Distributed Software Defined Radio Testbed for Real-time Emitter Localization and Tracking

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***Abstract*—We present a real-time TDOA localization testbed utilizing software defined radio and GPS based synchronization. A distributed software stack enables the localization of unknown signals by transporting the recorded baseband samples of several sensors over a backhaul network for centralized signal processing in a fusion center. To overcome the relatively large drifts of synchronization signals provided by standard GPS receivers, the system is permanently re-calibrated using a stationary reference beacon or alternatively a signal of opportunity. In a further step, we introduce a new generation of low-cost GPS disciplined oscillators to simultaneously achieve single digit meter accuracy and high update rates necessary for target tracking. The tracking is performed using a Kalman filter running on the output of the localization algorithm. Therefore, we also study the dilution of precision effect and adopt the filter accordingly. Further optimizations tackling the ambiguity problem in a three sensor system and optimum reference selection are introduced. Finally we present outdoor measurements to characterize the performance of the system.**

***Index Terms*—Positioning, Localization, Tracking, Synchronization, Software Defined Radio**

I. INTRODUCTION

Implementation of wide area localization systems utilizing time measurements from electromagnetic waves has been notoriously challenging due to its extreme demands on the synchronization. Nanosecond synchronization accuracy is necessary in order to obtain meter to sub-meter localization performance. The technical challenges and high costs involved in the implementation of such systems is one of the major reasons hindering the research community from experimental work in the area. Using a common clock connected to all distributed sensors results in highly stable synchronization for time difference of arrival (TDOA) measurements. However, such a solution involves a tremendous amount of cabling, very long setup times and large costs for a permanent installation. In a research environment, especially the long setup times can lead to the infeasibility of various experiments, e.g. if there is a time limitation of a single day. Consequently, it is desirable to work towards self-contained wireless sensor units. One approach to achieve this is to use distributed synchronization, e.g., based on GPS signals and a wireless backhaul solution. Another aspect in the design of a localization testbed is the choice of the underlying technology. The computer science community regularly follows the approach to use standardized technology such as the IEEE 802.11 (WiFi) family, sometimes with slight modifications to the device driver. While this approach leads to fast, reliable and cost effective results by abstracting away most of the physical layer signal processing from the researcher, it also sets very tight limits to the physical layer design space. Therefore, the electrical and communications engineering community often decides to use Software Defined Radio (SDR), e.g., using GNU Radio [1], as the basis of system design. This allows for highly increased freedom in the design of RF waveforms for localization research. Fig. 1 depicts the setup of a distributed localization testbed based on SDR.

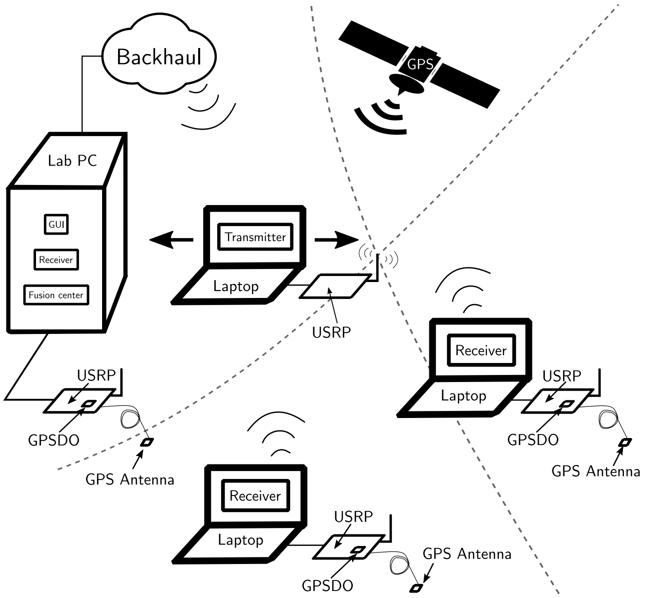


Fig. 1: Exemplary setup of the testbed with WiFi backhauling. Receiver clocks are synchronized using GPS.

In the past, several systems have been presented [2], [3], [4], [5], [6]. These solutions either use a common clock or exhibit large errors in the order of 100m or more. Further, some system are missing real-time capabilites and only support offline signal processing of recorded signals. In the current paper we are going to extensively describe how recent developments in software defined radio (SDR) and GPS synchronization technology enable the implementation of affordable real-time TDOA based localization systems.

The system is able to achieve single-digit meter accuracy without the use of a common clock. We specifically study two types of GPS disciplined oscillators (GPSDOs) used for the synchronization with different performance. For the first type, additional beacon signals are necessary to achieve an acceptable performance. This approach is similar to the one in [7] developed at the same time. Using the second type GPSDO, currently a last generation state-of-the-art device, we were able to obtain the same performance without the help of beacon signals. In [8] various related approaches for localization system synchronization are described; however, it is based on proprietary technology not easily available to civil research. To further improve the results our system performs tracking of the emitter location using a Kalman filter.

