Highly Accurate Evaluation of GPS Synchronization for TDOA Localization

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***Abstract*—Clock synchronization is critical for the operation of a distributed wireless network system. In this paper we investigate on a method able to evaluate in real time the synchronization offset between devices down to nanoseconds (as needed for positioning). The method is inspired by signal processing algorithms and relies on fine-grain time information obtained during the reconstruction of the signal at the receiver. Applying the method to a GPS-synchronized system show that GPS-based synchronization has high accuracy potential but still suffers from short-term clock drift, which limits the achievable localization error.**

***Index Terms*—Synchronization, Time Recovery, GPS, TDOA**

I. INTRODUCTION

Localization and tracking have emerged in recent years as an attractive solution to enable new business models for location-based services. For localization in dense urban and indoor areas the use of radio technologies such as WiFi and cellular network are proposed. Among the many proposals [1], ranging via the Time Difference of Arrival (TDOA) method is among the most promising ones [2]. In TDOA the tracked object is positioned relative to at least three Anchor Nodes (ANs) with known coordinates. The ANs are responsible to calculate a location estimate of the object from the observed differences in arrival times (represented by timestamps) of its signal. TDOA for positioning, however, sets stringent requirements towards synchronization, e.g., in the nanosecond range.

Common synchronization schemes can typically deliver synchronization accuracy in the order of milliseconds or microseconds. GPS as a synchronization option is more promising. The clock in each satellite is continuously calibrated against the world wide time standard, allowing GPS enabled devices on the ground to mutually synchronize their local clocks. Theoretically expected performance is in the order of nanoseconds [3]. Unfortunately, current methods to evaluate the GPS synchronization for positioning are not adequate [5].

In this paper we take a step forward by offering a novel evaluation method to calculate the clock offset. In particular, we propose to use fine-grained timing information internally available in the signal processing chain. Compared to traditional methods, we are able to provide more accurate estimations of (1) GPS synchronization in the nanosecond range and (2) momentary fluctuations of the clock drift (short-term clock drift). We are able to demonstrate that there is a remaining short-term clock offset even with GPS synchronization, which sets a lower bound on the localization error to tens of meters.

We favor TDOA-based localization with GSM signals due to the wide GSM adoption by end users.

II. SYNCHRONIZATION IN LOCALIZATION SYSTEMS

While most processes in distributed systems may be satisfied with synchronization accuracy of milli- or microseconds, positioning based on time requires nanosecond precision.

A. Clock Terminology

Every AN in a time-based localization system has its own clock. Assuming that the reference time of the whole system is $C(t) = t$, ideally, the local time of the ith AN (AN_i) should be $C_i(t) = t$. However, even if started at exactly the same time, local clocks will drift away from the reference time because of frequency deviations of the oscillator. Moreover, material and manufacturing tolerances cause individual clocks to drift differently.

TABLE I
NOTATION LIST

ΔC_{ij}	Relative clock offset	μ	Timing error
Δf_{ij}	Relative clock skew	$\overline{\mu}$	Averaged timing error
$\Delta\theta_{ij}$	Relative initial clock offset	$\Delta\mu_{ij}$	Relative timing error

Generally, the clock function of AN_i is modeled as

$$C_i(t) = \Delta f_i \cdot t + \Delta\theta_i \quad (1)$$

where the parameters Δf_i and $\Delta\theta_i$ are the **clock skew** and **initial clock offset** at AN_i, respectively. In this paper we use the nomenclature from [4] to define that $\Delta C_{ij}(t) = C_i(t) - C_j(t)$ is the **relative clock offset**, and $\Delta f_{ij} = \Delta f_i - \Delta f_j$ is the **relative clock skew** between AN_i and AN_j. Table I introduces the notations used in the paper.

Ideally, if all the nodes are perfectly synchronized, the corresponding relative clock offset $\Delta C_{ij}(t)$ and skew Δf_{ij} are equal to zero [4]. However, in practice this is unrealistic, and thus it is important to measure these parameters.

B. Quantifying Synchronization Accuracy

The degree of synchronization of two or more nodes can be evaluated off-line as done in [5], [8]. Off-line approaches are not appropriate for applications such as target positioning and tracking, for which on-line estimation of the clock skew and offset is important. A common on-line method to determine whether two devices (e.g., ANs) are synchronized is to compare their timestamps for receiving the same message emitted by an equidistant reference node [8].

