An Approach for Implementation of Ranging and Positioning Methods on a Software Defined Radio

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Abstract—**In this paper an approach for implementation of a time of flight ranging and positioning methods on a software defined radio (SDR) platform is presented. The proposed approach is intended to be implemented in software on a host computer without changing the existing hardware of the SDR platform.**

Using this approach a two way ranging (TWR) method is implemented on a SDR platform. All of the necessary processing is performed in C/C++. This implementation was tested in the 2.4/5 GHz ISM band, with a channel bandwidth of 25 MHz. It achieves a nanosecond timing precision, needed in time of flight (ToF) based ranging and positioning applications. A ranging accuracy better than 1 meter was achieved and demonstrated. The developed TWR system performs 100 distance estimations per second. Nevertheless, with the processing power of the currently available general purpose processors a distance estimation rate of over 500 estimations per second can be achieved. The proposed approach can be also used in positioning scenarios, by performing TWR with multiple anchor nodes.

I. INTRODUCTION

Indoor localization has gained popularity in the last decade. It should complement the global navigation satellite systems (GNSS) in areas where they are not available or can offer only poor precision and accuracy. Having localization capability in GNSS denied areas would additionally open new perspectives for future location based services (LBS).

A few different methods are usually used for radio frequency (RF) indoor localization. The simplest ones use the received signal strength (RSS) to estimate the position of a wireless node with an unknown position. WiFi fingerprinting [1] is the most popular among them. Nevertheless, it lacks positioning precision and is favored only because no additional hardware is needed, except the already available WiFi infrastructure. It can be implemented on almost any WiFi capable device.

If a higher positioning precision is required, methods utilizing time of flight (ToF) estimation are commonly used. Angle of arrival (AoA) can be also used, but it requires multiple, beam steerable antennas and more complicated hardware.

ToF based methods estimate the time of arrival (ToA) of a waveform, or frame, at the receiver in order to obtain the ToF and, therefore, distance. They have a higher complexity compared to the RSS methods. The higher complexity is due to large channel bandwidths needed for precise position (or distance) estimation. The large channel bandwidth requires high sample rate A/D converters and a complex hardware for processing of the acquired samples. The processing can be performed on an ASIC or on a programmable hardware like FPGA. Also processing in analog domain, e.g. estimation of ToA in impulse radio ultrawideband (IR-UWB) devices [2], is a common choice in order to reduce the complexity of the overall system.

In this paper an approach for implementation of ToF based positioning methods on a software defined radio (SDR) is proposed. This approach focuses on implementation of two way ranging (TWR) and can be further extended to support two- or three-dimensional positioning. This approach can be also used for implementation of other ToF based methods on systems which have wireless data transceivers, like WiFi. It would require minor hardware and software changes in these systems.

The proposed approach is implemented in software and runs in real-time without the need to use specialized hardware, like ASIC or FPGA. The received waveform is sampled with a sample rate of 50 MSps complex samples, i.e. the highest supported by the used SDRs, in order to achieve highest ranging accuracy and precision. The used 3 dB channel bandwidth is 25 MHz. Real-time processing of samples with such a high sample rate on a commercially available host computers is challenging. The proposed approach allows to process the samples acquired with these sample rates on a commercially available computers. A distance estimation rate of over 100 estimations per second is achieved using a single CPU core.

The following of this paper is organized as follows: In section 2 the related work is presented. In Section III the approach for implementing ranging and positioning methods on a SDR platform is given. Section IV discussed the implementation details of TWR using the proposed approach on a SDR platform. In Section V the performed tests and the obtained results are discussed. The conclusion and the future work are presented in Section VI and VII respectively.

II. RELATED WORK

Software defined radio (SDR) platforms are mainly used in data transmission applications and for evaluation and verification of different algorithms and methods used in these applications. Nevertheless, different ranging and positioning methods are lately being implemented on software defined radios.