The remainder of the paper is structured as follows. Sec. II defines a system model. Sec. III explains the software and hardware architecture used in our implementation. Subsequently Sec. IV discusses solutions for the synchronization and Sec. V for the tracking problem. Finally, Sec. VI provides measurement results to demonstrate the performance of the complete system. A short conclusion of the work is given in Sec. VII.

II. SYSTEM MODEL

We consider a system of M distributed receivers that are searching to localize a moving transmitter. In the literature, these receivers are also called anchor nodes, base stations, access points or sensors. The system is considered to be passive and has no communication from the transmitting target to the receivers for the purpose of the localization. For the sake of simplicity we assume a single transmitter, where the transmitted signal can be modeled as

$$y_r(t) = h_r s(t - t_r) + w_r(t), \quad r \in \{1, \dots, M\}, \qquad (1)$$

where $w_r(t)$ is a Gaussian noise process and t_r models the delay which is related to the propagation distance between the transmitter and receiver r. Similarly h_r models the attenuation of the channel. The TDOA based system is able to observe time differences $\tau_{ij} = t_i - t_j$ between receiver i and the reference j. In space this translates to equations of the form $\tau_{ij} = \frac{1}{c}(\|\boldsymbol{p} - \boldsymbol{p}_i\|_2 - \|\boldsymbol{p} - \boldsymbol{p}_j\|_2)$ with the speed of light c and the position of the target $\boldsymbol{p} = (x,\ y)^\top$. Based on that, a solution for the location can be found [9]. Algorithms of this type assume the TDOAs have already been obtained. Another way is to perform direct localization based on the signals as we have shown in [10]. As described in [11], this also enables us to incorporate a ray-tracing engine which can resolve multipath propagation. In our experimental real-time localization system algorithms [9] and [10] have been implemented.

III. SYSTEM ARCHITECTURE

The presented localization system is implemented based on the SDR methodology. This includes hardware for basic radio frequency and baseband signal processing and software to perform the major part of the digital baseband signal processing.

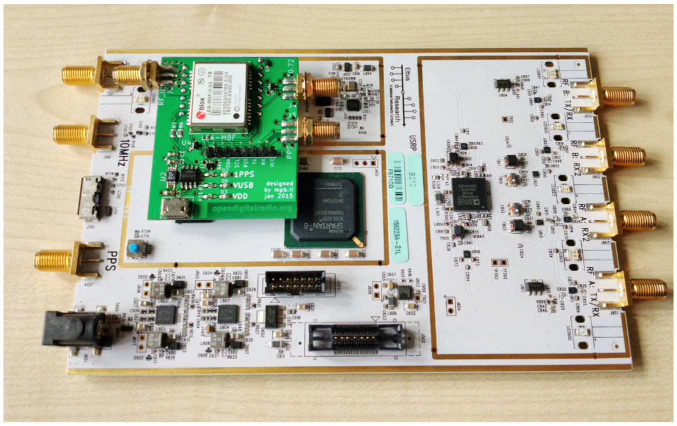


Fig. 2: The RF front-end (Ettus USRP B210, white) with a last generation embedded GPSDO mounted (u-blox LEA-M8F, green) for time synchronization with other distributed nodes.

1) Hardware: The baseline configuration of the system, as shown in Fig. 1, uses three receiver nodes and one transmitting target node that shall be localized. Each node consists of a RF front-end and a computer running the SDR framework. The RF front-ends Ettus USRP B210, shown in Fig. 2, are able to deliver complex samples at a rate of up to 56 million samples per second. In order to enable time synchronization the receiver nodes additionally need a GPS disciplined oscillator (GPSDO) that provides a clock signal for the front-end and a pulse per second (PPS) synchronization signal. We evaluated two devices, namely the LCXO manufactured by Jackson Labs Technologies and the u-blox LEA-M8F. Both can be pluged into the USRP B210 RF front-end. By default the USRP B210 is designed to receive a LCXO GPSDO, in order to mount the LEA-M8F we use a PCB specifically designed for that purpose [12]. Note that the driver for the USRP B210 has to be patched in order to support the LEA-M8F. To improve mobility, we use laptop computers. We are able to power the RF front-end as well as the GPSDO through the laptop battery. Furthermore, the system needs a backhaul network in order to communicate the baseband samples of the receiver nodes. This is achieved either by Ethernet or IEEE 802.11 (WiFi). When using WiFi, the nodes are completely self-contained and wireless, operation is only limited by the capacity of the laptop battery. To build the transmitting target object, that is to be localized, another USRP B210 is mounted on a long staff. Using SDR for transmission we maintain full flexibility in the choice of the transmitted signal.

