **Your design does not exploit concurrency.** The service brokers work concurrently to solve local reservation tasks. They map the natural concurrency seen between the management operations of autonomous network domains and seen between single networking devices. The CSM agents enable the customer to concurrently collect measurements at many locations in the network.

- **You ignore legacy.** Legacy software is existing software that is functionally essential, technologically obsolete, and hard to rebuild. The service broker architecture maps to existing legacy network management systems. It separates the application domain of that system (internal network management) from the new functionality (external service brokering). The CSM infrastructure is non-intrusive and can be set up in parallel to existing legacy systems. For our project no legacy system existed. Yet, the CSM implementation uses existing tools for packet capturing and for cryptography. The CSM implementation includes scripts to glue these legacy components to the CSM applications.

8.5.4 Agent-Level Pitfalls

- **You want your own agent architecture.** A software project may lose valuable time and resources in designing a new agent architecture thereby reinventing old designs.

  The service broker architecture and also the CSM architecture are not developed from scratch but inspired by existing agent designs. For the CSM node implementation existing mobile agent platforms could have been used. Yet, the thesis project was not a commercial one. The implementation of the node environment helped us to deepen the insight into mobile agent technology. There are also further arguments for the development of a new agent platform. (1) The CSM node need a particular service that delivers packet copies to the agents as fast as possible. This is not supported by off-the-shelf agent platforms. (2) The CSM node does not need the usual heavy-weight inter-agent communication facilities. (3) CSM introduces a simplified agent model that focuses on packet processing. Therefore, a novel an light-weight resource control mechanism could be deployed (see section 5.5. (4) Implementing a new platform allowed us to introduce a minimal agent interface specialized to the task of service monitoring.

- **Your agents use too much/too little artificial intelligence.** Too much focus on artificial intelligence can result in an agent framework overburdened with experimental techniques. On the other extreme, developers build so-called agents that do nothing to justify the use of the term.

  The service brokers act autonomous in behalf of the operator of their network domain. They incorporate intelligence that is tailored to- and specialized for a limited application area. The mobile CSM agents possess only little intelligence but they have mobility autonomy. Both of these agent-based approaches only use the kind of intelligence which is available and appropriate for their respective task.

8.5.5 Society-Level Pitfalls

- **You see agents everywhere.** After first learning about multi-agent systems, there is a tendency to view everything as an agents. This is not the case for neither the service broker nor the CSM agents. Both architectures consist of many components that are not agents. The agents that this thesis introduces are relatively few in numbers compared to other relevant entities such as networking devices, customer applications, traffic flows etc.

- **You have too few agents.** In some approaches only a small number of agents do all the work. Such approaches fail to exploit the power of the multi-agent paradigm. On one hand, the original bandwidth broker may be an example of such an approach. The bandwidth broker allocates the resources for its network, it reserves them, it signals to neighbor brokers and it reconfigures the network. The agents of the service broker architecture, on the other hand, bundle a coherent set of functionalities. Domain internal functionality is separated from external functionality and factored out into stand-alone agents. The device configuration is also factored out. Thus, the number of agents naturally fits the number of separate tasks. The CSM agents bundle the service test procedure of one customer. It is up to the developers of CSM agents into how many agents they want to separate the functionality. They can, for example use one single agent to perform a bunch of unrelated monitoring tasks or they can split these tasks into separate orthogonal agents. Both approaches have some advantages and disadvantages.

- **You obsess on infrastructure.** Since there are no widely used software platforms for developing multi-agent systems the developers of such systems devote significant resources for implementing a new platform from scratch. We only implemented platform functionalities for CSM and only those that were necessary. Much of the needed infrastructure support was offered by the development systems of the Java language. Unnecessary but popular features such as strong migration and inter-agent communication were neglected.

- **Your agents interact too freely and the system lacks structure.** The interaction in the broker architecture is clearly structured through a layered hierarchy and through a request-response based inter-broker protocol. The interactions within the CSM infrastructure are also very simple and clearly structured by a set of protocols.

8.6 Open Issues

In both the service broker architecture and the CSM infrastructure there are open issues which this thesis does not address. The next sections describe these issues and give some examples of related work that can help to fill the gaps.