In [3] and [4] the authors describe two different RADAR implementations on a SDR platforms. The implementation is possible because the transmitter and the receiver present in the SDR platforms are synchronized. In a RADAR application, the transmission and the reception are performed simultaneously and for a short period of time. The acquired samples are processed and another transmission follows after the processing is finished.

In [5] a TWR approach implemented on a SDR platform is presented. Nevertheless, this approach requires that some of the functionalities are implemented in hardware since they require significant processing complexity which cannot be achieved in software.

Positioning methods using SDR platforms are presented in [6] and [7]. These methods are based on time difference of arrival (TDOA). They do not perform ranging with respect to the anchor nodes. The waveforms from the anchor nodes are received and the position of the node with unknown position is estimated. A minimum of four anchor nodes are needed for a two-dimensional positioning.

III. AN APPROACH FOR IMPLEMENTATION OF RANGING AND POSITIONING METHODS ON A SDR PLATFORM

Implementation of ranging and positioning methods in software is mainly limited by the high sample rate and large channel bandwidth needed for achieving high spatial resolution and precision. This is mainly due to the need for processing of all of the arriving samples acquired by the A/D converter, in order to detect the arrival of a ranging frames. The needed processing of samples with the required sample rates cannot be achieved in software with a commercially available CPUs. The proposed approach avoids processing of all of the received samples, by scheduling the frames used for ranging and processing only the samples in which the received frames are expected.

A. Two way ranging

Two way ranging (TWR) is a ToF based distance (range) estimation method which can be also used for positioning. Its timing diagram is shown in Figure 1. It is preferred ranging method because the synchronization requirements between the nodes performing this method are significantly relaxed.

The TWR is performed using two transmissions. The node N_1 transmits a frame to node N_2 and when node N_2 receives this frame is replies back to node N_1 with a new frame. The node N_1 measures the round trip time t_{round} and the node N_2 measures the reply time t_{reply}. According to Figure 1 the ToF and, therefore, distance can be calculated as

$$t_{tof} = \frac{t_{round} - t_{reply}}{2} \tag{1}$$

Implementing TWR as descibed here on an SDR platform and in software is not possible due to the high computational complexity needed for detection of an arriving frame used for ranging. The high complexity is in the preamble detector needed for detection of the frame arrival. It must perform the processing in real-time and on a high sample rate stream of samples. It can be implemented only in hardware if high sample rates are required.

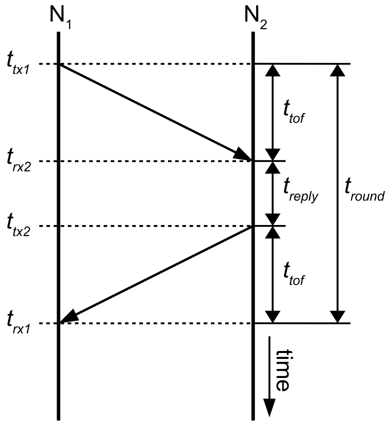

Fig. 1. Two way ranging

In order to overcome this issue, a TWR implementation with receive windows is used. This approach is shown in Figure 2. In this approach, node N_1 transmits a ranging frame (blue) and node N_2 schedules a window for reception (yellow). After finishing with reception of initially defined number of samples, node N_2 transmits back a frame to node N_1. The node N_1 schedules a receive window (yellow) with initially defined number of samples to be received. When the samples from the receive windows are received, the both nodes estimate the ToA of the received frames. By having the ToA of the received frames, the t_{round} and t_{reply} can be easily calculated.

For this approach it is important that the frame trasmitted from node N_1 falls into the receive window of node N_2 and the frame transmitted from node N_2 falls into the received window of node N_1. In order to achieve this, a mechanism for coarse synchronization between the nodes must be available.