2) Software: The software part of the localization system consists of four components: transmitter, receiver, fusion center (FC) and graphical user interface (GUI). A signal is created and transmitted by the transmitter component and several receiver components acquire the samples in a synchronized way. Those parts are implemented with the GNU Radio SDR framework [1]. For the transmitted signal we use BPSK as well as OFDM modulated signals. Baseband samples are then sent from the receivers to the FC using the ZeroMQ library [13].

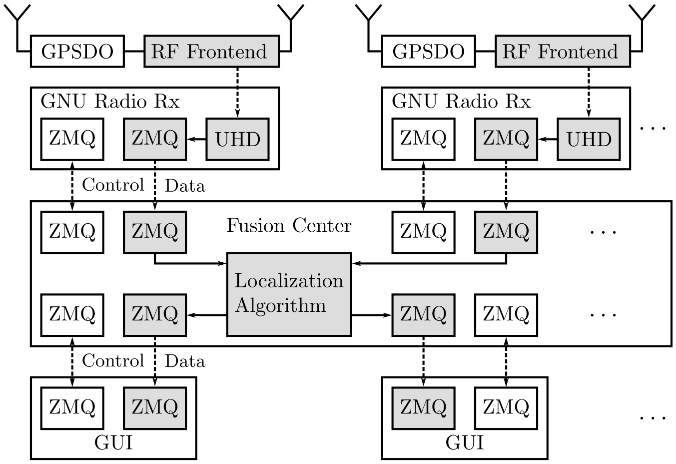
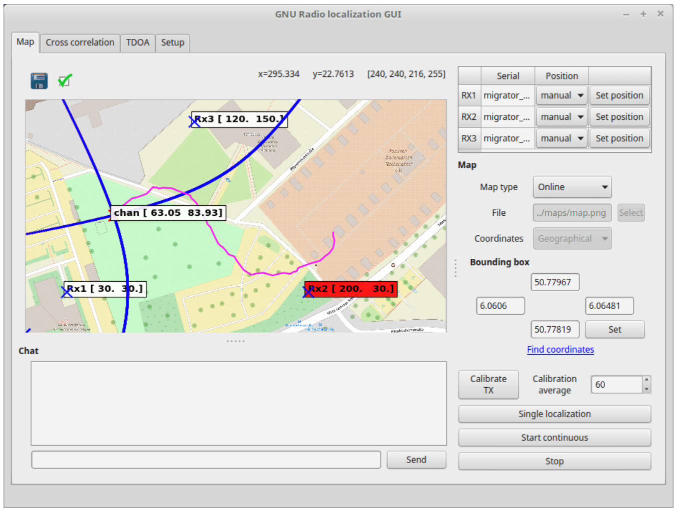


Fig. 3: The distributed system architecture is based on GNU Radio [1] and ZeroMQ [13], the signal processing path is depicted in gray, the control path in white.

Signal processing block supporting this messaging library have been integrated into the GNU Radio project. ZeroMQ is also used to communicate all necessary control commands from the GUI to the FC and from there to the distributed receiver nodes. For that purpose a remote procedure call (RPC) scheme has been implemented. Fig. 3 gives an overview of the interconnections among the system components. The signal path is depicted in gray, it uses a streaming signal processing approach, the control path is depicted in white. The final result is sent back to the GUI and displayed to the user as shown in Fig. 4.

System operation consists of two phases; initially all sensors have to be exactly synchronized to coordinated universal time (UTC) as provided by the GPSDO. This is crucial, because for TDOA localization samples have to be acquired exactly at the same time. In the second phase, localization can be performed. For that, a start command is issued from the GUI. Subsequently, the FC orders all sensors to start continues reception of the target signal. As the system shall be able to localize unknown signals it is necessary to transport baseband samples to the FC. Due to capacity limitations in the backhaul each sensor takes snapshots, e.g., 1000 samples in each acquisition. The solution for the location is then calculated for each snapshot in the FC. Afterwards, all results are transmitted to one or more graphical user interfaces. Note that all software components can run independently on different computers in the network. In principle the number of receivers and GUIs is not limited.

With the LCXO GPSDO the update rate is limited by the necessary synchronization calibration process described in the next section. In that case the framework is able to obtain signal snapshots at a rate of 0.66 Hz. As explained later with the LEA-M8F GPSDO calibration requirements are relaxed, the update rate is 2 Hz and could be increased further by optimizing the software of the FC and GUI components and the backhaul capacity.