In a real wireless network the timestamp for the received message reflects the signal propagation time as well as the time process at the receiver node [8]. Hence, a timestamp is best given close to the physical layer to avoid influences from processing time in the MAC or higher layers. At physical layer, a conventional timestamp is the hardware-given time when a sample of a packet is received. We can give the timestamp at the physical layer but we only use it after the packet was reconstructed. A conventional timestamp is limited by properties of the signal such as bandwidth and symbol rate. In the case of a GSM signal with symbol rate of $270.833KHz$, a conventional timestamp can not distinguish the time difference within one symbol interval ($3.7\mu s$).

III. SYNCHRONIZATION ACCURACY VIA TIME RECOVERY

The *time recovery* method was introduced to improve reliability of signal reconstruction. We go one step further and exploit the method to achieve highly accurate calculation of the synchronization misalignment among nodes.

A. Pulse Sampling and Time Recovery

In an ideal system, where the transmitter and receiver are perfectly synchronized, timestamps are taken at the optimal sampling moment of a symbol as shown in Figure 1(a). In practical systems, however, the receiver is not synchronous with the incoming data due to free running oscillators of the transmitter and receiver. This results in shifted sampling $\mu(k)$ before (as in Figure1(a)) or after the peak. $\mu(k)$ is the normalized timing error given by:

$$\mu(k) = \frac{\Delta T(k)}{T_s}, \tag{2}$$

where $\Delta T(k)$ is the offset between the actual and optimal sampling positions and T_s is the constant sampling interval. If now two receivers are not perfectly synchronized with each other, $\mu(k)$ will differ per receiver as seen in Figure 1(b).

To correct for shift in the sampling position, the time recovery method was developed. The sample stream is fed into a Timing Error Detection (TED) module to extract the timing error information between the actual and optimal sample positions. This information is passed to a loop filter, which outputs the normalized timing error $\mu(k)$ used to adjust the sampling position to be closer to the optimal one [7].

B. Relative Clock Offset and Skew Evaluation

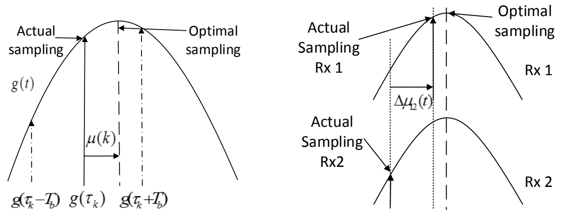
We propose to apply the normalized timing error $\mu(k)$ of sample k to determine more accurately the clock offset and skew. At the physical level a conventional timestamp $T'(k)$ for the kth sample from the beginning of the sample stream can be obtained as follows:

$$T'(k) = T'(1) + T_s * (k-1), \tag{3}$$

where $T'(1)$ is the conventional timestamp for the first sample in the stream. In Equation (3) the resolution of the conventional timestamp is limited by T_s. With the $\mu(k)$ obtained by the time recovery, we can improve the resolution as:

$$T(k) = T'(k) + \mu(k) \cdot T_s, \tag{4}$$

where $T(k)$ is the enhanced timestamp. Now, assuming that the kth sample is the first sample of the received packet, $T(k)$ is the enhanced timestamp for this packet.



(a) Adjusting sampling position (b) Time offset (asynchronization)

Fig. 1. Time recovery

In the case of on long term clock drifts, the relative clock offset $\Delta C_{ij}(t)$ between the two receivers is not larger than one sample interval and can be calculated as:

$$\Delta C_{ij}(t) = \mu_i(t) \cdot T_s - \mu_j(t) \cdot T_s = \Delta\mu_{ij}(t) \cdot T_s, \tag{5}$$

where $\Delta\mu_{ij}(t) = \mu_i(t) - \mu_j(t)$. If there is no short-term clock drift, $\Delta\mu_{ij}(t)$ would be constant. Otherwise, $\Delta\mu_{ij}(t)$ would fluctuate. We can use this to identify the presence of short-term clock drift by monitoring the behavior of $\Delta\mu_{ij}(t)$.

IV. IMPLEMENTATION APPROACH

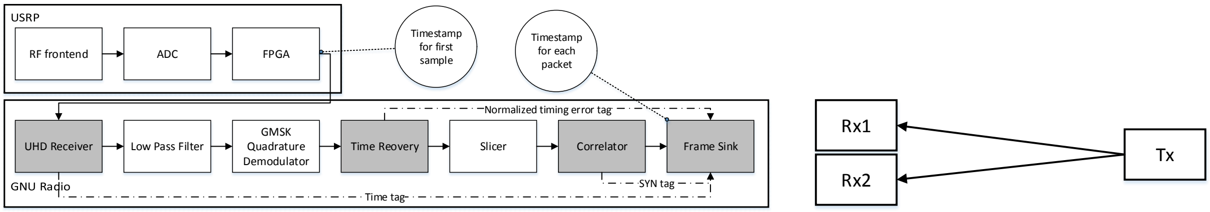
We used the Universal Software Radio Peripheral (USRP) hardware and the open-source GNU Radio software set to run the ANs. The operation of the USRP N210 model can be controlled by a GPS Disciplined Oscillator (GPSDO) kit, allowing the device to lock to the more stable GPS signal.