The main advantage of this approach is that both nodes must not process a continuous stream of samples in order to detect an incoming ranging frame. Only the samples in the received

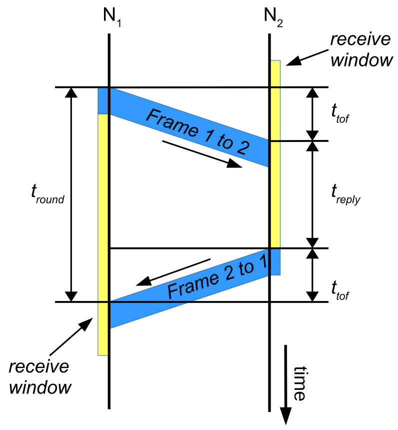

Fig. 2. Two way ranging using receive windows

windows must be processed. Having a better synchronization between the two nodes would lead to shorter receive windows and, therefore, less computational effort at the nodes.

B. Synchronization of the receive windows

In order to implement a real-time TWR in software using SDR platforms the two nodes must be synchronized, i.e. the transmitted ranging frames must be received in the scheduled receive windows. In the approach proposed in this paper, one of the nodes, e.g. N_1, is the master and the second node, e.g. N_2, is the slave. The master node N_1 starts by transmitting beacon frames periodically, with a given period, e.g. 10 ms. Node N_2 synchronizes its receive window to this beacons frames and after receiving a becacon frame in the receive window, it transmits back a ranging frame to node N_1, similarly as shown in Figure 2.

Before performing TWR, node N_2 performs a synchronization of the receive window with the beacon frames transmitted by N_1. The synchronization process is shown in Figure 3.

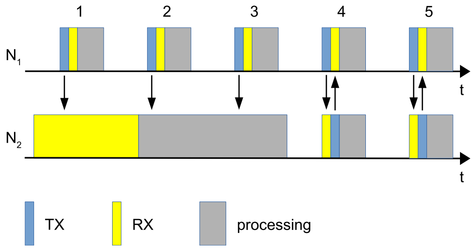

Fig. 3. Time diagram of the proposed receive window synchronization scheme

The slave node, N_2, starts by listening and acquiring samples (first yellow rectangle). The time for which node N_1 acquires samples, must be longer than the period at which the beacon frames are transmitted, in order to ensure reception of at least one beacon frame. The processing is performed immediately after reception (gray rectangle) and the node N_2 searches for the received beacon frame. The processing is performed on a host computer and would take significant amount of time. During this time the incoming beacon frames would not be received. Nevertheless, after the beacon frame is detected in the previously acquired samples, node N_2 can estimate the time at which the next beacon frame should be received. It schedules a receive window at this time instant and transmits a frame back to node N_1 after the receive window is finished.

Node N_1, on the other hand, schedules a receive window after each transmitted beacon frame. In this receive window, the frame transmitted by node N_2 should be received. This is shown in period 4 and 5 in Figure 3.

After acquiring samples at both nodes, containing the received ranging frames, processing at the host computers is performed. The node N_1 estimates the ToA of the frame transmitted by node N_2, and subtracts the time of transmission of the beacon frame in order to calculate the round trip time. The node N_2 estimates the ToA of the bacon frame and subtracts it from the time at which it transmits a frame back to node N_1 in order to calculate the reply time. Having both the round trip time and the reply time, the ToF and, therefore, distance can be estimated. The both, round trip and reply times should be available at one of the nodes for the purpose of ToF, i.e. distance estimation. They can be transmitted in the next TWR cycle by including these times in the header of the transmitted ranging frames.

Due to the clock offset between the nodes, it can occur that the receive window position at node N_2 drifts with respect to the transmitted frame. Therefore, for each next scheduled TWR node N_2 must reschedule the receive window according to the position of the received beacon frame. The beacon frame duration is shorter compared to the receive window duration and, therefore, some small drift can be tolerated, but it must be tracked and corrected.

Initially, the TWR is performed periodically, but once the nodes get synchronized, they can reschedule the TWR process.

IV. IMPLEMENTATION OF THE PROPOSED APPROACH ON A SDR PLATFORM

The presented approach is implemented in C/C++ in order to test it further on an SDR platform.

Node N_1 transmits a frame having a structure shown in Figure 4.