GNU Radio localization GUI

x=295.334 y=22.7613 [240, 240, 216, 255]

	Serial	Position	
RX1	migrator_...	manual	Set position
RX2	migrator_...	manual	Set position
RX3	migrator_...	manual	Set position

Map type: Online
File: ../maps/map.png
Coordinates: Geographical
Bounding box: 50.77967, 6.0606, 6.06481, 50.77819
Calibration average: 60

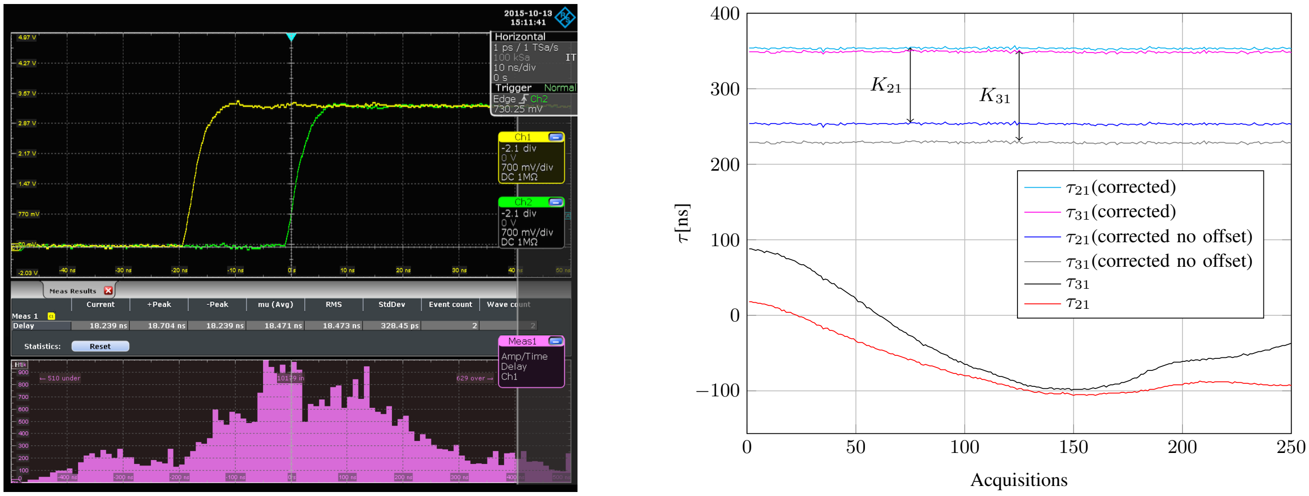
Fig. 4: Graphical user interface of the localization testbed. Map data is obtained from OpenStreetMap [14]. Tracking performed using the algorithm of Chan [9] together with the Kalman filter described in Sec. V.

IV. SYNCHRONIZATION

In practice, when trying to achieve high accuracy in a TDOA based localization system, two major challenges clearly stick out, synchronization and multipath propagation. Multipath propagation is out of the focus of this paper and has been partially examined in [11].

Synchronization is difficult mainly due to the wide separation of the sensor nodes. As we are interested in a wireless synchronization method to avoid the logistic effort associated with a cabled common clock system, we choose GPS based synchronization. This works by equipping each sensor with a Global Positioning System disciplined oscillator (GPSDO). The GPSDO disciplines the local oscilator using a time pulse derived from the GPS signal. Hence all the local oscillators in the sensor network will be synchronized. Each GPSDO outputs a clock signal, e.g., 10 MHz and a pulse per second (PPS) signal. The clock signal is used to drive the digital and analog circuits of the RF front-end and the PPS signal is used to control the synchronized operation.

To achieve synchronization in a SDR system typically two steps are necessary. First, the RF front-ends have to be synchronized to UTC on a hardware level. Note that due to latencies in the link between RF front-end and the host computer and the impact of the operating system it is not feasible to perform the synchronization purely in software on the host side. Hardware level synchronization is indispensable to achieve synchronization in the order of nanoseconds. Second, once synchronization of the RF front-ends has been achieved, a command can be issued to all sensors to start the recording of baseband samples at an absolute point in time. Typical SDR frameworks such as GNU Radio [1] provides an application programming interfaces (API) for both steps. Timestamps associated with the recorded samples enable the



	Current	+Peak	-Peak	mu (Avg)	RMS	StdDev	Event count	Wave count
Meas 1								
Delay	18.239 ns	18.704 ns	18.239 ns	18.471 ns	18.473 ns	328.45 ps	2	2

(a) (b)

Fig. 5: Drift of GPS based synchronization used for the distributed receiver nodes, measured with (a) an osciloscope and (b) with the TDOAs of a stationary target, sample rate 50 MS/s, interpolation factor 10, signal bandwidth 5 MHz.