8.6.1 Multicast Support

Supporting multicast with DiffServ is an open research issue. The work in [MXZP00] proposes an enhancement of the experimental multicasting boarder gateway protocol. The extension can be used to perform an admission control between DiffServ domains. The border routers of the domains calculate a measure of the current DiffServ load based on exponential averaging. Based on that calculation they deny multicast join requests or relay them to an alternative, less loaded border router.

The providers will probably not offer Differentiated Services based resource reservations for free. In the area of multicasting this leads to the problem of cost sharing for DiffServ based multicasting. In [EHSB99] the authors propose a cost sharing scheme which is based on link weights that are calculated based on how many users share a link.

The StreamCom project [STR] proposes DiffServ to reserve resources for multicasted streaming data (video). The receivers of the data subscribe to the stream on the application level (to a ticket server) and do not directly contact DiffServ brokers, thus the project studies ways to mediate the payment from the user to the application server and finally to the DiffServ broker.

8.6.2 Collaboration of Monitoring Agents

In the CSM infrastructure the home application receives all the results of CSM agents that it has sent. This thesis does not specify how the home application analyses and interprets the results of the agents because this depends on the service being monitored. Yet, there are generic high-level techniques to identify different failure situations in communication networks based on the input of several measurement stations. In [LCL00] the authors describe methods to derive *codebooks*. A codebook is an optimal subset of events that must be monitored to distinguish the problems of interest from one another while ensuring the desired level of noise[6] tolerance. These methods are useful to develop and deploy a specific monitoring agent.

In the CSM infrastructure each agent performs monitoring for exactly one customer. One possible extension is that monitoring agents of the same or even of different customers may coordinate their actions and for example exchange results. The programmable coordination architecture for mobile agents MARS [CLZ00] proposes a shared and programmable tuple-space for inter-agent communication

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[6] Erroneous event notifications: missing events or confusion between events.

within a node. In CSM this could be implemented as a set of additional node services. Yet, the strong isolation of the CSM agents may break. Therefore, the CSM security model should then be extended for example with MARS' access control lists.

8.6.3 Service Advertisement and Discovery

The service providers need a way to advertise their services and the customers need a way to find services that match their needs. The flexible syntax of the broker signaling protocol (see section 2.3.4) allows the customer to use the query message to find out about the services that a broker offers. Yet, it is not well understood how the customer locates a service broker, how the service brokers can autonomously issue queries between themselves, and how a broker can autonomously announce a service. Work on these issues may profit from related work [Ric00] that has been performed in the area of mobility support for local computing environments.

Further, a requested end-to-end service may be composed of a set of domain services that differ in the way they are described. The QBone project avoided this issue by defining only a single service (the QPS) and declaring it globally well-known (see section 8.1.1). Yet, the commercial Internet will probably come up with a wide variety of different IP services, so the automatic service mapping is an open research issue.

8.6.4 Routing

The service brokers need access to the internal and the external routing. This is inevitable since the service broker must determine how collaborating providers are affected by a given service request. For QoS brokers, the path of the QoS enhanced traffic within the domain of a broker must be known in order to reserve local resources.

The CSM nodes also need access to the routing. With this information they can build up an overlay network and provide topology and forwarding services to the CSM agents (see section 4.4 and 5.7). The customer can use CSM query messages to find the ideal node for a given measurement or (s)he can forward the agent along a whole path.

Both the service broker architecture and the CSM nodes thus need a way to fetch routing information. The internal service brokers may also need a way to set new routes. Such a mechanism may rely on the existing routing protocols such as BGP [RL95].

The CSM nodes and possibly also the service brokers need a routing mechanism that allows them to dynamically set up and manage a an overlay network. CSM nodes need it to forward agents, the service brokers may need it to establish SLAs between brokers that are not direct neighbors.

8.6.5 Artificial Intelligence

Distributed software agents are suitable for implementing computational models of artificial intelligence. Intelligence helps the agents to cope with unforeseen situations and lets them act more autonomous. Service brokers may use their intelligence for example to map various kinds of service requests to distributed resources. In [CF00] a distributed constraint resolution technique is proposed to allocate resources for QoS VPNs.