The components of the receiver are shown in Figure 2(a). Grey blocks indicate modifications to apply our proposed method. We make use of *stream tags* to attach tags with control information to the data stream. First, a time tag, which indicates the starting time of the stream, is attached to the first sample of the stream in the UHD receiver. All following samples are numbered relative to the first sample. Second, forward the normalized timing error $\mu(k)$ for each output sample in the time recovery block. Third, a SYN tag indicating the first sample in the packet is passed to the frame sink. The combination of the three tags is used to calculate the enhanced timestamp of each packet according to Equation (4).

V. MEASUREMENT RESULTS

A. Measurement Setup

To calculate the synchronization offset between two GPS-synchronized receivers, the set up in Figure 2(b) was used. Assuming the same delays in hardware, two factors can cause a time offset between two receivers, multipath propagation and synchronization offset. Two receivers are co-located to isolate



(a) GMSK receiver with enhanced timestamp

(b) Measurement Setup

Fig. 2. Implementation and Measurement

only the effect of the synchronization component. This ensures as much as possible the same propagation path of the signal.

To simulate a GSM signal, the GMSK modulation is applied. The symbol rate is $250KHz$, which is lower than the GSM symbol rate ($270.8KHz$). The packet length is 1502 bits and packet interval is $0.04864s$. To minimize the noise and ease result presentation we work with the value $\overline{\mu}$ averaged over the $\mu(k)$ of the samples of one packet (Table I).

B. GPS Synchronization Evaluation

In order to obtain statistically accurate results we took measurements over a 12 hours period. First, we used the conventional timestamp given by the FPGA to calculate the GPS synchronization offset. Assuming a constant relative clock skew, we calculated the relative clock offset and average skew. Due to the limited conventional timestamp resolution, we are not able to determine whether there is a short-term clock drift between the receivers. The observed zero clock offset prevents us from calculating the relative clock skew.

In order to check for short-term clock drift in the same 12 hours measurement we performed a second evaluation based on the proposed enhanced timestamp. According to our measurements (Figure 3), there is a remaining short-term clock drift caused by oscillator imprecision and temporarily lost lock to satellites. In order to improve readability, the graph plots only part (34 seconds) of the 12 hours period.

Quantitative evaluations are further possible, if we consider the difference $\Delta\mu_{12}(t)$ per packet between the two receivers. Then, according to Equation (5), we can calculate the relative clock offset. Results over the whole 12 hours are shown in Figure 4. Fluctuations in the $\Delta\mu_{12}(t)$ value correspond to the variation in synchronization. Our findings show that the maximum registered clock offset between the two receivers is $423ns$ with most calculated offsets within $200ns$. This is still very large for time-based localization, since a corresponding positioning error of 60 meters is to be expected.

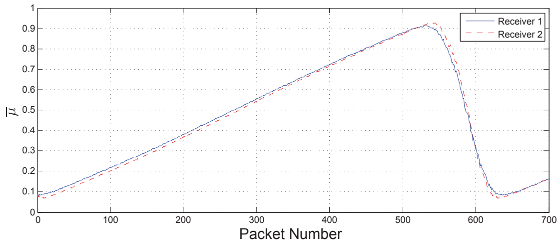


Fig. 3. Clock drift with GPS synchronization

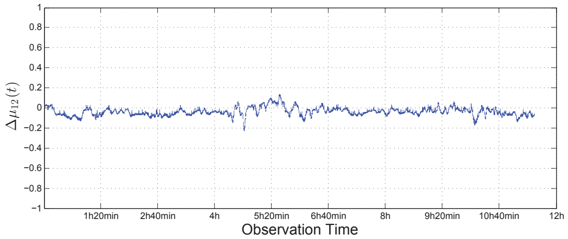


Fig. 4. $\Delta\mu_{12}(t)$ with GPS synchronization for 12 hours

VI. CONCLUDING REMARKS

The main findings of this paper are (1) an accurate evaluation of the clock offset in case of GPS-based synchronization; and (2) a lower bound of positioning error set by the minimum achievable synchronization offset of 200ns. Further improvements, if possible at all, would require hardware modifications.

The excellence of our method is its ability to calculate instantaneously clock drifts with accuracy down to nanoseconds. Moreover, the method is applicable to any system, independently of the clock source and can be also used with a range of symbol rates and modulation schemes.

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