FC to check for consistent synchronization over the course of the system operation time. Assuming a proper implementation of the synchronization APIs, the performance for the TDOA localization is limited by the GPSDO performance as well as the signal-to-noise ratio of the transmitted signals. It is therefore important to study the synchronization problem on different levels.

First, one can directly measure at the PPS outputs of the GPSDOs. GPSDO performance has been studied in [15], [16]. Under good conditions a standard deviation of 50 ns for the GPS time estimate can be expected for standard receivers like the one contained in the LCXO GPSDO. However, for TDOA it is necessary to take differential measurements between two synchronized receivers, which considerably increases the error. Accordingly, we use an oscilloscope connected to two different GPSDO PPS signals and plot the histogram of the difference. A measurement screenshot is shown in Fig. 5(a). In this case the GPS antennas have been placed on the window shelf of the laboratory which clearly deteriorates the performance compared to a clear skyview.

Second, the TDOAs are usually estimated by finding maxima of the cross-correlations of the different sensor outputs. In Fig. 5(b) the effect of the GPSDO drift on the TDOA estimation is depicted.

Third, subsequently an algorithm such as [9] is used to solve for the location. The blue track in Fig. 6 shows how the drift in the synchronization translates into a drifting localization result of a non-moving object. The experiment involves 3 sensors and the resulting error is in the order of 50 meters.

A. Calibration of Time Synchronization

In order to overcome the GPS synchronization issues we introduce two approaches. The first approach is to use an additional signal from a stationary source to permanently recalibrate the system.

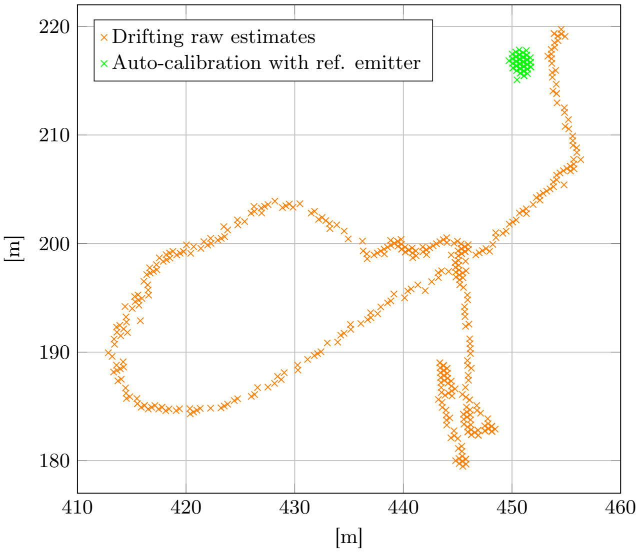


Fig. 6: Drift in the estimated location of a *stationary* object induced by drifting synchronization (orange). Using automatic calibration with a beacon signal, the green result can be obtained.

This calibration signal can be a beacon signal such as in [7] or alternatively a signal of opportunity from a local broadcasting station, e.g., DAB, DVB-T, commonly seen by all sensors. If the signal of the emitter to be localized is a known and a multiple access method exists, the calibration signal can be transmitted in-band. This practice is followed by [7]. However, in our case we assume arbitrary signals, therefore it is necessary to use an out-of-band calibration signal and retune the sensors between the calibration and the target signal. Due to hardware limitations, this re-tuning leads to a limited acquisition and update rate of the system. The calibration procedure for TDOA can be described in the following way. The measured TDOAs are erroneous

$$\hat{\tau}_{ij} = \tau_{ij} + e, \tag{2}$$

where the error e contains a deterministic offset due to the synchronization error and a Gaussian noise component due to the measurement in the receiver. We are able to estimate the deterministic part by comparing the TDOAs of the beacon calibration signal with its expected TDOA

$$e = \hat{\tau}^b_{ij} - \tilde{\tau}^b_{ij} \tag{3}$$

If the location of the calibration signal is erroneous, this results in a constant offset K_{ij}

$$\tilde{\tau}^b_{ij} = \tau^b_{ij} + K_{ij} \tag{4}$$

That means even if the location of the calibration emitter is unknown, the system can be calibrated by determining the constants K_{ij} using additional ground truth information. The GUI of our system includes a feature for that purpose. To perform this calibration it is necessary to take measurements with the target emitter placed at a known location. In Fig. 6 it can be seen (red points) that the calibration algorithm is able to keep the synchronization error within about ±2 samples of the expected values and thereby the localization error within a few meters.