The service broker architecture does not specify how artificial intelligence is implemented. Yet, we propose a flexible broker signaling protocol (see section 2.3.4) which allows the agents to negotiate between each other in a dynamic way. Such a communication protocol is a crucial factor for implementing distributed intelligence.

The presented CSM agents implement little intelligence. Instead, they are specialized for a well defined monitoring job. Yet, CSM agent developers may develop agents which represent expert systems on a specific monitoring task. A CSM agent for network intrusion detection [BK98, JMKM99] is just one example.

Chapter 9

Summary and Conclusion

The Internet Engineering Task Force (IETF) has proposed extensions to the Internet protocol that address pending problems of today's Internet technology: quality-of-service support and security. The Differentiated Services (DiffServ) architecture (see section 1.2.3) allows network providers to offer quality-of-service guarantees to specially marked traffic classes. The security architecture for the Internet protocol (IPSec - see section 1.2.2) standardizes the use of tunneling and cryptographic mechanism for transparent per-packet privacy and authenticity of Internet communication. Both the DiffServ and the IPSec technology allows the Internet service providers to offer enhanced IP services and thus to generate additional revenues. Yet, the enhanced services introduce additional network management complexity especially if several providers have to collaborate. Provider collaboration is necessary for example for end-to-end quality-of-service support because Internet traffic often travels through several provider networks.

This thesis thus addresses the following questions:

1. How can the management of enhanced IP services be automated so that a customer can order and receive a multi-provider service on-line?
2. How can the smooth service operation and multi-provider collaboration be monitored and verified by either the customers or the providers in a flexible way?

The thesis claims that agent technology (see section 1.3) offers answers to the aforementioned questions. Part I of the thesis presents an intelligent agent based approach to solve problem 1. Part II of the thesis presents a mobile agent based solution to address problem number 2.

The results of part I and II are summarized in section 9.1 respectively section 9.2.

9.1 Management of IP Services with Intelligent Agents

Inspired by the management architecture for Differentiated Services this thesis proposes a service management architecture based on intelligent software agents (see chapter 2). These so called service brokers act on behalf of their provider organization. An External Service Broker (ESB) interacts with ESBs of peering providers in order to automatically set up an end-to-end enhanced IP service on customer demand. ESBs negotiate service level agreements that specify the terms and conditions of the service to be delivered. The external service brokers use Internal Service Brokers (ISB) that have detailed knowledge of the administered network topology and capacity. The individual networking devices are managed by element managing agents that hide the heterogeneity of the devices.

The main innovation of the broker architecture is that it refines the established but not clearly defined concept of bandwidth brokers and that it generalizes the concept towards the management of other enhanced IP services such as VPNs. The architecture exploits the the key advantages of software agent technology: goal-driven autonomy (for IP service provisioning), heterogeneity support (different provider network technologies), and collaboration/communication (for multi-provider services).

The main benefit of the service broker architecture is that it provided the design and a reference framework for two particular service broker implementations within the CATI project ([SBGP98], see section 2.1). The first implementation is an internal service broker for QoS VPNs [KBG00]. The second implementation is an external service broker for DiffServ services, including the inter-broker signaling protocol BSP described in section 2.3.4. BSP allows the communication parties to encode information in object hierarchies of arbitrary depth and with flexible field lengths. BSP's encoding of object states support the step-wise negotiation of service parameters. Due to its flexibility and extensibility, the protocol is currently being reused in further projects.

One particularly interesting problem in the area of IP service related inter-provider collaboration is the reservation of network resources in order to support DiffServ QoS guarantees. The DiffServ architecture was designed as a scalable technology, but inter-domain resource reservation is not described in detail. Up to now there is no consensus how DiffServ reservations should be signaled. Signaling of each customer resource request to all involved providers may cause huge scalability problems. Chapter 3 of this thesis discusses different signaling options and evaluate the involved trade-off: signaling overhead versus end-to-end quality guarantees and network utilization. An adaptive reservation scheme using no signaling and based on measurements, a limited signaling scheme that uses a heuristic to determine whether to signal or not, and a mapping of end-to-end signaled requests into resource aggregates were discussed. A newly developed network simulator generates the following results:

- The adaptive reservation introduces no signaling overhead. Yet it provides only soft guarantees (there is loss of reserved traffic) and it needs over-reservation. The adaptive reservation scheme is sensitive to the size of the inter-network and the traffic characteristics. In a typical network scenario 7% of moderately fluctuating traffic is lost, but 20% of heavily fluctuating traffic is lost. In a network scenario with 5 provider networks 2% of traffic is lost, but the same network type with 40 provider networks loses 7%.

