COST Action IC0906 WiNeMO

Topic: Content-Centric Architectures for Moving Objects

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Abstract

The goal of this white paper is to describe representative usage scenarios and their corresponding requirements, as well as state-of-the-art technological solutions and open research directions for key functionalities related to content-centric architectures for networks of moving objects. The usage scenarios presented include smart transport, data dissemination in partially connected environments, collaborative sensing, and situation and presence-aware services. The functionalities discussed include name resolution, routing, forwarding, discovery, content sharing, in-network caching, and the generalization of content-centric networking to service-centric networking.

Contributing organizations

Athens University of Economics and Business (GR) – Vasilios Siris (topic leader)

CNR (IT) – Chiara Boldrini, Raffaele Bruno, and Marco Conti

University of Berne (CH) – Carlos Anastasiades and Torsten Braun

University of Coimbra (PT) – Marilia Curado and David Palma

University Lusofona/SITI (PT) – Paulo Mendes and Bruno Batista

University of Zagreb (HR) – Ivana Podnar Žarko and Krešimir Pripužić

1. Introduction

Content or Information-Centric Network (ICN) architectures have been a research topic that has attracted a high interest in the recent years. Content-centric architectures present a paradigm shift from the current Internet's end-to-end communication model, towards a communication architecture where content is the central focus. Such a shift reflects the fact that the Internet is increasingly used for the dissemination of information, rather than for pair-wise communication between end-hosts. Employing content-awareness to the network can help address a number of limitations in the current Internet's architecture, including mobility support, efficient content distribution and routing, and security concerns.

This white paper was produced within COST Action IC0906: Wireless Networking for Moving Objects (WiNeMO). Its goal is to first describe representative usage scenarios for content-centric architectures within environments that contain a potentially large number of moving devices, with different capabilities and communication requirements. Next, the white paper targets to describe state-of-the-art technological solutions for key functionalities of content-centric networking applied specifically to moving objects, and to identify current open research problems.

2. Usage scenarios and requirements

In this section we present various usage scenarios. For each usage scenario we describe the communicating entities that are involved, the type of information they exchange, the communication requirements, such as performance, QoS/QoE, etc. The usage scenarios discussed include smart transport, data dissemination in partially connected environments, collaborative sensing, and situation and presence-aware services.

2.1 Smart transport

Smart or intelligent transport systems have the goal to improve safety, efficiency, environmental sustainability, and comfort of transportation. Relevant applications include fleet management, highway congestion management, freight management, and public safety applications. The need for such applications stems from the high rate of fatalities and injuries, which are higher in developing countries, as well as traffic congestion which increases as the number of vehicles increases, significantly reducing highway and fuel efficiency, while increasing CO^2 emissions.

In smart transport systems, communicating entities can be vehicles (private or public, such as civilian, public transport, commercial, and emergency vehicles, taxis, etc), freight containers, human devices (e.g., smartphones), and infrastructure nodes (e.g., local or centralized servers). Communication can involve communication between a moving entity and an infrastructure node (e.g., vehicle-to-infrastructure communication) or direct communication between moving entities (e.g., vehicle-to-vehicle communication). Moreover, the communicating entities can be both producers and consumers of information. The data (content or information) exchanged can include location information, distance & time travelled, operational status, sensor information, fuel consumption, etc.

Information exchange can involve data collection and data dissemination. Data collection involves transmission of information from many sources to one or multiple collection points. The latter can involve a set of collection points that must all receive the data from the sources or for which reception from one collection point is sufficient (anycast). Data dissemination involves transmitting information to all or a subset of entities. Another aspect is the initiator of information exchange: receiver-driven (e.g., probe-based) or pull-based and sender-driven or push-based. Sender-driven (push-based) information is typical for fault alerts, emergency information, etc. On the other hand, receiver-driven (pull-based) communication is typical for generic location and status monitoring applications.

Key requirements and challenges for communication and information exchange in smart transport environments include the following:

- Scalability and efficient information collection and dissemination
- Mobility of moving entities and highly variable network topology
- Communication availability and reliability
- Real-time constraints and prioritization
- Delay and disruption tolerance
- Security and privacy

Two key features of ICN architectures include location-independent naming of information/content objects and connectionless (stateless) end-to-end communication. These features allow ICN architectures to inherently support broadcast/multicast and many-to-many communication, receiver mobility, delay and disruption tolerance, and content-aware traffic management and prioritization. Hence, scalable end efficient information collection and dissemination can be supported by identifying the name of the information to be collected or disseminated, rather the host endpoints from/to which the information will be collected/disseminated; the former can be a single name, which results in data collected/disseminated from/to multiple entities.

Inherent support for broadcast/multicast together with requests for content by their names, which allows more effective exploitation of in-network caching, can help to achieve scalable and efficient information collection and dissemination. Receiver-driven (pull-based) control helps to minimize/avoid Denial-of-Service (DoS) attacks. Finally, the focus on naming information objects, rather than communication end-points, shifts the focus on security and privacy to mechanisms that act on the information objects, rather than the communication channel between end-points.

2.2 Data dissemination in partially disconnected environments

This scenario involves mobile communication entities (terminals carried by users, vehicles equipped with on-board radio units, etc.) that are disseminating information through opportunistic techniques, i.e., move and replicate data objects in the network by taking advantage of direct contacts between nodes with the objective to ensure that users receive the data they are interested in despite the fact that a multi-hop path from the source to the destination of the message does not exist.

Conceptually, *data dissemination systems can be seen as variations of the publish/subscribe paradigm*: publisher nodes generate contents and inject them into the network, subscriber nodes declare their interest in receiving certain types of content (e.g., sports news, radio podcasts, blog entries, etc.) and strive to get it in some ways. Nodes can usually be publishers and subscribers at the same time. The main difference between message forwarding and content-centric dissemination is that source and destination of a message are typically well known when routing a message (and clearly stated in the header of the message itself), while, in content-centric dissemination, content generators and content consumers might well be unaware of each other. A future of users generating content items on the fly while moving, and distributing this content to the users in their proximity, can be realistically envisioned for the next years. In order to make this future a reality, new strategies for disseminating content items must be designed, while at the same time accounting for a wise usage of network resources, which can be easily saturated in this scenario.

Among the various techniques that can be considered to improve the efficiency of data dissemination, we advocate approaches that use the social dimension to control the data dissemination process. Indeed, users' mobility patterns are strongly influenced by their relationships with other users, location preferences, activities, etc. Thus, social-awareness can be exploited to identify those nodes that are better fit to cache certain content items.

2.3 Collaborative sensing

We may divide collaborative sensing applications into two groups: opportunistic sensing and participatory sensing. The former are sensing applications where individuals with sensing and computing devices collectively measure and map phenomena of common interest, and share the collected data without active user involvement [GYL11]. In contrast to opportunistic sensing, participatory sensing requires an active involvement of individuals to contribute sensor data (e.g., taking a picture, reporting a road closure).

In general, we can envision an application where smartphones are used as sources of sensing information (e.g., user behaviour and location) and can also collect environment information from external wireless sensors (e.g., pollution data). Such external sensors would be carried on bikes or cars, while smartphones would report the sensed data to a central service to enable data processing and visualisation in real-time. An information centric communication paradigm is adequate for building opportunistic sensing applications because it enables filtering of sensed data on smartphones for regions with sufficient number of data readings. More importantly, it enables active delivery of sensed warnings in near real-time to smart phones. In such a setup, application users, even if they are not carrying sensors, could get warnings about highly-polluted spots in their vicinity.

Hereafter, we describe a set of usage scenarios related to large-scale opportunistic sensing technology able to augment people daily experience in urban scenarios based on the intelligent analysis of sensorial data opportunistically collected from the environment and from users (by mobile and static devices), and shared among a large set of personal devices by means of an information-centric network.

Large-scale sensing systems may support a diverse set of applications, from predicting traffic jams and modelling human activities, social interactions and mobility patterns, to community health tracking and city environmental monitoring. These applications will generate a lot of traffic, which exacerbates the need to manage better the bandwidth utilization, have strong requirements regarding security/privacy (since sensorial information can be sensitive) and have good support to mobility. Emerging information-centric architectures fulfil most of these requirements natively. General security issues are addressed at the item/data packet level rather than at communication channel level (so we can transmit information securely despite the channel we are using). Mobility is facilitated since the network focus shifted from hosts to information and the in-network storage (proposed by most of the ICN architectures [NDN] [PURSUIT] [SAIL]) can reduce network bandwidth utilization and delay, improve user Quality of Experience, decrease server resource requirements and enhance service availability.