A second approach working without calibration signals is to use a specific time mode available in certain GPS receivers. GPS receivers calculate a 3 dimensional position and the time using the signals of at least 4 satellites [17]. The largest error in this process arises from the propagation of the satellite signals through the ionosphere. This sets a natural limit to the performance of single frequency GPS receivers and thus to the accuracy of the emitted time pulse and causes the drift in the measurements as described above. An effective solution to this problem is to exclude the GPS receiver position from the equations. Obviously, this is only possible in timing applications such as the described localization system, where the GPS receivers are stationary and the position is very well known. When the time mode is used it can be observed that the standard deviation of the time pulse can be decreased up to one order of magnitude. The results in section VI have been obtained with the LEA-M8F and the time mode enabled.

V. TRACKING

For further improvement of the localization we apply Kalman filter (KF) based tracking [18] to the output of the localization algorithm. The KF updates the state $\boldsymbol{x}_k$ based on a motion model contained in matrix $\boldsymbol{\Phi}$ and the measurement matrix $\boldsymbol{M}$

$$\boldsymbol{x}_k = \begin{pmatrix} x_k \\ y_k \\ v_{xk} \\ v_{yk} \\ U_{xk} \\ U_{yk} \end{pmatrix} \quad \boldsymbol{\Phi} = \begin{pmatrix} 1 & 0 & \Delta t & 0 & 0 & 0 \\ 0 & 1 & 0 & \Delta t & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & \rho & 0 \\ 0 & 0 & 0 & 0 & 0 & \rho \end{pmatrix}$$

$$\boldsymbol{M} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \end{pmatrix} \quad \boldsymbol{Q} = \begin{bmatrix} \boldsymbol{0}_{4\times 4} & \boldsymbol{0}_{4\times 2} \\ \boldsymbol{0}_{2\times 4} & \sigma_a^2 \Delta t^2 \boldsymbol{I}_2 \end{bmatrix}.$$

We model the acceleration as a random variable. Hence $\boldsymbol{Q}$ is a covariance matrix where σ_a^2 is the covariance of the acceleration, ρ is a correlation coefficient of the acceleration and Δt the (fixed) time between observations. The KF algorithm consists of a recursive two-step procedure. First, the prediction step generates a-priori estimates $(-)$

$$\boldsymbol{x}_k(-) = \boldsymbol{\Phi}\boldsymbol{x}_{k-1}(+) \tag{5}$$

$$\boldsymbol{P}_k(-) = \boldsymbol{\Phi}\boldsymbol{P}_{k-1}(+)\boldsymbol{\Phi}^\top + \boldsymbol{Q}. \tag{6}$$

Then the update step calculates the a-posteriori estimates $(+)$ by merging the a-priori estimates with the new observation of the target location $\boldsymbol{y_k} = (x,\ y)^\top$

$$\boldsymbol{x}_k(+) = \boldsymbol{x}_k(-) + \boldsymbol{K}_k[\boldsymbol{y_k} - \boldsymbol{M}\boldsymbol{x}_k(-)] \tag{7}$$

$$\boldsymbol{P}_k(+) = [\boldsymbol{I} - \boldsymbol{K}_k\boldsymbol{M}]\boldsymbol{P}_k(-) \tag{8}$$

$$\boldsymbol{K}_k = \boldsymbol{P}_k(-)\boldsymbol{M}^\top[\boldsymbol{M}\boldsymbol{P}_k(-)\boldsymbol{M}^\top + \boldsymbol{R}_k]^{-1}. \tag{9}$$

The covariance matrix $\boldsymbol{R}_k$ of the noise depends on the geometry of the sensor network. We therefore introduce the concept of geometric dilution of precision (DOP) to capture this effect.

A. Dilution of precision

DOP models how measurement errors translate into localization errors with respect to the location of the target. As shown in [19] we define the Jacobian $\boldsymbol{H}^j_k$ of the TDOAs evaluated at the new observation $\boldsymbol{y}_k$ calculated by the localization algorithm with reference receiver j

$$\boldsymbol{H}^j_k = \begin{bmatrix} \vdots \\ (\frac{\partial}{\partial \boldsymbol{p}}\tau_{ij}|_{\boldsymbol{p}=\boldsymbol{y}_k})^\top \\ \vdots \end{bmatrix}, \quad i \in \{0, .., M\} \setminus \{j\} \tag{10}$$

where $\frac{\partial}{\partial \boldsymbol{p}}\tau_{ik} = \frac{1}{c_0}\left(\frac{\boldsymbol{p}-\boldsymbol{p}_i}{\|\boldsymbol{p}-\boldsymbol{p}_i\|_2} - \frac{\boldsymbol{p}-\boldsymbol{p}_j}{\left\|\boldsymbol{p}-\boldsymbol{p}_j\right\|_2}\right)$ describes the change in each TDOA measurement for a change in location $\boldsymbol{p}$. The DOP is then defined as

$$\text{DOP}^j = \sqrt{tr((\boldsymbol{H}^{j\top}_k \boldsymbol{H}^j_k)^{-1})} \tag{11}$$