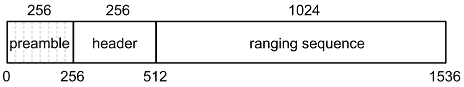

Fig. 4. Structure of the frame used for performing TWR

The preamble is consisted of 8 copies of a pseudo-random waveform. The header consists of multiple fields, containing source and destination addresses, sequence number, reply and round trip time etc. A CRC is used for error checking. Finally, a m-sequence (maximum length sequence) is used for ranging. The length of the m-sequence is 1023 and the generating polynomial is $x^{10}+x^3+x^2+1$. The frame is modulated using BPSK modulation, up-sampled by a factor of 2 and filtered using square root raised cosine (SRRC) filter. This frame is transmitted from node N_1, periodically.

The node N_2 schedules a long receive window at the beginning. In order to find the received frame, the receiver filters the acquired samples using SRRC filter and performs autocorrelation using an auto-correlator shown in Figure 5.

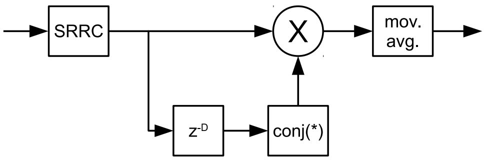

Fig. 5. Auto-correlation based preamble detector

If a beacon frame is received, the autocorrelator would produce a flat top peak at the output. This peak is used to estimate and correct the frequency offset between the nodes and as a marker for the start of the beacon frame. Using this peak, the samples containing the frame are extracted and further processing is performed. At first, the start of the header is detected and the data contained in it is demodulated. Further, a cross-correlation of the received frame with a locally generated m-sequence is performed. The cross-correlation produces a peak which is used for precise ToA estimation. In order to perform subsample ToA estimation, the peak is interpolated using quadratic interpolation and its position is precisely estimated.

After performing ToA estimation, the node N_2 calculates the time of the next transmission from node N_1 as

$$t_{n1tx} = t_{ToA} + (n+1)T_{tx} \tag{2}$$

where t_{ToA} is the estimated ToA, T_{tx} is the beacon transmit period and n is the number of not received beacon frames due to long processing time of the received samples. The receive window duration is t_{slot} which is also the duration of the slot in which the beacon frame from node N_1 is transmitted. A transmission of a frame from node N_2 to node N_1 is scheduled immediately after the receive window, i.e. at time

$$t_{n2tx} = t_{ToA} + (n+1)T_{tx} + t_{slot} \tag{3}$$

Node N_1 also schedules a short receive window after each transmission of a beacon frame. In this window the frame from node N_2 is expected. The samples received in the receive windows at the both nodes are processed on the host computer. Since these windows are relatively short, the processing is finished and the ToA is estimated before the next TWR takes place. The estimated ToAs are used to calculate the round trip time and the reply time. The obtained values are exchanged between the two nodes when the next TWR takes place.

The both nodes control automatically the receive gain and the transmit power. When for a single TWR, the received signal power levels are too small, the transmit powers and the receive gains are increased, and respectively decreased if the received signal power levels are too large. In case that the slave node N_2 does not receive a beacon frame from node N_1, in a few successive receive windows, it schedules a long receive window in order to acquire the beacon frame. The receive gain is also actively controlled in this phase.

V. TESTING AND RESULTS

The proposed approach was tested using SDRs in an indoor scenario. The used SDRs are Ettus Research USRP N210 radios with SBX analog front-ends, working in the 2.4 GHz ISM band. The beacon transmit period T_{tx} is 10 ms, and the duration of the slot for transmission of the beacon frame, t_{slot}, is limited to 400 us. The beacon frame is the same as in Figure 4, up-sampled by a factor of 2. The frame length, t_{frm}, is 61.6 us and can be further extended if longer ranging sequence is required. Both radios sample the in-phase (I) and quadrature (Q) signals with a rate of 50 MSps. The acquired samples are 8 bit wide, which is satisfactory for a BPSK modulation and ranging applications. The 3 dB bandwidth of the transmitted waveform is 25 MHz. The roll-off factor of the used SRRC filters is 1.