We can distinguish large-scale sensing systems in two different ways: group and community. The former scenario encompasses sensing applications used by people that share a common goal or interest, such as environmental context. Community sensing starts to have an impact in the presence of a large number of people, for instance to extract higher-level community and social behaviours, as well as environmental activities. In any of these scenarios moving personal devices will need to have access to information based on current collective sensing interests.

In order to test and evaluate the solutions regarding ICN architectures and large-scale sensor systems we will consider the following use-cases:

Use-case A: Tracking the spread of disease across a city

When a pandemic occurs, it will be very useful to detect, and monitor the evolution of disease spreading. In this scenario it will be very important to know how to identify who has been in contact with a potentially infected person, as well as to know, when and where the contact took place. In the case of a pandemic, for example, the distance and contact time with the person, the logical places for the meeting and the relationship with the person are all important context information affecting the probability of disease spreading. Advances in biosensors and intelligent networks may allow the incorporation of this understanding into personal devices for disease detection or monitoring, while advances in data mining and modelling may allow the output of such devices to indicate new disease outbreaks and project their impact.

Use-case B: Integrated Physical and Social Networks

Millions of people participate regularly in online social networks. However such social networks do not allow people to know what their friends are and what they are doing, while keeping the required privacy levels. In our envisioned scenario, private information will be located in personal devices and not in the cloud and the information made available to friends will also include behaviour inferred from the group and community behaviour and not only from individuals.

User-case C: Augmented information distribution

Within a city, there are areas with typically high-density populated communities, e.g., a university campus. In such dense areas, people often face the problem of finding partners doing activities of interest to them, or for instance searching if there are free spaces available in the gym or in the library. There are also queries that will support a decision making process, such as knowing when the next bus will reach the bus stop near the library, and how many people are waiting in the bus stop, in order to decide to leave the library or not. All these community services in urban areas can be enabled by analysing the pervasive data streams collected from personal mobile phone sensors, such as GPS information of people in a bus stop.

2.4 Situation-aware and presence services

Situation and context-awareness are important properties when designing content-centric applications running on moving objects. They influence, on one hand, the end-user experience of an application, and, on the other, content dissemination and processing techniques as they depend on the current status of the environment. In terms of the environment, we have to take into consideration both the status of a moving object and its surrounding neighbouring objects as well as the fixed network infrastructure.

This section presents a use case scenario for context-aware services running on moving objects that involves an energy-efficient presence service. Presence is defined as the willingness and ability of a user to communicate across a set of devices with other users and represents an essential prerequisite for real-time communication [RFC2778]. Presence is today viewed as a primary service offered by contemporary unified communication platforms, and is often referred to as the dial tone of the 21st century. Presence services enable users (watchers) to subscribe to presence information generated by their contacts (presentities), and to receive their presence updates in real-time. However, existing presence solutions typically ship all generated presence updates from presentities to watchers, without taking into account watcher context. Indeed, watchers are not really interested to closely and continuously follow their contacts, but would rather prefer to receive filtered presence notifications at their own convenience. In addition, presentities would also like to control the disclosure of their presence information to watchers, especially when it comes to personal context-related presence information. For example, Alice would like to receive a presence notification when her contact Bob is nearby (e.g., in the office next door, or on the same floor), in a good mood, while his presence status is set to available. On the other hand, Bob specifies that his current location during office hours may only be shown to his boss, wife, and a few colleagues. As Alice is on the list of Bob's colleagues, his presence status is sent to Alice including the current location when conditions of her presence-related subscription are met.

Presence information is event-based and generated in an ad-hoc fashion. It is disseminated in real-time from one source to many destinations following the publish/subscribe communication model. Mobile objects, e.g., smartphones equipped with various sensors, are nowadays increasingly seen as sources of rich presence information (e.g., my current location is room C07-12, the room in noisy, well illuminated, etc.) [PZKPA11]. However, due to potentially huge numbers of mobile objects that can be regarded as content sources publishing sensor data with high publishing rates, such data needs to be filtered out in real-time close to data sources, e.g., even on a smartphone. Data filtering needs to be context-aware such that only valuable content is delivered to interested destinations in accordance with their presence-related subscriptions. Moreover, data filtering on the mobile phone will greatly reduce the energy consumption on mobile objects and prevent messaging overload experience within the fixed network.

The requirements for the above presence scenario are similar to the collaborative sensing scenario discussed in the previous section, since they are both envisioned for highly-dynamic and heterogeneous environments comprising large numbers of mobile objects, such as smartphones, which require a fixed infrastructure, e.g., a service running within a fixed network. Mobile objects are both content sources and destinations, while they may connect in an ad hoc fashion to neighbouring objects such as wireless sensors. As the number of content sources is potentially extremely high, the amount of generated data over time could become huge, and requires efficient real-time processing within a fixed network, typically in a cloud. Additionally, since mobile objects are content destinations, we need to restrict the number of notifications delivered to mobile objects to prevent user spamming. Our original publish/subscribe model for delivering top-k publications within a sliding window of size w (top-k/w publish/subscribe) enables such a restriction [PPZA12, PPZA11].

We envision the following requirements and challenges for real-time processing of vast data volumes, which are produced and consumed by mobile objects:

- efficient and scalable real-time processing within the core network,
- context-aware data filtering close to data sources,
- data filtering prior to delivery to mobile destinations to prevent information overload, and
- network dynamicity and diversity.

3. Technological solutions and research directions

This section presents an overview of the state-of-the-art for relevant solutions, and identifies open research directions. First, we present an overview of how routing differs in ICN architectures, in relation to routing in the current Internet. Next, we consider the key functionalities of ICN architectures and discuss how various proposals differ in the integration and interaction of these functionalities within the overall architecture. Next, we discuss in more detail routing and mobility in content-based publish/subscribe systems, followed by forwarding and discovery in coupled ICN architectures for mobile environments. Then, we discuss the generalization of content-centric networking to service-centric networking. Next, we present an overview and categorization of approaches for content sharing in opportunistic networks. Finally, we present solutions for self-organization of in-network caching.

3.1 Towards content-centric routing

Nowadays routing found in typical packet switching networks consists in the discovery of paths between routers or nodes, forwarding packets hop by hop until the desired destination is reached. Even though several routing algorithms and techniques have been proposed and perfected in past years, using for instance Quality of Service (QoS) metrics [KJ12] or multicast approaches, dealing with the growing demand of multimedia based streams. The increasing amount of available content on the Internet, in particular audio and video streams, involves large amounts of data, in particular when considering recent services such as 3D-movies. Moreover, more and more services are expected to be available in a near future, extracting and inferring additional real-time information from these streams, allowing objects included in a video to be linked to other content, providing a sense of augmented reality in every stream [FC09].

Current networks as the Internet rely nowadays on the usage of caching mechanisms or content distribution servers and clusters (centralized or not). In fact Content Distribution Networks (CDNs) are subject of current investigation and support several well-known services on the Internet. Moreover, considering the distribution of audio and video streams, QoS routing has been suffering a shift into Quality of Experience routing (QoE), where parameters such as the Mean Opinion Score (MOS) of videos are taken into account [TM12].

Presently, users connect their terminal nodes to residential gateways or directly to internet providers' routers, relying on pre-existing configurations that allow the access to static content available on Caching Servers or CDNs. As an alternative solution, peer-to-peer overlays are also becoming more widely available. However, these networks are particularly inefficient in situations where content sharing nodes are isolated from each other [CH11].

In a future Internet the user experience could strongly benefit from changes in the paradigm of content distribution. Such changes could include caching contents closer to the end users; dynamic content interactively or automatically adapted according to the users' needs and terminal nodes (not only considering the network structure); content aware routers and optimized routing paths (according to bandwidth, latency, etc.). Focusing on a paradigm change from host-centric to content-centric networks, several architectures can be defined in which routing plays an important role.

A common design for content-centric routing addresses publisher/subscriber systems where content is addressable by an identifier that is handled by a naming system. The desired content by a user may be found at several levels of the network hierarchy, and it will be retrieved when found, from a cache or from the server. Content-centric approaches such as PSIRP (Publish Subscribe Internet Routing Paradigm) [GM11] and DONA (Data Oriented Network Architecture) [KC07] follow a different naming approach, using cryptographic fingerprints computed over pieces of content. To realize these content centric approaches, existing routers must be adapted into content-aware routers, taking into account not only content requests but also caching according to pre-defined strategies [AN10]. Moreover, routing strategies should include retrieving the desired data from the most suitable source, or even retrieving different data pieces from multiple sources.