One can then show that

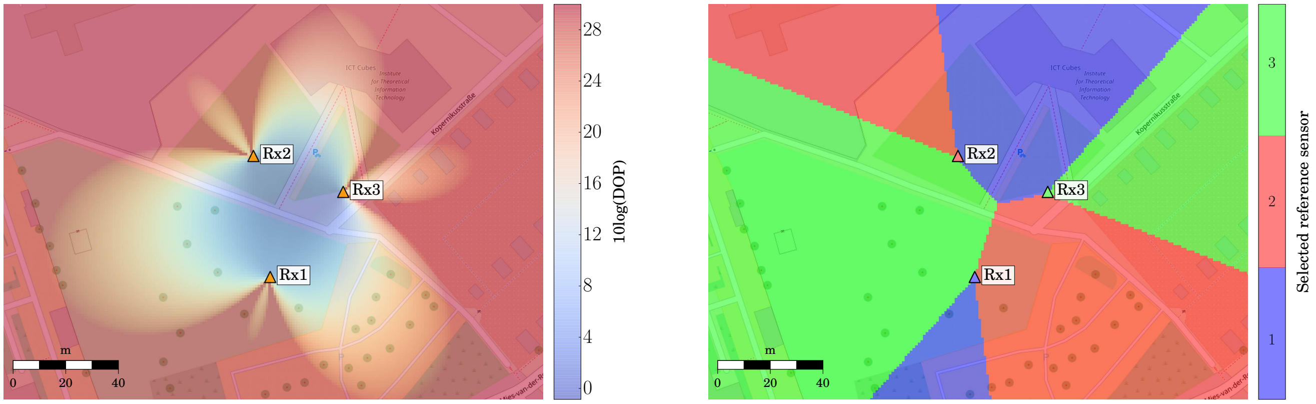
$$\boldsymbol{R}_k = (\boldsymbol{H}^{j\top}_k \boldsymbol{H}^j_k)^{-1} \boldsymbol{H}^{j\top}_k \boldsymbol{C}_\tau \boldsymbol{H}^j_k (\boldsymbol{H}^{j\top}_k \boldsymbol{H}^j_k)^{-1}, \tag{12}$$

To determine $\boldsymbol{C}_\tau$ we make the common simplifying assumption of equal sensor signal to noise ratio (SNR), hence

$$\boldsymbol{C}_\tau = \sigma_\tau^2 \begin{pmatrix} 1 & 0.5 \\ 0.5 & 1 \end{pmatrix}. \tag{13}$$

Suitable values for ρ, σ_a and σ_τ have to be determined empirically.

TDOA algorithms with only three receivers exhibit an ambiguity problem in certain regions close to and behind the receivers. The comprehensive analysis in [20], [21] exactly describes the regions where the problem occurs. In our system



(a)

(b)

Fig. 7: DOP analysis of the sensor setup used in the experiment with reference receiver selection (a). Optimum reference receiver selection (b), depending on the target location and based on the criteria in (15).

we resolve the ambiguity selecting the solution y_k^l that lies closer to the KF prediction:

$$l = \underset{n\in 1,2}{\arg\min} \left\| \boldsymbol{y}_k^n - \boldsymbol{M}\boldsymbol{x}_k(-) \right\|_2 . \tag{14}$$

This improves the performance in the vicinity of the receivers. However, as can be seen in Fig. 7(a), locations exactly behind a receiver additionally suffer from a very high DOP.

B. Reference receiver selection

Another way of improving the localization performance is to select the reference receiver for the localization algorithm based on the current location of the target. For high SNR this can be formulated as an optimization problem where we want to select the reference j from the set of M receivers such that

$$j = \underset{r\in\{1,..,M\}}{\arg\min} \ \mathrm{DOP}^r . \tag{15}$$

An example for the reference receiver selection in a 3 sensor network is depicted in Fig. 7(b).