The master node is consisted of a single USRP N210 and a host computer with a Intel(R) Core(TM) i5-5300U @ 2.30GHz processor. The slave node is consisted also of a single USRP N210 and a host computer with a Intel(R) Core(TM) i5-5300U @ 2.30GHz processor. A single core is used in both cases for performing the described approach and processing of the acquired samples.

The slave node N_2 at start receives samples in a long window with duration of $t_{long} = T_{tx} + t_{slot} = 10.4\ ms$. The time needed for processing of these samples and estimating ToA of the beacon frame is about 45 - 49 ms. This means that five transmissions of the master node would not be received at N_2. Nevertheless, the next received window is scheduled to receive the sixth transmission of the master node.

After initial estimation of the time of arrival of the beacon frame, a receive window with duration of one slot, t_{slot}, is scheduled and received. The samples are processed on a host computer in order to find the frame and to estimate the time of arrival. On the slave node the processing of theses samples requires approximately 0.9-1.4 ms, using a single CPU core. Having a slot of 10 ms between the beacon frames from the master node, the slave node would be in idle state for approx. 8 ms, taking into account that some time, less than a millisecond, would be needed for preparing the frame to be sent back to the master node. This gives the opportunity to use this system in localization scenarios, since in the remaining 8 ms four additional ranging frames received from other anchor nodes can be processed. Another opportunity is to increase the distance estimation rate of up to 500 distance estimations per second. The applications that need such a high distance estimation rate are probably rare, but these additional measurements can be averaged to obtain better distance estimation precision.

Further the implemented system was tested in a ranging scenario in order to evaluate its accuracy and precision. Omnidirectional antennas with gain of 2.5 dBi were used on both nodes. The first tests were performed in an anechoic chamber in order to minimize the reflections from surrounding objects, which can affect the accuracy of the system. The floor plan of the anechoic chamber is shown in Figure 6. The dimensions

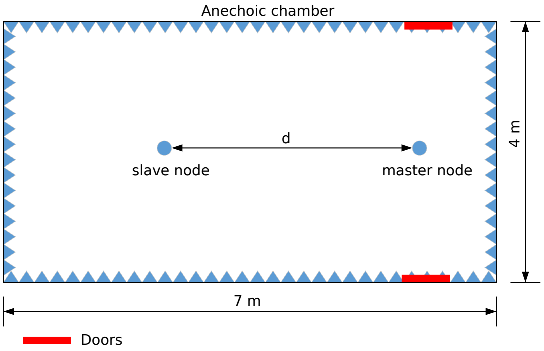

Fig. 6. Anechoic chamber floor plan and testing scenario

of the chamber are 4m x 7m x 2.8m (WxLxH). The distance d between the two nodes was changed from 1 to 5.4 meters in steps of 40 centimeters. The nodes were placed on a height of 1.5 meters. For each distance, hundreds of measurements were performed in order to statistically evaluate the obtained results.

In Figure 7 the estimated distance as a function of true distance is shown. The shown estimated distances are actually the averages of the obtained distance estimates. This gives an overview of the accuracy of the system. As can be seen, the accuracy of the system in this case is less than a half meter.

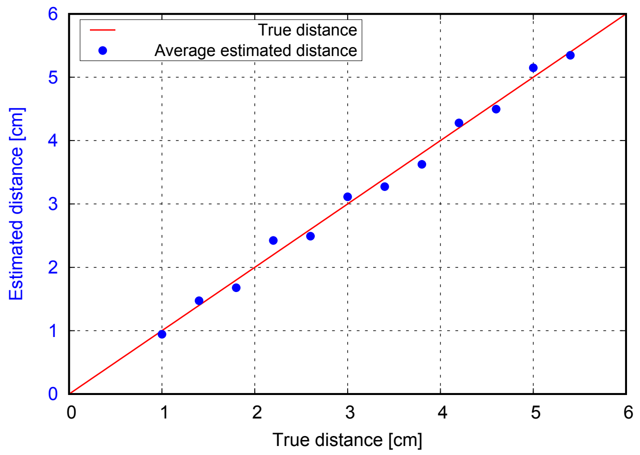

Fig. 7. Estimated distance as a function of true distance for the anechoic chamber scenario