Taking into account the above mentioned details, routing in future content/information-centric networks will have to consider the existing caching mechanisms and the used storage & search approach, so that users' requirements may be met in such heterogeneous networks, being able to correctly route and transport the existing data.

3.2 Name resolution and data transport

Information-Centric Network (ICN) architectures depart from the current Internet's host-centric end-to-end communication paradigm, and adopt an information (or content) centric communication paradigm where information objects, rather than host end-points, are named. Subscribers request information objects by their names, and the network is responsible for locating the publishers of the information objects and transporting them from the publishers to the subscribers. Three key functions of Information-Centric Networks are the following:

- Name resolution: This involves resolving (or matching) the name of an information object with its location or the publisher of the information object. Name resolution is performed by the Name Resolution System. The name resolution system can have a hierarchical structure: subscribers and publishers communication with a local name resolution server, which in turn communicates with other name resolution servers.
- Topology management/routing: This functionality involves determining a path from the publisher to the subscriber. Different domains can implement different topology management and routing procedures and, similar to the name resolution system, topology management can be performed in a hierarchical manner.
- Forwarding: Forwarding involves moving information from the publishers to the subscriber along the determined path. Possible forwarding mechanisms include hop-by-hop forwarding based end-system ids, label switching, and forwarding based on a series of link identifiers selected by the source.

Different ICN proposals involve a different degree of coupling between name resolution and routing/forwarding. At one extreme (tight coupling), the same nodes perform both functions in an integrated manner. This is the approach followed by CCN/NDN [J++09][NDN]: Receivers express their request for content using Interest packets. Interest packets are routed based on the name of the requested content, using longest prefix matching, either to the node that contains a data packet with the requested name or to an intermediate node that has cached the requested data packet. Once the data packet is found, it is returned to the requester following the reverse path of the Interest packet. At the other extreme (decoupled), the functions are implemented in different nodes and/or different modules. This is the approach followed by architectures such as PSIRP/PURSUIT's PSI (Publish-Subscribe Internet) [N++10][PURSUIT] and 4ward/SAIL's NetInf architecture [A++11][SAIL]. With such an approach the name resolution system is independent of the routing/forward network that transports content from the publisher to the subscriber. Proposals such as DONA [C++07] and COMET [C++11] propose overlay solutions that run on top of an IP infrastructure, hence inherent IP's routing and forwarding functionality.

Decoupling the resolution and routing/forwarding functions allows more flexibility in where and which entities implement this functionality. This flexibility can allow different or existing mechanisms, e.g., for routing and forwarding, to be used in different domains that have specific characteristics or restrictions, such as satellite networks or home networks. Decoupling allows usage of different paths for control traffic and data traffic, with the latter exploiting multiple paths from an information publisher to a subscriber. Another property with decoupling name resolution and routing/forwarding is that the resolution layer can employ a receiver-driven (pull-based) communication mode, whereas the routing/forwarding layer can employ either a receiver-driven (pull-based) or sender-driven (push-based) communication mode; this, for example, allows a receiver to declare (through a subscription message) his interest in receiving future content related to some content category. Once the publishers (senders) creates such content, they can send it (push-based) to the receiver without require requests for each individual content. On the other hand, when resolution and routing/forwarding are coupled, then implementation of sender-driven (push-based) functionality requires either overlay solutions to inform receivers of the availability of content, or polling-based solutions where the receivers periodically poll the senders for new content.

It is interesting to note that for architectures that employ a similar level of coupling between name resolution, topology control/routing, and forwarding, the same mechanisms and algorithms can be implemented for the same functionality.

3.3 Routing and mobility in content-based publish/subscribe systems

In this section we focus on state-of-the-art routing algorithms in distributed publish/subscribe systems and discuss how mobility influences such algorithms. The architecture of publish/subscribe systems is composed of nodes that actively participate in content generation, dissemination, and delivery such that there is no need for central coordination. In other words, each node takes the role of content publisher, subscriber, and broker. In distributed publish/subscribe systems, all nodes coordinate their actions to achieve a common goal, and that is to provide the publish/subscribe service both to themselves and to other nodes in the system.

The core mechanism behind a distributed publish/subscribe service is routing of publications and subscriptions among the nodes in an overlay network. The main issue with routing algorithms is their scalability, which requires careful balancing the number of propagated messages in an overlay network as well as the amount of stored routing information at overlay nodes. The routing information is maintained by all nodes using routing tables which map node identifiers (usually identifiers of their neighbouring nodes) to subscriptions received from these nodes.

[BQTV09] classifies routing strategies in distributed publish/subscribe systems into the following categories: flooding, selective routing, and gossiping.

Flooding can be implemented as either **subscription** or **publication flooding**. This type of routing causes large message overhead since the overlay network is frequently flooded by messages containing either subscriptions or publications.

Selective routing is further classified as covering-based (the publish/subscribe architecture model from [BQTV09] considers filtering-based instead of covering-based routing. However, covering-based routing is an advanced version of filtering-based routing, and is more often used in practice) and rendezvous routing. This type of routing tries to reduce message overhead in an overlay network as much as possible. Selective routing is based on the following two observations: 1) subscribers are usually interested in a small portion of published publications and 2) subscriber interests usually overlap. When this is not true, selective routing leads to flooding of an overlay network with either subscriptions or publications.

Gossiping algorithms used in unstructured peer-to-peer overlay networks can further be categorized as basic gossiping, which is purely probabilistic, and informed gossiping, which is partially probabilistic and partially deterministic. These strategies are best suited to systems with a high churn rate, i.e., with a highly-dynamic peer-to-peer network topology, to improve the reliability of publication delivery.

In a distributed publish/subscribe system with **publication flooding**, subscriptions are stored at subscriber nodes and are therefore not propagated further into the overlay network. When a publication is published, the overlay network is completely flooded with it. Upon receiving a newly published content, each node first forwards this publication to its neighbours, i.e., further into the overlay network, and then checks if the publication matches any of its own subscriptions. Obviously, this strategy is best suited to situations when the majority of nodes is interested in most of the published publications. However, if the number of publishers or publishing rate is high, the overlay network is overloaded with flooded publications.

In a distributed publish/subscribe system with **subscription flooding**, the overlay network is flooded with every new subscription activation or cancellation. In this routing strategy, publishers match publications they publish against all active subscriptions in the system. Besides that, they are responsible for direct forwarding (i.e., using a network layer protocol) of matching publications to subscribers. This strategy is best suited to environments that share the processing load in situations where the majority of nodes are also publishers. However, if the frequency of subscription updates is large, the overlay network is overloaded with subscription updates.

Covering-based routing in distributed publish/subscribe systems is an extension of subscription flooding, which tries to reduce the number of propagated proxy subscriptions by relying on the coverage property between subscriptions. A subscription is covered by another subscription if every publication that matches the covered subscription also matches the covering subscription, while the opposite does not hold. In case the interests of subscribers do not overlap, this strategy is reduced to subscription flooding and the overlay network is overloaded with subscription updates.

With covering-based routing, a subscription is propagated further through an overlay network only if it is not covered by a previously propagated and still active subscription. Otherwise, a processing node stores it in the list of covered subscriptions, and stops its further propagation. Additionally, processing nodes maintain routing tables mapping identifiers of their neighbours to all uncovered proxy subscriptions received from them. A new publication is matched to proxy subscriptions at all nodes on the reverse path from the publisher to the subscriber. In other words, the publisher forwards this publication to those neighbours from which it has previously received matching proxy subscriptions, and each of the neighbours repeats the process and forwards the publication to its neighbours with matching subscriptions. The process stops when there are no matching subscriptions stored at a node.

In every distributed publish/subscribe system with **rendezvous routing**, the following two methods exists: 1) a method that maps each subscription to a rendezvous node and 2) a method that maps each publication to a rendezvous node. Such a mapping is usually achieved by dividing the attribute space into a finite number of subspaces, and then by assigning each subspace to a different rendezvous node. In this way publications matching a subscription are mapped (assigned) to the same rendezvous node as subscription. Both mapping methods are typically implemented on top of a structured peer-to-peer network, which is then responsible for routing of publications and subscriptions to nodes to which they are mapped.

When a new subscription is activated, the subscriber node forwards the subscription augmented by its identifier to the subscription's rendezvous node. Similarly, when a publication is published, the publisher forwards the publication through the overlay to the publication's rendezvous node. When a rendezvous node receives an incoming publication, it matches the publication to previously received subscriptions. In this way, each rendezvous node takes responsibility for storing of subscriptions that are mapped to it and matching of them with incoming publications that are also mapped to it. In addition, it is also responsible to deliver matching publications to their subscribers directly (i.e., using a network layer protocol). This strategy is best suited to situations when we want to balance the processing and memory load among overlay nodes. Additionally, when this routing strategy is used, no redundant matching needs be performed in the system, which is a big advantage compared to covering-based routing.