- The limited signaling reservation scheme signals reservations only as far through the networks as necessary (according to a heuristic). Limited signaling also produces loss of reserved traffic, but it is more robust than the adaptive reservation. In a typical network scenario 5% of moderately fluctuating traffic is lost, and 11% of heavily fluctuating traffic. In a network scenario with 5 providers, 0% is lost and an average of 1.9 signals per flow are exchanged between providers. In the same network type with 40 provider networks less than 1% traffic is lost and an average of 2.5 signals per flow are exchanged between providers. The number of signals grows less than linear compared to the network growth. When end-to-end signaling is applied 0% traffic is lost in all cases. Yet, the number of signals exchanged is proportional to the number of provider networks. For the 5 provider scenario an average of 2.5 signals are exchanged between the providers, for the 40 provider scenario an average of 16 signals are exchanged.

- End-to-end signaling introduces a large signaling overhead but completely prevents loss of reserved traffic. SLA updates generate even more overhead than reservation signaling. Yet, the simulation shows that if SLAs reserve relatively little more than needed (20% over-provisioning) then then number of SLA updates are already an order of magnitude (10 times) smaller than the number of reservation signals. Thus over-provisioned SLAs massively help to reduce the number of (expensive) SLA updates.

Outlook. The work in the first part of the thesis is mostly conceptual and followed a top-down approach. There was more interest in the service enabling processes that take place between the providers and less in the processes within a provider domain. The approach described in part I of the thesis follows the Internet philosophy which lets the network providers chose their own internal management processes. Nevertheless, if new IP services and particularly the Differentiated Services shall become available Internet-wide then the inter-provider management must be specified and implemented. Large initiatives that deploy such services (most prominently the Internet2 - see section 8.1) developed their work in parallel with this thesis. However, they have chosen a bottom-up approach. First, they work out the basic mechanisms within a domain. Thus, up to now they were able to avoid the inter-provider problems discussed in this thesis. Yet, they have also identified these challenges such as for example the automatic establishment of multi-provider services but defer it to later project phases. The Internet2 QBone researchers are currently designing an broker communication protocol and have identified the problem of signaling scalability. The presented evaluation of the DiffServ signaling options can help them in this process. The results derived from this thesis are published in reviewed conference proceedings [GBK99, GB99] and can are thus available to initiatives such as the Internet2 and Eurescom P1008-PF (see chapter 8).

9.2 Customer-Based Service Monitoring with Mobile Agents

When Internet users request enhanced Internet services such as DiffServ or VPNs they should have a mean to verify that the Internet service really is enhanced. This is difficult because of several reasons: (1) Such services consist of per-packet actions and transformations that the provider performs *within the provider network*. (2) Traditional network monitoring foresees only a small range of fixed metrics (e.g. throughput in bytes per second). The new IP services can only be verified by applying new metrics to the traffic. (3) The customer should not be able to abuse the service monitoring facilities.

In case several providers collaborate, a reliable and tamper-proof service monitoring facility becomes even more important. A malicious provider may participate in such a service offering to get additional revenues but may not allocate the proper resources, since this generates cost. Both the customers of the service and the partner providers have an interest to identify such malicious providers.

Part II of this thesis proposes a customer-based service monitoring (CSM) infrastructure based on mobile agents. Using mobile agents for remote service monitoring is a novel approach. At their border routers the providers deploy non-intrusive execution environments (nodes) for the mobile agents. The agents are fully programmable and perform their measurements based on IP packet copies which are delivered to them by the node. The node implements security mechanisms that protect the node resources, protect the agents from each other, and ensure that the agents can only monitor traffic for which they have explicit permission.

Using mobile agents for CSM has several key advantages over stationary approaches:

- The customer's monitoring activity can take place within the provider networks.
- Mobile agents are programmable and easy to deploy and distribute. Thus, a new measurement metric for a new IP service is rapidly deployed.
- Mobile agents can perform their monitoring even when the customer is disconnected from the Internet and can thus for example further analyze potential connectivity problems.