The cumulative distribution function (CDF) of the distance estimation error is shown in Figure 8. Each CDF curve corresponds to each estimated distance. The CDFs are a measure of the precision of the acquired distance estimates and show how these estimates are distributed around the mean value.

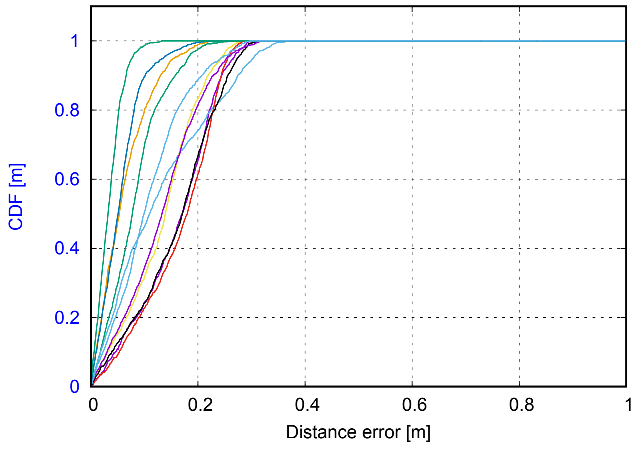

Fig. 8. CDF of the distance estimation error for each measurement distance (anechoic chamber)

As can be noticed from the obtained results, the estimated distances follows the true distances very good. From the CDF plot in Figure 8 it can be seen that the ranging precision for all of the distances is below ±0.4 meters. The CDFs for different distances are not the same, because the system automatically changes the receive gain and transmit power in order to compensate for the path loss and to obtain optimal use of the dynamic range of the A/D converter in the SDR. Therefore, different SNR levels would be present for different distances.

The system was also tested in a realistic scenario, i.e. hallway, where multiple reflections are expected. The floor plan of the hallway used for testing is shown in Figure 9. The hallway has brick walls and multiple wooden and metallic doors, which would introduce multiple reflections. The nodes are placed on a carts on a height of 80 cm and the distance between them is changed from 1.4 to 10 meters with a step of 0.4 meter. For each distance between the nodes a few hundreds distance estimates are performed. In Figure 10 the mean estimated value for each distance is shown. As can be noticed in Figure 10, the largest error is less than a meters. This shows that even in a scenario in which large number of reflections are expected, the ranging error can be kept under 1 meter in most of the cases. The CDFs of the distance estimates for each distance are given in Figure 11. From the CDFs it can be noticed that the distance estimation precision is less