Basic gossiping, as a routing strategy in distributed publish/subscribe systems, is similar to publication flooding since subscriptions are stored at subscriber nodes and are not propagated further into the overlay network. When a publication is published, it is randomly spread through an overlay network as a gossip. More precisely, in each round of publication spreading, one or a few nodes that have received this publication previously, spread it further to some other neighbours chosen at random. Upon receiving a newly published publication, a node matches the publication against its own subscriptions, and after that randomly chooses one or a few of its neighbours and forwards the publication to them. Publication spreading through an overlay network stops after a predefined number of rounds. This routing algorithm is probabilistic and thus does not guarantee publication delivery to all interested subscribers.

Informed gossiping is similar to basic gossiping since both strategies are probabilistic. For both routing strategies, nodes store their own subscriptions, but in case of informed gossiping each node additionally stores subscriptions of its close neighbours. In addition to matching of an incoming publication to its own subscriptions, each node also processes the subscriptions of its neighbours. This is the deterministic part of publication spreading which is followed by the probabilistic part when the node forwards the publication to a randomly chosen set of its neighbours. Similar to basic gossiping, the spreading of a publication through the overlay network stops after a selected number of probabilistic rounds. Therefore, while basic gossiping is purely probabilistic, informed gossiping is partially probabilistic and partially deterministic, and the probability of successful delivery of a publication to subscribers is increased when compared to basic gossiping.

The traditional publish/subscribe systems commonly support the following messages: *publish*, *subscribe* and *notify*. When used in mobile settings, the set of messages needs to be extended with following: *connect* and *disconnect* which enable nodes to create new connections and destroy existing ones [PL04]. Additionally, the publish/subscribe system needs to cache published content such that it can be delivered to temporally disconnected subscribers.

There are two possible approaches to caching published content. The first approach which we call the queuing approach stores publications in special queues during subscriber disconnections [CMP06]. The second approach is based on publication persistency and caches the published content on nodes which it traverses [PL04]. When a subscriber reconnects to the system, it reactivates its subscriptions and therefore receives valid stored publications from neighbouring nodes. The second approach is an extension of the subscribe-unsubscribe-subscribe procedure that does not modify the applied routing algorithm. Here we shortly list the extensions of routing algorithms for mobility:

- When a broker receives a *publish* message, it first stores the publication in a local container, and subsequently delivers it to interested subscribers and neighbouring nodes. The broker removes the notification from the container when its validity period expires, and maintains a list of valid publication ids that have been sent to subscribers and other nodes.

- When a broker receives a *subscribe* message, either from a subscriber, or a neighbouring node, it checks the list of persistent publications and delivers a matching valid and previously undelivered publication to the subscriber, or the neighbouring node.
- When a broker receives a *connect* message from a subscriber, it activates the subscriber's subscriptions. The subscriber must provide a list of active subscriptions.
- When a broker receives a *disconnect* message from a subscriber, it deactivates the existing subscriber subscriptions, and terminates delivery paths in the network.

3.4 Coupled ICN in mobile environments

Mobile networks are diverse with respect to size, node mobility and network density. Depending on the characteristics and scenarios, different forwarding strategies may be applied, e.g., multi-hop or single-hop and unicast or broadcast communication.

In opportunistic and delay-tolerant systems such as PodNet [LK07], the communication is based on direct one-hop communication between neighbouring nodes. Routing is replaced by the replication of information and the mobility of the nodes. Different replication strategies can be found in literature, such as epidemic routing with and without constraints, e.g., [VB00], [SP05] or probabilistic routing with history information, e.g., [LD03].

Although these approaches work well in sparse environments, they are inefficient in dense mobile environments. Content-centric networking (CCN), e.g., [J++09], is a promising coupled ICN approach for (mobile / multi-hop) communication. Content is forwarded based on content names instead of host identifiers. Instead of trying to reach specific nodes that may move away, the user broadcasts request to receive content objects from any nodes in the vicinity. Likewise, content sources may transmit content objects at the same time to multiple requesters without additional costs.

Given a known content name the user has to discover an available content source, which is equivalent to routing interest messages. The content will travel the reverse path back to the requester. In [VR11] different routing strategies are considered for CCN. The authors conclude that structured solutions such as geographic hash tables may only be used in networks without host churn whereas unstructured flooding is beneficial in small networks with high host churn to limit the propagation.

While broadcasting and flooding may support flexible mobile communication, it may also introduce the broadcast storm [TN99] problem. Therefore, suppression mechanisms are required to limit the forwarding of messages minimizing the number of transmitted duplicates and collisions resulting from broadcast requests.

The Listen-First-Broadcast-Later (LFBL) [MP10] algorithm limits forwarding of interest messages at every node based on its relative distance to the content source. Additional header fields indicate the relative hop distance from the previous forwarder to the destination. Messages are only forwarded by nodes closer to the destination than the previous forwarder. Although this approach may limit forwarding of certain messages, relative hop distance information may yield very imprecise information in dense environments, particularly, if messages are transmitted from the cache. Other approaches target probabilistic forwarding or suppression by overhearing and analysing the number of duplicates received in the same time period.

Network coding may additionally increase the reliability and the throughput of mobile CCN communication [MW12] avoiding duplicate transmission by re-encoding packets at every hop. On the downside, this approach may result in increased processing overhead and transmission delays.

The wireless multi-hop communication is also challenging due to shared physical medium access and omni-directional signal propagation. Even with unicast multi-hop communication the throughput decreases with the number of n hops by at least 1/n [HA07]. By using broadcast communication and in dense environments, the throughput is expected to degrade even more due to higher collision probabilities and longer transmission delays. Therefore, it may be beneficial to limit the propagation of messages and adaptively identify the nearest content source to ensure a certain QoS.

Content discovery is applied to identify available content names in the vicinity prior to data transfers. Content or service discovery in information/content-centric networks may be divided into directory-based and directory-less approaches. A directory is a public entity that stores information about all content or services in the network. Centralized or distributed directory-based approaches may be applied. Centralized approaches are based on the existence of one or multiple directory servers that store all information in the network. Content providers advertise their information to these public directories to enable content discovery by other nodes. Due to required directory reachability and scalability, central approaches may not be well suited for mobile ad hoc networks.

A directory is a public entity that stores information about all content or services in the network. Centralized or distributed directory-based approaches may be applied. Centralized approaches are based on the existence of one or multiple directory servers that store all information in the network which depend on the supporting infrastructure. Content providers advertise their information to these public directories to enable content discovery by other nodes. Due to required directory reachability and scalability, central approaches may not be well suited for mobile ad hoc networks.

Directory-less approaches may be categorized in proactive discovery and reactive discovery. In reactive discovery, the discovering nodes flood all requests on demand based on specific forwarding strategies. This is an implicit discovery strategy since content information is only returned if found. In proactive discovery users may request or overhear available content names in the entire network or in parts of it, and store them in a local registry. Accumulated content information may be additionally announced by content publishers to neighbour nodes.

There is a rich set of literature for service discovery in Mobile Ad-hoc Networks (MANETs) or Delay-/Disruption-Tolerant Networks (DTNs). Similar to these existing works, CCN discovery may exploit Bloom Filters [LK07] or attenuated Bloom Filters [LH07] to increase the discovery efficiency. Another approach to discover new content objects and differences in content collections may be based on the Difference Digest [EG11].

3.5 Service-Centric Networking

In this section, we propose and discuss the generalization of content-centric networks to service-centric networks. Users may ask the environment to receive individual and potentially location-dependent services such as content mash-ups and media conversion services. Other examples of such services are filtering services in collaborative sensing or presence services as presented in Section 2.

Content-centric networking can be enhanced to support such more general services. Service-Centric Networking (SCN) has been proposed in [BH+11]. In SCN, data is not just retrieved, but can be processed (by any network node) before being presented to the user. Names should not only be used for content but also for services to be invoked. SCN achieves uniform naming of services and content by using an object-oriented approach introducing object names for both services and content. SCN leverages the concept of Interest and Data messages as defined by an underlying ICN infrastructure such as CCN/CCNx [J++09]; a client sends Interest messages for services to be invoked and the results from service execution are returned in Data messages. The underlying ICN infrastructure should support name-based routing of Interest messages as well as routing of Data. SCN provides several advantages:

While in traditional (web) service scenarios, services must be registered by the web service provider at a registry and must be looked up by the client before the service is invoked, service registration is replaced in SCN by announcing service availability in the underlying ICN infrastructure, e.g., in the CCN routing tables. This results in a lower delay and avoids relying on an additional registry component. When invoking a service, no specific server needs to be addressed, but rather the service specified by its name. The ICN infrastructure should then automatically route the service request encoded in an Interest message to the closest server supporting this service.