- Mobile agents enable the customer to perform distributed tests in a flexible way. Measurements that originate from different locations can be correlated to identify a corrupted CSM node. CSM agents can dynamically roam to problem areas of the network where the number of measurement agents and increases thus delivering a better picture of the service state.

- Mobile agent technology provides state-of-the-art security models and mechanisms.

In order to validate these advantages we implemented a CSM system. The CSM implementation (see chapter 5) introduces a number of new concepts:

- **T-components and filters.** The CSM agents calculate their results based on time-stamped IP packet copies. This guarantees the non-intrusiveness of the approach. The packet copies are generated by a specialized T-component which the agent cannot directly access. The agents have to request the copies from the CSM node. For that purpose they hand a filter object to the node that describes the desired IP packets. The node applies a second filter which describes the packets that the user associated with the agent has access to. This guarantees that the agent cannot monitor other customers' traffic.

- **Isolated execution environment.** The CSM node isolates each agent into a separate execution environment. Agent wrappers feed the agent with monitored packets that are stored in a queue. The agent holds only one object reference that only allows the agent to deposit node service request objects. The agent wrapper manages the execution thread of the agent. The agent is thus effectively isolated from the rest of the node. On a Sparc ULTRA 5 a fast agent in an execution environment can handle up to 13'000 IP packets per second.

- **Light-weight resource control.** The architecture of the execution environment allows the CSM node to perform a light-weight resource control of CPU time, memory, and network traffic consumption. The control does not require byte-code rewriting or an enhanced virtual machine. For the CPU control, the agent wrappers account the execution time of the agent's packet handling method. A resource controller periodically checks if some agents' in-queues are filling up and if so, which agent did make the least effective use of its CPU time. This agent is then terminated. The resource controller has only a minor impact on the performance. If the node is busy the controller uses 5% of the node CPU time. For the memory control the Java object serialization mechanism is exploited.

- **Agent overload control.** Each agent has to implement a regular packet handling method and an emergency packet handling method. The latter is called when the agent's in queue is filling up. Thus, the agent is given a chance to get rid of the queued packets quickly and thus avoid node congestion and subsequent termination of agents.

- **Flexible result delivery and display.** The CSM protocol provides a framework for agent developers that allows the agents to transmit monitoring results in arbitrary formats. The customer uses the home application to transmit agents and to display their results. The home application provides a display framework that allows the customer to display results in different ways (for example graphical or numerical).

Other features of the CSM implementation mainly exploit state-of-the-art technology (for example Java's class loader and the security manager) and well known tools (UNIX scripting, PGP, and Tcpdump). Using a fast T-component (t-bone) the CSM implementation is able to monitor traffic at approximately 9 Mbps, the latency between the T-component and the agent is as low as 1 millisecond, the latency between the T-component and the customer-driven home application is 55 milliseconds (for details see chapter 7).

The implemented CSM system allows the customers to develop new tests to verify the proper operation of the enhanced IP services. This thesis presents several examples of such tests which cannot be performed with traditional systems (see also section 6).

- **Encryption verification.** One important innovation that this thesis presents is the on-line cryptographic tests of the VPN traffic. These tests can reveal if due to error, misconfiguration, or malevolence the VPN traffic is not or insufficiently encrypted. An inherent property of cryptographic mechanisms is that their output material has the same statistical properties as random data. The VPN control agent exploits this property. It uses the χ^2 statistics to define two randomness tests: the byte-frequency test that tests for uniform distribution and the run-length test that tests for independence within the data. Both tests can for example reveal if the VPN traffic is compressed instead of encrypted. Agent developers can easily create further (statistical) tests. None of todays static network monitoring tools can support such tests. If the tested data must first be delivered to a statistical test software that runs at the customer site, then this introduces huge networking overhead. If a VPN tunnel is monitored for two hours at a line speed of 1.544 Mbps (T1) then the customer must download 1.3 GByte of data to analyze it. With CSM, only a 30 KByte VPN agent must be uploaded. Note, that the implemented agent can monitor the VPN traffic up to a speed of 3 Mbps (with limited loss up to 5 Mbps).