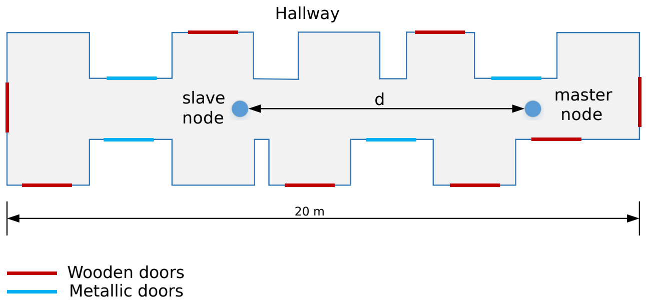

Fig. 9. Hallway floor plan and testing scenario

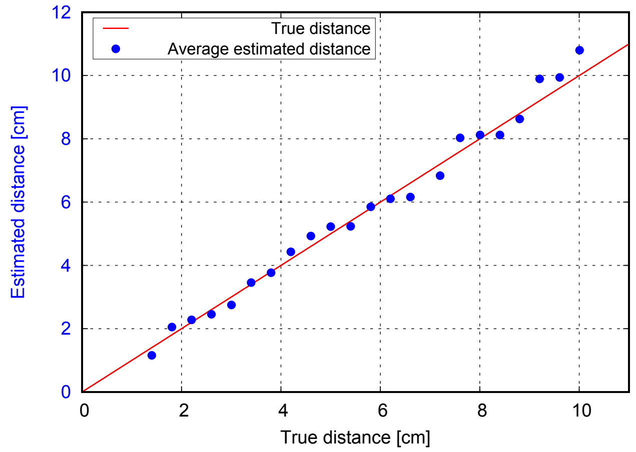

Fig. 10. Estimated distance as a function of true distance for the hallway scenario

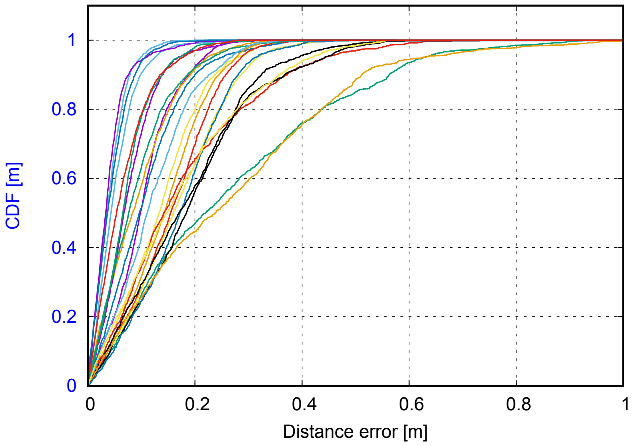

Fig. 11. CDF of the distance estimation error for each measurement distance (hallway)

than ±1 meter with respect to the mean value. The decreased precision is due to the lower SNR for larger distances. Also lower SNR would be present in cases where the wave traveling the direct path and the wave being reflected from an obstacle combine destructively.

It should be noted here that the group delays of the signals in SDRs were not calibrated. It can be expected different group delay of the signal in SDRs for different receiver gains and different transmit powers. This would affect the ranging precision and accuracy and, therefore, these delays should be estimated beforehand and compensated.

In order to reduce the number of reflections and to achieve better ranging and positioning accuracy, directional antennas can be used. Usually patch antennas with radiation angle of 180 degrees or less are preferred, since they can be placed near walls without radiating toward them and introducing additional reflections.

VI. Conclusion

In this paper an approach for implementation of a TWR on a SDR platforms is described. This approach do not require any additional hardware changes in the SDR platform and is completely implemented in software. The software implementation is preferred for experiments since different changes can be introduced easily and can be deployed immediately. Hardware implementation, on the other hand, is notably more complicated and time consuming. Nevertheless, this approach is not exclusively intended for implementation on SDR platforms. It can be adapted for implementation of existing data transceivers, by introducing minimal changes in hardware. Also in this case the processing can be performed in software, which reduces the overall cost.

It has been shown that software implementations of this approach offers accuracy and precision of under 1 meter, in indoor scenario. The precision and the accuracy mainly depend on the used waveforms and the distance estimator itself, as well as the used bandwidth and the transmit power.

This approach can be further extended and it can be used for localization using multiple master, i.e. anchor, nodes and trilateration.

The signal processing performed in software is efficient and can offer more than 500 distance estimations per second. This can satisfy the needs of most of the applications requiring ranging and position estimation.

VII. Future work

The future work would include improvement of the ranging accuracy and precision of the developed system. The calibration of the SDRs should be performed at first, in order to compensate the variable group delays for different receive gains and transmit powers of the used radios. Further, this approach should be extended for use in positioning scenarios. The main problem to be solved is the scheduling of the transmissions between different master nodes, i.e. anchor nodes. These transmissions should not collide and a mechanism for negotiation of the time of transmission between these nodes should be established.

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