SCN leverages the features of the underlying ICN infrastructure such as CCN. Thus, routers can cache data resulting from service calls and provide these data on subsequent requests. Although the benefits of caching are reduced for personalized services (e.g., commercial transactions), caching significantly reduces network traffic and response times for popular content and services. We further propose advanced caching mechanisms, where cached data can not only be retrieved from the cache, but also processed prior to transmission, e.g., in case of transcoding multimedia content.

In particular, caching is beneficial in case of mobility. Mobile users might request data or services when being mobile. This data might be stored in the network only, e.g., in case of cloud applications, and cached at network elements close to the user. After changing network access, users might request personal data again, with a high chance of being still cached close to the user.

Traditional location-based services work as follows: 1) the client contacts a (central) server, 2) the position of the client is determined, 3) the closest server is detected, and 4) the service request is redirected to the closest server. In SCN, location-based services can be easily built by deploying service entities at various locations and populating routing entries appropriately. Then, service requests (mapped to CCN Interest messages) are routed to the closest (typically the local) server for processing the request independent of user locations.

SCN service requests are sent by the client to the network using an object name identifying the service. With the help of the underlying ICN infrastructure, the request is routed to the most appropriate location. Optimizations can consider the distance between client and server or between server and data, etc. Therefore, a new instance of the service can be started on a resource close to the user that invokes the service or close to the content data. Another option is to automatically deploy services on routers that previously received many service requests.

SCN could be useful for a variety of services such as file storage and retrieval, audio/video streaming and recording, processing of stored images and video, e-Commerce applications like ticket ordering, e-banking, on-line shopping, location- based services (gas, food, travel, weather, events etc.), cloud computing, e.g., to instantiate virtual machines and data bases as well as telecommunication services, e.g., signalling functions using distributed data bases.

SCN proposes to extend routers / ICN network elements by additional content processing functions. A service entity could collect presence information and inform users about desired events accordingly. The presence service discussed in Section 2.4 is an example that can be implemented and combined with the SCN approach discussed above. Moreover, filtering service for collaborative sensing can be deployed in a service-centric network.

3.6 Content sharing in opportunistic networks

This subsection presents an overview of the approaches proposed for content dissemination in opportunistic networks by categorizing them based on the specific problem targeted and the adopted technical approach. The main categories considered in this subsection include social-based schemes, publish/subscribe and unstructured peer-to-peer (P2P) systems, and infrastructure-based approaches. Most relevant examples for each category will be also discussed with a special focus on social-based schemes, such as ContentPlace.

PodNet and Content-centric strategies

Initial research efforts on content dissemination in opportunistic networks were made within the PodNet project. The PodNet Project [PodNet] was the first initiative to explicitly address the problem of disseminating content in a network made up of users' mobile devices in an opportunistic fashion. Within the PodNet project, *heuristics were defined in order to drive the selection of content items to be cached based on the popularity of the content itself*. Such heuristics enforced a cooperative caching among nodes and were shown to clearly outperform the simple strategy in which each node only keeps the content it is directly interested in. The main limitation of PodNet is that the policies that it defines only focus on one of the two actors of content dissemination, i.e., on the content itself. Each policy, in fact, is exclusively a function of the popularity of the channel and individual user preferences or different user capabilities to disseminate messages are not considered at all. These strategies might work when users are well mixed and homogeneous, and items can easily travel from one side of the other of the network. However, when node movements are heterogeneous and communities of nodes tend to cluster together, this approach can be quite limited [BCP10].

Social-aware schemes

To overcome the limitation of pure content-centric dissemination a category of proposed solutions focuses on the definition of more elaborate heuristics that could exploit user diversity and the social characteristics of user behaviour. In this case, *heuristics are proposed that take into account the social dimension of users*, i.e., the fact that people belonging to the same community tend to spend significant time together and to be willing to cooperate with each other. The ContentPlace [BCP10] dissemination scheme is one of the first fully-fledged solutions to incorporate the idea of communities with a systematic approach to data dissemination. ContentPlace assumes that people movements are governed by their social relationships, and by the fact that communities are also bound to particular places (i.e., the community of office colleagues is bound to the office location). Therefore, users will spend their time in the places to which their home communities are bound, and will also visit places of acquainted communities. Different communities will have, in general, different interests. Therefore, the utility of the same data object will be different for different communities. Given that communities represent the sets of nodes with which the user interacts most, intuitively, caching items that are popular within these communities will increase the probability that such items will be actually delivered to people that are interested in them. Social-aware content dissemination generally results in a quicker and fairer content dissemination with respect to social-oblivious policies [BCP10]. In addition, social-aware dissemination heuristics often (as in the case of ContentPlace) do not make any assumption on the characteristics of the underlying contact process or on the distribution of content popularity. They directly learn this information using online estimation. This implies that social-aware content dissemination strategies are expected to be resilient to mobility and content popularity changes. The main drawback of this class of heuristic-based content dissemination policies lies in the overhead they introduce for collecting and managing the information on which the heuristic reasoning is based.

PUBLISH/SUBSCRIBE schemes

An alternative category of content dissemination approaches brings the ideas of *publish/subscribe overlays* into the realm of opportunistic networks. Publish/subscribe systems are based on content-centric overlays in which broker nodes bring together the needs of both content publishers and subscribers by matching the content generated by publishers with the interests of subscribers and by delivering the content to them. Keeping publishers and subscribers decoupled is of great importance in opportunistic networks, since they might be seldom connected at the same time to a stable network. How the publish/subscribe ideas can be adapted to an opportunistic environment is well exemplified by [Y++07], in which the pub/sub overlay is built exploiting the knowledge on the social behaviour of users. More specifically, the main idea is that nodes belonging to the same social community spend significant time together, and thus, for each community, a broker node is selected as the node that can reach most easily all other nodes in the community. As in the case of social-aware dissemination schemes, the main drawback here lies in the overhead required for rotation of broker functionalities, broker election, subscription collection, and information unsubscription.

Global Optimization

A third category focuses on finding a *global, optimal solution to the content dissemination problem*, unlike heuristic approaches that focus on local optimization problems. Such a global solution, typically unfeasible for practice, real scenarios, is then approximated using a local, distributed strategy. The idea here is to define a global utility function and to solve a global optimization problem as if nodes' caches were a big, cumulative caching space. Typically, protocols belonging to this class focus less on the specific definition of the utility function, while devoting great attention to the global optimization problem, and to how to translate such centralized optimization problem into a distributed one. To the best of our knowledge, the work in [RC09] has been the first to provide a comprehensive analysis of a global optimization problem applied to content dissemination in opportunistic networks. The main contribution of the body of works focusing on global optimization is the formalization, using a rigorous mathematical framework, of the content dissemination process. Thanks to this approach, if a solution to the optimization problem can be found, then such a solution is guaranteed to be optimal, or close to. Differently, with heuristic content dissemination schemes it is not clear to which extent they can be outperformed by other strategies or how far from optimal they are. On the downside, two are the main drawbacks of this approach. First, global optimization requires global knowledge of the network and a priori information on how users behave (e.g., their preferences for content and their movements) that in practice is very unlikely to be available. Second, modelling techniques required to formalize and analytically solve the content dissemination problem usually imply reducing the complexity of the system under study. If the simplifying assumptions are embedded into the content dissemination problem, there might be the case that the proposed solution is not optimal when applied to real scenarios, as happens in [RC09].