- **Customer-defined aggregation and separation of monitored traffic.** Traditional network monitoring tools have a fixed filter mechanism with which they aggregate or separate data (for example into counters). Thus, for example the QBone project had problems measuring whether DiffServ traffic was protected from regular traffic because not all monitoring devices could filter according to the DSCP byte. Further, the SNMP RMON MIB had to be extended because it could not filter according to protocols of higher layers (e.g. HTTP). The CSM agents can program their own internal filters and for example implement meters that aggregate flows using the same DSCP value, or separate flows having the same end-point addresses but using different DSCP values. Also, CSM agents can easily be programmed to analyze the higher protocol layers. Our ping measurement agent for example analyzes the ICMP protocol to derive several measurements of performance metrics.

- **Localization of service problems.** Traditional end-to-end network management can identify problems but not localize them. The presented bottleneck bandwidth agent not only measures the bottleneck bandwidth between two communication end-points. If the agent is deployed at several points in the network then it can also locate the bottleneck link. Similarly, the one-way delay measurement agent and the round-trip delay measurement agent provide delay measurements of every intermediate part of the traffic path.

- **Protection from malevolent providers.** Traditionally, the provider regularly (e.g. monthly) delivers a service performance report to the customer. Yet, it is easy for a malicious provider to forge such a report. It is much more difficult to forge measurement results when they are collected by the customers' mobile agents, because the provider does not know in advance the metric to be tested and the time and location of the measurements. The customer can distribute agents with obfuscated code or nonsense agents to confuse the provider. In the future, mobile cryptography may become mature to protect the agent code. Also, the customer can perform consistency checks by collecting different measurements at different locations, for example at the peering routers next to the provider to be tested.

We also implemented agents that calculate traditional measurement metrics such as: traffic loss, packet anomalies (broken packets or packets in wrong orders), throughput, one-way and round-trip delay, and jitter.

Outlook. A key strength of the CSM infrastructure is that customers, providers, and third-party vendors can all develop monitoring agents. The CSM agents presented in chapter 6 represent only a small subset of interesting monitoring applications. Further applications that can be deployed are:

- Customizable event notification, that uses for example random-early detection or other heuristics instead of fixed thresholds.

- Trace-back of distributed denial-of-service attacks.

- Network intrusion detection.

Note, that with each new IP service that is being introduced the number of interesting applications and thus the value of the CSM infrastructure increases.

A whole range of new CSM applications become available when the the CSM nodes offer further services to the agents:

- The injection of test traffic may become a node service. Then, the CSM agents can themselves perform active measurements from within the provider networks.
- An agent-to-agent communication service allows the CSM agents to exchange results within a CSM node. Result sharing means more effective use of the node resources and allows the customers to build agent hierarchies.
- A log file and management information base access node service can provide additional and pre-processed information to the CSM agents.

Finally, the CSM model could be extended from a non-intrusive monitoring model towards a full-fledge active networking model. Instead of working on IP packet copies, the CSM agents would have access to the original packet. They can thus control the packet forwarding and themselves perform packet transformations. Due to security, trust, and performance problems such an extension will probably not be deployed anytime soon. Section 6.5 describes the CSM node service and model extensions.

The presented CSM node implementation can handle a traffic rate of approximately 9 Mbps. It was tested on a real wide-area VPN tunnel and on a network of virtual routers. The throughput of the Tcpdump based T-component is limited to 4 Mbps which is mainly due to the fact that in our setting the limited network capacity between the T-component and the CSM node was shared with the test traffic. The performance limitation of the node is not so severe because the node usually only receives a subset (described by filters) of the complete network traffic. Nevertheless, the performance of the T-component needs to be improved when CSM nodes are to be deployed in the network backbone. Such high-performance T-components probably need specialized hardware.

When CSM is to be deployed Internet-wide, the implemented overlay routing mechanism (distance vector routing) may not scale. Then, integration of CSM node routing into the scalable two-tier Internet routing may be necessary. Further, a node advertisement and discovery mechanism would ease the customers' task to find the ideal node for an IP service test (see section 8.6 for more details).

Epilogue. Emerging IP services such as DiffServ and VPNs will enable the Internet community to deploy a new generation of valuable Internet applications. This thesis shows that agent technology provides solutions for the Internet-wide deployment of such new IP services. I hope that my work removes some of the obstacles in the way towards the often conjured golden age of the open information society.