VI. RESULTS

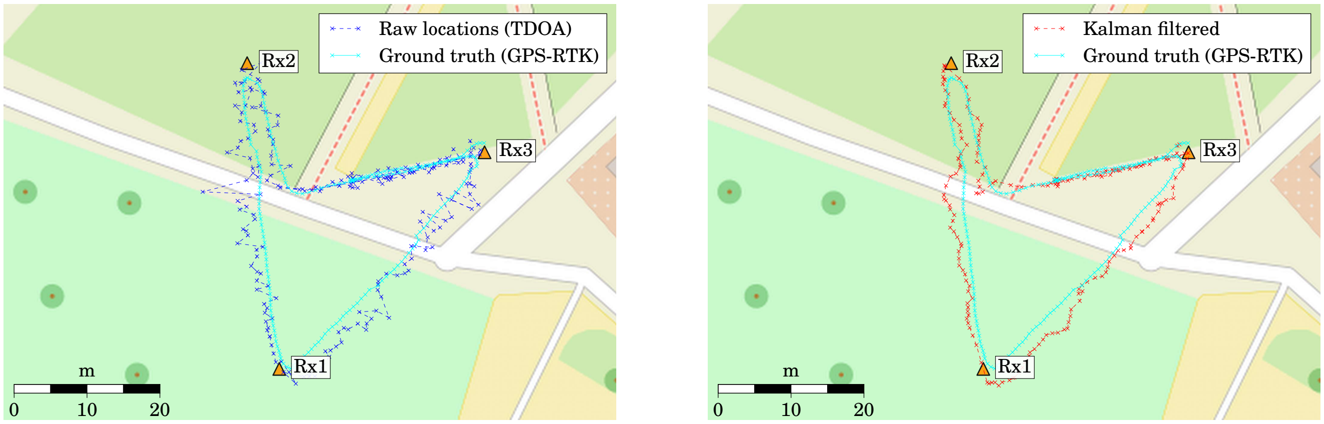
In order to evaluate the performance of the TDOA localization system we have carried out several outdoor measurements in front of the *ICT cubes* building of RWTH Aachen University. The evaluation itself is not a trivial task as it can be very challenging to obtain accurate ground-truth.

A. Obtaining ground-truth

We solve the problem of obtaining highly accurate ground truth using GPS real time kinematic (RTK) technology. RTK is a type of differential GPS that is based on carrier phase measurements. In good conditions, i.e., clear skyview, no multipath, it has an accuracy of ±2-3 cm. A RTK system consists of two units, the basestation and the rover. Both have to be connected by a datalink to enable the calculation of the differential solution in the rover. A set of tools called *rtklib* [22] provided initial affordable access for research to RTK and is regularly used. However, for our evaluation we primarily use the very recently released u-blox C94-M8P. This is an affordable fully embedded solution including a basestation, rover and UHF datalink. To obtain the absolute location of our RTK basestation with centimeter accuracy, we use *SAPOS* [23], the German network RTK solution operated by the government. For this initial survey SAPOS acts as a virtual RTK basestation and one of our RTK capable receivers has to act as the rover. We then place our own RTK basestation on the surveyed point and the RTK rover together with the target emitter on the staff, such that we can always accurately determine the ground-truth. For this to work properly it is very important to have the GPS antenna mounted on a ground plate on top of the staff with unobstructed skyview. The carrier phase measurements necessary for the RTK are highly susceptible to multipath reflections, a human body close to the antenna of basestation or rover is sufficient to prevent the functioning of the system.

B. Pedestrian tracking

With the ground-truth recording problem solved, the system has been used to track the movement of a pedestrian. The measurement area was about 50×50 m in size. A number of 3 sensors has been used, connected to the FC with a WiFi backhaul. The exact locations of the sensor antennas have been obtain with the RTK reference and the GPSDOs have been set to time mode. Signals transmitted by the target where binary phase shift keying signals with a bandwidth of 50MHz. The receiver bandwidth has been set to 50MHz with a subsequent lowpass filter. The received signals have been interpolated by a factor of 10. Finally the value for σ_τ, for the KF measurement noise has been measured as 3.16×10^{-9} s with a stationary target in the middle of the area. For pedestrian tracking, a good value for the KF process noise standard deviation σ_a has been determined experimentally to be 0.41 m/s^2 and the correlation coefficient $\rho = 0.15$. The measured tracks are shown in Fig. 8. The root-mean-square error compared to the RTK solution is 2.27 m for the raw localizations and 1.64 m for the Kalman filtered result.



(a)

(b)

Fig. 8: Localizing a walking pedestrian. The ground truth from the GPS-RTK is plotted in cyan. Raw localizations in (a) and the output of the Kalman filter in (b).

VII. CONCLUSION

We have described our implementation of a software defined radio based radio localization system composed of low cost state-of-the-art components. Our system performs time difference based localization in real-time based utilizing a distributed software framework. Results demonstrate the high accuracy that can be achieved with current technology even if a common clock system is not available and GPS has to be used for synchronization. Localization accuracy is further improved with the help of Kalman filter based tracking. The flexibility of the Software Defined Radio has enabled the investigation of different waveforms and it's parameters and sets the basis for employing the testbed in further research on advanced concepts.

VIII. ACKNOWLEDGMENTS

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