Infrastructure-based approaches

More recently a new category of content dissemination solutions has emerged, which is characterized by the *exploitation of a broadband wireless infrastructure in conjunction with the opportunistic network of user devices*. The idea here is to partially relieve the burden of disseminating content from the infrastructure by exploiting opportunistic content dissemination among users. One of the best representatives for this strategy is the work in [5], which proposes a tight interaction between the infrastructure and the opportunistic network. Conceptually, the approach is based on the idea of *offloading* part of the dissemination process from the operator infrastructure to the opportunistic network formed by the user devices. The scenario is that of a very large number of users located in a relatively small region (e.g., a campus, a city, the location of a very popular event, etc.), who are interested in the same content items. According to a traditional “operator-exclusive” approach, the content items are sent from the operator to each individual user through the wireless infrastructure. Each user thus generates a load on the operator infrastructure equal to the bandwidth required to download the content items. It is argued that, due to the proliferation of high-end mobile devices and the bandwidth requirements of multimedia services, that this will not scale, and that the capacity of the operator infrastructures will not keep the pace. On the other hand, according to a purely opportunistic approach, content items must be available at some user nodes, and is then disseminated through one of the schemes described in this section. While such an approach is certainly valid for content items generated by users themselves, an integration between the operator-exclusive and the purely opportunistic approach brings significant advantages when content is produced by some provider, and disseminated to a large set of users subscribed to an operator network. Scalability is the main open point of this approach, due to the high density that can be reached for both users and content items.

Approaches inspired by unstructured P2P systems

Finally, the last category we have identified in the literature includes proposals that tackle the dissemination problem using an analogy with unstructured P2P systems. To the best of our knowledge, [Z++11] is one of the most significant works in this area, which formulates the dissemination problem by means of P2P universal swarms and to provide solid theoretical results regarding the advantage of cooperative strategies against greedy approaches. The main contribution of [BCP10] actually lies more in deriving strong theoretical results than in proposing particularly novel algorithms for data dissemination. Specifically, the authors derive the conditions under which the data dissemination process is stable, i.e., all users are able to receive the content items they are interested into. They formally prove that cooperation between users, i.e., the fact that users cache on each other's behalf content items they are not personally interested in, significantly extends the stability conditions. Furthermore, they derive optimal caching policies that - under stable conditions - minimize the time required for each user to receive what they are interested into. As in the case of dissemination strategies based on global optimization, the main drawback of this approach lies in the simplifying assumptions that are required in order to derive the theoretical results.

The mentioned opportunistic routing schemes make forwarding decisions based on locally collected knowledge about node behaviour to predict which nodes are likely to deliver content or bring it closer to the destination. There are a number of proposals for opportunistic routing in Delay/Disruption Tolerant Networks (DTN), each with a different goal and based on different evaluation criteria. The work of [MM11] presents a study of classification and evaluation methods to characterise, analyse and compare existing and future proposals for opportunistic routing in DTNs.

Given that opportunistic networks are intrinsically networks of *people,* the social aspects of communications should never be overlooked when designing content dissemination strategies. For this reason, we believe that social-awareness should be a key feature of all content dissemination strategies that will be designed in the future. Moreover, the added value of opportunistic networks is that they are not only a standalone Future Internet environment, but they can also be exploited in order to complement and enhance the functionalities of traditional infrastructure-based networks, as we have seen for the fourth category of dissemination protocols described above. We reckon that this synergy will lead the way towards innovative and cooperative content dissemination strategies, from which both users and providers will benefit.

In order to support social-awareness for content dissemination strategies in opportunistic networks, a recent trend is looking at social structures, inferred from the social nature of human mobility, to bring messages close to a destination. To have a better picture of social structures, social-based opportunistic routing solutions should consider the dynamism of users' behaviour resulting from their daily routines. One example is the dLife [MMS12] proposal, a routing algorithm able to capture the dynamics of the network represented by time-evolving social ties between pair of nodes, addresses this challenge.

Since social information is quite useful to aid data forwarding in opportunistic networks, dLife combines two novel utility functions based on the notion of Time-Evolving Contact Duration [MSMS12] to derive, from users' social daily routines, the social strength among users and their importance. Experimental results based on synthetic mobility models and real human traces show that, by incorporating the dynamism of users' social daily behaviour in opportunistic routing, wiser forwarding decisions are performed leading to better delivery probability, cost and latency than proposals based only on social structures, i.e., Bubble Rap [HCY11].

3.6 In-network caching self-organization

One of the features of an information-centric architecture is to consider the existence of caches within the network. These caches can be implemented in different ways, e.g., it is possible to consider the existence of a cache in every node of the network or only in specific nodes, but its importance is unquestionable. Caches contribute to load balancing traffic and reduce perceived latencies, since the information comes from a near location, assist systems to be more fault-tolerant and helps to reduce exploration and usage costs. However, it was not considered as part of the network model. Taking in account the scenario of opportunistic networks, such as the ones encompassing mobile sensing devices, we need to add, to the list of desired properties of the cache system, the absence of any central coordination and the existence of some algorithm to detect communities that share some kind of interests (e.g., usage patterns for content objects). This means that the system needs to be self-organizing in order to know what content to cache and where to cache it.

Hence, we envision that the control of in-network caching systems, aiming to support information-centric networking, will rely on the following major properties: self-organization to detect similarities needed to infer data needs in real-time; cache synchronization to mitigate the problems of local caching rules; scalable communication among caching system to support cooperation; distributed cache placement/activation.

The concept of self-organization has been applied in several forms, with very different meanings and to solve many different problems [BG09]. Zhenping Li et al [LWZC10] proposed an adaptation of a self-organizing map (SOM) to community detection (detection of similarities). A SOM is a type of artificial neural network that is trained using unsupervised learning. Network communities can be qualitatively described as graphs that represent the density of network nodes. A SOM represents topographic organizations in which nearby locations in the map represent inputs with similar properties. Authors validated the proposed algorithm using benchmark computer generated networks and several social based networks. The results show the scalability of the proposed method, its accuracy (close to 100%) and that the algorithm can successfully identify communities independently of their size and heterogeneity. However, the number of communities must be defined, instead of emerged from the network itself, which means that its application in very dynamic networks can be problematic.

Besides the detection of similarities in a self-organized in-network caching system, it is important to emphasize the need to have a network in which all nodes have an accurate view of the overall system. To mitigate the potential lack of accuracy due to an ineffective acquisition phase, A. Tyrrell et al. [TAB10] proposed to integrate synchronization into the communication phase. The proposed Meshed Emergent Firefly Synchronization (MEMFIS) model is based on the Mirollo and Strogatz [RS90] mathematical model for firefly synchronization (MS model). MEMFIS relies on the detection of a synchronization word common to all nodes, which is embedded into each packet along with payload data. The detected timings of received synchronization words serve as input to the slot synchronization algorithm, which is placed on the physical layer and based on the MS model. MEMFIS is not a synchronization protocol exchanging explicit timing information in the form of time stamps. From the Medium Access Control (MAC) layer point of view, slot synchronization emerges while nodes transmit data. Apart from the insertion of the synchronization word, which anyhow is required to decode payload data, no additional overhead or signalling between nodes is required. The performance of MEMFIS is evaluated against three key requirements: the scalability with respect to the network size, the adaptability with respect to different network topologies, and the robustness in case of unreliable detection of synchronization words. Authors have evaluated MEMFIS in a simulated environment and concluded that synchronization emerges faster and with low signalling overhead. Nevertheless, MEMFIS needs to be studied and validated in more dynamic environments like opportunistic networks. Although the proposed algorithm is very focused on wireless slot synchronization, the Mirollo and Strogatz model may be of interest when applied to allow the synchronization of the caches.

The communication among nodes in a self-organizing system may be supported by a Peer-to-Peer system (P2P). However, P2P systems suffer with the dynamic behaviour of nodes. Structured P2P systems may be difficult to administer in the case of high churn rate, because new or modified resources must be immediately (re)assigned to the corresponding peers. Recently the trend is to investigate “self-structured” P2P systems. These are called self-structured because the association of descriptors to hosts is not pre-determined but adapts to the modification of the environment. A. Forestiero et al. [BAH10] presented a P2P system, called Self-Chord, that inherits from Chord the ability to construct and maintain a structured ring of peers, but features enhanced functionalities achieved through the activity of ant-inspired mobile agents. While in Chord, ordering is the outcome of a global planning, in Self-Chord it is obtained by the operations of ant-inspired agents that move the resource keys across the ring. These agents do not operate forever, but are generated and die as the ants to which they are inspired.

The problem of placing caches closer to the end user is not a new problem and has already been subject of study although not in the same way that is consider in this work. For instance, S. Bhattacharjee et al. [BCZ98] presented a study that highlighted the benefits of associating caches with switching nodes throughout the network, rather than in a few hand-chosen locations. Authors also considered the use of various self-organizing or active cache management strategies, in which nodes make globally consistent decisions about whether or not to cache an item in order to reduce overall latency.