List of Figures

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List of Abbreviations

ACL	Agent Communication Language
AES	Advanced Encryption Standard
AF	Assured Forwarding
AH	Authentication Header
ANAISOFT	Advanced Network and Agent Infrastructure for the Support of Federations Of Workflow Trading Systems
ANEP	Active Network Encapsulation Protocol
API	Application Program Interface
ASCII	American Standard Code for Information Interchange
ARM	Application Response Management
ASN.1	Abstract Syntax Notation 1
ATM	Asynchronous Transfer Mode
BB	Bandwidth Brokers
BGP	Border Gateway Protocol
BSP	Broker Signaling Protocol
CA	Certificate Authority
CATI	Charging and Accounting Technogoy for the Internet
CCM	Connection Control and Management
CNEC	Competence Network for Electronic Commerce
CoSS	Composite Service Server
CPU	Central Processing Unit
CSM	Customer-based Service Monitoring
CSS	Customer - Customer Server
DES	Data Encryption Standard
DiffServ	Differentiated Services
DNS	Domain Name Lookup System
DoS	Denial-of-Service
DS	Differentiated Services
DSCP	Differentiated Services Code Point
EASE	Embedded Advanced Sampling Environment
ECB	Electronic Code Book
EF	Expedited Forwarding
EM	Element Manager
ESB	External Service Broker
ESP	Encapsulating Security Payload

FDDI	Fiber Distributed Data Interface
FIPA	Federation for Intelligent Physical Agents
FTP	File Transfer Protocol
FWTS	Federations of Workflow Trading Systems
GB	Giga-Bytes
GPS	Global Positioning System
GUI	Graphical User Interface
HENP	High Energy Nuclear and Particle
HTML	Hypertext Markup Language
HTTP	Hypertext Transfer Protocol
IANA	Internet Assigned Numbers Authority
ICMP	Internet Control Message Protocol
IDEA	International Data Encryption Algorithm
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IKE	Internet Key Exchange
IntServ	Integrated Services
IP	Internet Protocol (Version 4 or 6: IPv4, IPv6)
ISAKMP	Internet Security Association and Key Management Protocol
ISB	Internal Service Broker
ISDN	Integrated Services Digital Network
ISO	International Organization for Standardization
ISP	Internet Service Provider
ITU	International Telephone Union
JNI	Java Native Interface
JVM	Java Virtual Machine
KB	Kilo-Bytes
MAC	Message Authentication Code
MB	Mega-Bytes
MD5	Message Digest 5
MIB	Management Information Base
MPLS	Multiprotocol Label Switching
MTU	Maximum Transmission Unit
NAI	Network Analysis Infrastructure
NLANR	National Laboratory for Applied Network Research
NSF	National Science Foundation
NTP	Network Time Protocol
OC	Optical Carrier
OSI	Open System Interconnection
PC	Personal Computer
PGP	Pretty Good Privacy
PHB	Per-Hop Behavior
PKI	Public Key Infrastructure
POP	Point-of-Presence

QoS	Quality-of-Service
QPS	QBone Premium Service
RAA	Resource Allocation Answer
RAR	Resource Allocation Request
RFC	Request for Comments
RIP	Routing Information Protocol
RSA	Rivest, Shamir, and Adelman Algorithm
RTFM	Real-time Traffic Flow Measurement
RTT	Round-Trip Time
SA	Security Association
SB	Service Broker
SIBBS	Simple Inter-domain Bandwidth Broker Signaling
SLA	Service Level Agreement
SLS	Service Level Specifications
SMI	Structure of Management Information
SNF	Swiss National Science Foundation
SNMP	Simple Network Management Protocol
SPI	Security Parameter Index
SPO	Service Parameterization Object
SSH	Secure Shell
SWITCH	Swiss Academic & Research Network
TCP	Transmission Control Protocol
TMF	Telecommunications Management Forum
UDP	User Datagram Protocol
URL	Uniform Resource Locator
TMN	Telecommunications Management Network
VPN	Virtual Private Network
WAN	Wide Area Network
WWW	World Wide Web

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Curriculum Vitae

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1982 - 1987	Secondary School Interlaken.
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