A more recent trend relies on the creation of cache systems based on peer-to-peer networks. In [IRD02], the authors presented Squirrel, a decentralized peer-to-peer web cache. Web caches are often deployed on dedicated machines at the boundary of corporate networks, and at Internet service providers. The key idea in Squirrel is to allow client desktop machines cooperating in a peer-to-peer fashion to provide the functionality of a web cache. Currently, web browsers on every node maintain a local cache of web objects recently accessed by the browser. Squirrel enables these nodes to export their local caches to other nodes in the corporate network, thus synthesizing a large shared virtual web cache. That way, each node performs web browsing and web caching. Squirrel uses a self-organizing, peer-to-peer routing substrate called Pastry as its object location service, to identify and route to nodes that cache copies of a requested object. Squirrel thus has the advantage of requiring almost no administration, compared to conventional cooperative caching schemes. Moreover, Pastry is resilient to concurrent node failures, and so is Squirrel. Upon failure of multiple nodes, Squirrel only has to re-fetch a small fraction of cached objects from the original web server. Authors conducted the tests based on web trace data and showed that Squirrel is feasible, efficient, and comparable in performance to a dedicated web cache in terms of latency, external bandwidth and hit ratio. At the same time, Squirrel has the advantages of being inexpensive, highly scalable, and resilient to node failures. Moreover, it requires little administration. Nevertheless, there are some factors that can degrade the performance, such as the existence of popular content in a given area, which place pressure on certain nodes, and geographically distributed Squirrel networks with higher internal latency.

Considering more dynamic scenarios, the work of M.Legény et al. [LB11] is a good example, where authors used a cache system, in which nodes maintain the topology of their vicinity, in order to reduce the communication overhead in a fully distributed, dynamic self-organizing network and keep this data structure up-to-date throughout minor and rapid changes in the network. Their work focuses on biologically inspired, fully distributed self-organization algorithms for large overlay networks, with an emphasis on clustering and load balancing. For clustering purposes the authors choose a family of algorithms called On-Demand Clustering (ODC), more specifically the Spyglass algorithm [LB10]. It has been shown that ODC results in emergent self-organization behaviour, i.e., clusters are formed and expanded when local demand for that rises. Authors used a model where a load-balancing problem generates the demand for the clustering. Regarding the caching strategies authors consider: No caching; Reference algorithm; Static pre-caching; On demand cache. Authors tested the cache strategies (No Cache; On Demand Cache; On Demand Cache with Pre-Caching; Random Cache; Size Sensitive Random cache; Success Based cache; Change Based cache; Type Sensitive Change Based Cache) with a focus on the communication overhead and the clustering/load balancing performance. The results are not very conclusive because they showed that some cache strategies are more suitable than the others, depending of the evaluation criteria and the scenario. Despite that, all examined smart caching strategies beat the reference algorithms in terms of overall performance. Moreover, experiments pointed out that fast topology change naturally stimulates self-organization, i.e., tends to bring matching, and not overloaded nodes into the direct neighbourhood at no cost, resulting in possibly smaller clusters but better overall load-balancing and job processing curves. Despite the fact that this work has not been directly applied in opportunistic networks and it does not consider information centric concepts, it gives good indications in terms of key areas: caching, self-organization and clustering.

In [MB11] authors proposed MIX, a cooperative caching system to improve data availability in mobile information systems. Authors assumed that the cooperative caching architecture has only one server, also called the base station (BS), and many mobile users (MU). The communication between the BS and MUs is a wireless link. MU is the mobile device used to send requests to a server and it can move freely in a cell or from a cell to another cell. Each MU has a service zone in which they can communicate with others. The connection among MUs is a wireless P2P network. The conducted tests were focused on cache discovery cache admission and cache replacement and showed that MIX improved data availability and access performance. Cache hit ratio achieved 70%. Although authors did not prove the scalability of the model, they did not address the problem of cache consistency and they considered the existence of good connectivity in the vicinity of the nodes (in disruptive scenarios the algorithm may not be adequate). The article enforces the importance of caching in mobile environments as an effective way of reduce latencies, and improve data availability.

4. Conclusions

The goal of this white paper is to describe representative usage scenarios and their corresponding requirements, state-of-the-art technological solutions, and open research directions for key functionalities related to content-centric architectures for networks of moving objects. The usage scenarios presented include smart transport, data dissemination in partially connected environments, collaborative sensing, and situation and presence-aware services. The functionalities discussed include name resolution, routing, forwarding, discovery, content sharing, and the generalization of content-centric networking to service-centric networking.

5. References

[AN10] Somaya Arianfar, Pekka Nikander, and Jorg Ott, “On content-centric router design and implications”. In *Proceedings of the Re-Architecting the Internet Workshop* (ReARCH '10). ACM, New York, NY, USA, Article 5 , 6 pages. DOI=10.1145/1921233.1921240 http://doi.acm.org/10.1145/1921233.1921240

[A++11] Bengt Ahlgren et al., “Content, Connectivity, and Cloud: Ingredients for the Network of the Future,” IEEE Communications Magazine, vol. 49, no. 7, pp. 62–70, July 2011.

[BAH10] Brocco, Amos and Malatras, Apostolos and Hirsbrunner, Béat, "Enabling efficient information discovery in a self-structured grid", Future Gener. Comput. Syst. 26 (2010), pp. 838--846.

[BCZ98] Bhattacharjee, S. and Calvert, K.L. and Zegura, E.W., "Self-organizing wide-area network caches", in INFOCOM. Seventeenth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE vol. 2, (, 1998), pp. 600 - 608.

[BG09] Berns, Andrew and Ghosh, Sukumar, "Dissecting Self-* Properties", in Proceedings of the Third IEEE International Conference on Self-Adaptive and Self-Organizing Systems (Washington, DC, USA: IEEE Computer Society, 2009), pp. 10--19.

[BQTV09] Baldoni, R., Querzoni, L., Tarkoma, S. & Virgillito, A. (2009). Distributed Event Routing in Publish/Subscribe Systems. Middleware for Network Eccentric and Mobile Applications. Springer Berlin Heidelberg.

[BH+11] Braun, T.; Hilt, V.; Hofmann, M.; Rimac, I.; Steiner, M.; Varvello, M.; , "Service-Centric Networking," Communications Workshops (ICC), 2011 IEEE International Conference on , vol., no., pp.1-6, 5-9 June 2011, doi: 10.1109/iccw.2011.5963587

[CMP06] Gianpaolo Cugola , Amy L. Murphy , Gian Pietro Picco. Content-based Publish-Subscribe in a Mobile Environment. The Handbook of Mobile Middleware, 257–285, 2006

[CCP10] C. Boldrini, M. Conti, and A. Passarella. Design and performance evaluation of ContentPlace, a social-aware data dissemination system for opportunistic networks. Computer Networks, 54:589–604, March 2010.

[CH11] Jaeyoung Choi; Jinyoung Han; Eunsang Cho; Kwon, T.; Yanghee Choi; , "A Survey on content-oriented networking for efficient content delivery," *Communications Magazine, IEEE* , vol.49, no.3, pp.121-127, March 2011 doi: 10.1109/MCOM.2011.5723809 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5723809&isnumber=5723785

[C++07] B. Chun, A. Ermolinskiy, K. H. Kim, S. Shenker, and I. Stoica, “A data-oriented (and beyond) network architecture,” ACM SIGCOMM Computer Communication Review vol. 37, no. 4, pp. 181-192, August 2007.

[C++11] W. Koong Chai et al., “CURLING: Content-Ubiquitous Resolution and Delivery Infrastructure for Next-Generation Services,” IEEE Communications Magazine, vol. 49, no. 3, pp. 112–120, March 2011.

[EG11] D. Eppstein and M. T. Goodrich and F. Uyeda and G. Varghese. What’s the difference?: efficient set reconciliation without prior context. In ACM SIGCOMM’11, pp.: 218 – 229

[FC09] Future Content Networks Group, “Why do we need a Content-Centric Future Internet?”, Prague 2009, url: http://www.future-internet.eu/fileadmin/documents/prague_documents/FIA-FCN_Internet_Architecture_20090507.pdf

[GM11] Gajic, B.; Riihijarvi, J.; Mahonen, P.; , "Intra-domain topology manager for publish-subscribe networks," *Telecommunications (ICT), 2011 18th International Conference on* , vol., no., pp.394-399, 8-11 May 2011 doi: 10.1109/CTS.2011.5898957 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5898957&isnumber=5898895

[GYL11] Ganti, R.K.; Fan Ye; Hui Lei; , "Mobile crowdsensing: current state and future challenges," Communications Magazine, IEEE , vol.49, no.11, pp.32-39, November 2011

[HA07] P. Hofmann, C. An, L. Loyola, and I. Aad. Analysis of UDP, TCP and voice performance in IEEE 802.11b multihop networks. In Proc. of EW'07, pp.: 1 – 5

[HCY11] P. Hui, J. Crowcroft, and E. Yoneki, "Bubble rap: social-based forwarding in delay tolerant networks," Mobile Computing, IEEE Transactions on, vol. 10, pp. 1576–1589, November, 2011

[IRD02] Iyer, Sitaram and Rowstron, Antony and Druschel, Peter, "Squirrel: a decentralized peer-to-peer web cache", in Proceedings of the twenty-first annual symposium on Principles of distributed computing (New York, NY, USA: ACM, 2002), pp. 213--222.

[J++09] V. Jacobson, D. K. Smetters, J. D. Thornton, M. Plass, N. Briggs, and R. Braynard. Networking Named Content. In Proc. of CoNEXT, 2009.

[KJ12] Kim, Anbin; Jeong, Seong-Ho; Park, Pyung-Koo; Ryu, Ho Yong; , "QoS support for advanced multimedia systems," *Information Networking (ICOIN), 2012 International Conference on* , vol., no., pp.453-456, 1-3 Feb. 2012 doi: 10.1109/ICOIN.2012.6164442 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6164442&isnumber=6164338

[KC07] Teemu Koponen, Mohit Chawla, Byung-Gon Chun, Andrey Ermolinskiy, Kye Hyun Kim, Scott Shenker, and Ion Stoica. 2007. A data-oriented (and beyond) network architecture. *SIGCOMM Comput. Commun. Rev.* 37, 4 (August 2007), 181-192. DOI=10.1145/1282427.1282402 http://doi.acm.org/10.1145/1282427.1282402

[LB10] M. Legeny, B. K. Benk, "Design of Novel Self-Organization Algorithms through Simulation", in Proceedings of EUROSIS (, 2010), pp. 10--15..

[LB11] M. Legeny, B. K. Benko, "Topology Cache aided Self-Organization for Ad-hoc Mobile Networks", Cyber Journals: Multidisciplinary Journals in Science and Technology - Journal of Selected Areas in Telecommunications (JSAT) (2011), pp. 56-63.

[LD03] A. Lindgren and A. Doria and O. Schelen. Probabilistic routing in intermittently connected networks. In ACM Mobile Computing and Communicaitons Review, 2003, pp.: 19-20

[LH07] F. Liu and G. Heijenk. Context Discovery using Attenuated Bloom Filters in Ad-Hoc Networks, In Journal of Internet Engineering, 2007, Vol. 1, No. 1, pp.: 49 – 58

[LK07] V. Lenders and G. Karlsson and M. May. Wireless ad hoc podcasting. In IEEE SECON '07, pp.: 273 – 283

[LWZC10] Li, Zhenping and Wang, Ruisheng and Zhang, Xiang-Sun and Chen, Luonan, "Self-organizing map of complex networks for community detection", Journal of Systems Science and Complexity 23 (2010).

[MB11] Minh, Thu Nguyen Tran and Bich, Thuy Dong Thi, "An Efficient Model for Cooperative Caching in Mobile Information Systems", in Proceedings of the IEEE Workshops of International Conference on Advanced Information Networking and Applications (Washington, DC, USA: IEEE Computer Society, 2011), pp. 90--95.

[MM11] Waldir Moreira and Paulo Mendes, "Survey on Opportunistic Routing for Delay/Disruption Tolerant Networks", Technical report SITI / University Lusófona, SITI-TR-11-02, 2011.

[MMS12] Waldir Moreira, Paulo Mendes, Susana Sargento, " Opportunistic Routing based on daily routines", in Proc. of IEEE AOC, San Francisco, USA, June, 2012

[MP10] M. Meisel and V. Pappas and L. Zhang. Ad hoc networking via named data, In Proc. ACM MobiArch'10, pp.: 1-6

[MSMS12] Waldir Moreira, Manuel de Souza, Paulo Mendes, and Susana Sargento, "Study on the Effect of Network Dynamics on Opportunistic Routing", in Proc. of AdHocNow, Belgrad, Servia, July 2012.

[MW12] M-J. Montpetit and C. Westphal and D. Trossen. Network Coding Meets Information-Centric Networking: An architectural Case for Information Dispersion Through Native Network Coding, Technical report, arXiv:1201.2387v1 [cs.NI], pp.: 1-6

[NDN] Named Data Networking project, http://www.named-data.net/index.html

[N++10] N. Fotiou, P. Nikander, D. Trossen, and G. Polyzos. Developing information networking further: From PSIRP to PURSUIT. In Proc. of 7th ICST Int'l Conf. on Broadband Commun., Networks, and Systems, 2010.

[PL04] Ivana Podnar and Ignac Lovrek. Supporting Mobility with Persistent Notifications in Publish/Subscribe Systems. Proc. DEBS'04, 80-85, 2004

[PodNet] The PodNet Project. http://podnet.ee.ethz.ch/.

[PZKPA11] Ivana Podnar Žarko, Mario Kušek, Krešimir Pripužić and Aleksandar Antonić. Presence@FER: An Ecosystem for Rich Presence, Proceedings of the 11th International Conference on Telecommunications, pp. 133-140, 2011

[PPZA11] Krešimir Pripužić, Ivana Podnar Žarko and Karl Aberer. Distributed Processing of Continuous Sliding- Window k-NN Queries for Data Stream Filtering. World wide web-internet and web information systems 14 (5-6); pp. 465-494, 2011

[PPZA12] Krešimir Pripužić, Ivana Podnar Žarko and Karl Aberer. Top-k/w publish/subscribe: A publish/subscribe model for continuous top-k processing over data streams, Information Systems (2012), http://dx.doi.org/10.1016/j.is.2012.03.003.

[PURSUIT] PURSUIT Project, http://www.fp7-pursuit.eu/PursuitWeb/

[RC09] J. Reich and A. Chaintreau. The age of impatience: optimal replication schemes for opportunistic networks. In Proc. of ACM CoNEXT '09, pp.: 85–96.

[RFC2778] M. Day, J. Rosenberg, and H. Sugano, "A Model for Presence and Instant Messaging (RFC 2778)," IETF, February 2000. [Online]. Available: http://www.ietf.org/rfc/rfc2778.txt

[RS90] Renato E. Mirollo and Steven and H. Strogatz, "Synchronization of pulse-coupled biological oscillators", SIAM J. Appl. Math 50 (1990), pp. 1645--1662.

[SAIL] SAIL Project, http://www.sail-project.eu/

[SP05] T. Spyropoulos and K. Psounis and C. S. Raghavendra. Spray and wait: an efficient routing scheme for intermittently connected mobile networks. In Proc. of ACM WDTN' 05, pp.: 252 - 259

[TAB10] Tyrrell, A. and Auer, G. and Bettstetter, C., "Emergent Slot Synchronization in Wireless Networks", Mobile Computing, IEEE Transactions on 9, 5 (2010), pp. 719 - 732.

[TM12] Tran, H.A.; Mellouk, A.; Hoceini, S.; Souihi, S.; , "User QoE-based adaptive routing system for future Internet CDN," *Computing, Communications and Applications Conference (ComComAp), 2012* , vol., no., pp.90-95, 11-13 Jan. 2012 doi: 10.1109/ComComAp.2012.6154009 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6154009&isnumber=6153941

[TN99] Y-C. Tseng and S-Y. Ni and Y-S. Chen and J-P. Sheu. The Broadcast Storm Problem in a Mobile Ad Hoc Network, In Proc. ACM/IEEE MobiCom'99, pp.: 153 – 167

[VB00] A. Vahdat and D. Becker. Epidemic routing for partially-connected ad hoc networks. Tech Rep. CS-2000006, Duke University, 2000

[VR11] M. Varvello and I. Rimac and U. Lee and L. Greenwald and V. Hilt. On the Design of Content-Centric MANETs. In IEEE WONS'11, pp. : 1-8

[W++11] J. Whitbeck, M. Amorim, Y. Lopez, J. Leguay, and V. Conan. Relieving the wireless infrastructure: When opportunistic networks meet guaranteed delays. In Proc. of IEEE WoWMoM 2011.

[Y++07] E. Yoneki, P. Hui, S-Y. Chan, and J. Crowcroft. A socio-aware overlay for publish/subscribe communication in delay tolerant networks. In Proc. of ACM MSWiM, 2007.

[Z++11] X. Zhuo, Q. Li, G. Cao, Y. Dai, B. Szymanski, and TL Porta. Social-Based Cooperative Caching in DTNs: A Contact Duration Aware Approach. In Proc. of IEEE MASS, 2011.