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Achieving Millimeter Precision Distance Estimation using Two-Way Ranging in the 60 GHz Band

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***Abstract*— The large channel bandwidth of about 2 GHz available in the 60 GHz ISM band enables millimeter precision ranging and positioning. The high localization precision, combined with the multi-gigabit data throughputs achievable in this band represents the launch pad for the development of many new applications. In this paper, we propose an approach for implementation of high-precision ranging in the 60 GHz band. This approach can be also used for achieving precise localization. Our approach uses two-way ranging (TWR) for distance estimation between two wireless nodes. It requires minimal hardware implementation effort and performs all the necessary processing in software. The proposed approach was implemented on a custom baseband processing unit with commercial 60 GHz analog frontends. Tests were performed indoors in a lab environment. The obtained results show that a precision and accuracy of less than 5 mm can be achieved. This excellent result outperforms other similar solutions currently available.**

Index Terms—Ranging, 60 GHz, TWR, localization, high precision

I. INTRODUCTION

In the recent decade, indoor localization is becoming an interesting topic due to the plethora of location-based services and applications requiring positioning. These applications mainly rely on global navigation satellite systems (GNSSs), for outdoor, and on WiFi for indoor positioning. A combined solution of GNSS and WiFi offers an accuracy of few meters for outdoor scenarios, fulfilling the requirements of many applications. Nevertheless, in indoor environments the situation is significantly different. The GNSS signal is rarely available and the only possibility for positioning is to use the existing WiFi signals. The problem stems from precision of WiFi indoor localization solutions, which is usually not better than a few meters.

Radio frequency (RF) indoor positioning can be performed by measuring different parameters of the received radio signal. The simplest approach for distance and position estimation utilizes the received signal strength (RSS) of the radio signal at the receiver. Since the received signal power decays with distance, this approach is simple and straightforward. Friis equation [1] can be used for distance estimation in free space. However, in indoor environments, due to multipath propagation, this would be possible only with limited precision. Methods like fingerprinting [2], i.e. creating signal strength maps, can additionally improve the localization precision and accuracy, but the process of creating these maps can be time consuming.

To achieve higher ranging and localization precision and accuracy, the so-called time of flight (ToF) methods are more suitable. In these methods, the time needed for a radio wave to travel from the transmitter to the receiver is estimated, from which the distance or the position is easily calculated. The main advantage of these methods is that they do not require any tedious process to be performed beforehand, as for example map generation in fingerprinting methods. To find a position of a user (mobile node), i.e. user equipment (UE), anchor nodes (access points) must be deployed in advance. Their positions must be known beforehand. These methods are also not immune to multipath propagation of the radio waves. Estimating the ToF when multipath components arrive at the receiver can significantly degrade the result. Nevertheless, contrary to the RSS based methods, it is possible to improve the distance and position estimate accuracy by simply increasing the bandwidth of the used RF signal. Having a large bandwidth, multipath components can be easily resolved. In line of sight (LOS) scenarios, the first component would be the one travelling the direct path and it would be used for ToF, i.e. distance estimation.

The ToF approach is already used in GNSS and other specific localization applications. For indoor use, there are proprietary solutions operating in the 2.4/5 GHz ISM bands [3], as well as UWB solutions [4]. The 2.4/5 GHz ISM band solutions are lacking accuracy due to the relatively small channel bandwidths available in these bands. They usually have issues in resolving multipath components, which directly affects their accuracy. The UWB solutions use larger bandwidths, i.e. 500 MHz, hence they can easily resolve multipath components and use only the direct path for distance estimation. They can achieve much better accuracy and precision. Finally, at 60 GHz there is a huge ISM band, which varies from country to country, spanning up to 9 GHz. At least a few channel of 2 GHz are usually available in this band, which means excellent ToF estimation accuracy and precision.

In this paper, we present a method for implementing a so-called two-way ranging (TWR) algorithm in the 60 GHz band. The implementation is performed on a specialized software defined radio (SDR) board, i.e. baseband processing unit [5]. The distance estimation algorithm is implemented in software and executed on a host computer. With the implemented approach, an accuracy and precision of less than 5 millimeters is achieved. The same system can be used for high precision localization if more anchor nodes are deployed.

The rest of this paper is organized as follows: Section II presents the related work in this area, Section III describes the proposed approach, Section IV presents the performed experiments and obtained results and Section V concludes the paper and gives future work directions.

II. Related Work

Previous work on localization systems in the 60 GHz band is not as extensive as, for example, for UWB systems. The main reason is that the 60 GHz devices are still more expensive compared to UWB devices and the overall approach is more complex. Nevertheless, this is beginning to change, since 60 GHz systems offer higher ranging and positioning precision while, at the same time provide gigabit throughputs, which is not the case with UWB systems.

Ohlemueller et al. [6] presented the first work on ToF-based ranging in the 60 GHz band, according to the best of our knowledge. The authors used orthogonal frequency division multiplexing (OFDM) and a scheme called "round trip phase". They achieve a precision of less than 30 centimeters due to relatively small channel bandwidth, i.e. 400 MHz.

Ehrig et al. [7] implemented a system, which performs TWR using the algorithm in [6], and simultaneously enables a high data throughput. The ranging precision is again below 30 centimeters while, at the same time, achieving a data transmission with 1 Gb/s throughput.

Maletic et al. [8] analyze the use of both Sub-6 GHz band and millimeter wave (mmWave) for localization purposes. In their work, the Sub-6 GHz band is used for angle of arrival estimation and mmWave is used for distance estimation. Combining the two, the position of a UE can be easily estimated. Having base stations and UEs with collocated Sub-6 GHz and mmWave transceivers is envisioned in the next generation 5G networks.

Xing et al. [9] proposed a back propagation neural network algorithm, which significantly improves the precision of RSS-based methods. Anyway, the achieved accuracy and precision are one order of magnitude worse compared to ToF methods.

Indirayanti et al. [10] presented a transmitter at 60 GHz and used it for ToF-based ranging. The achieved precision is few millimeters, but the bandwidth used is 6 GHz.

From the previous work can be concluded that ToF-based methods offer excellent precision and accuracy. Nevertheless, they can be further improved and the implementation can be further simplified.

III. RF Ranging in the 60 GHz band

The main complexity of ToF-based methods lies in the time of arrival (ToA) estimation. A maximum likelihood (ML) estimator is used in most of the cases [11] but the limited channel bandwidth constraints the achievable accuracy.

There are a few different ToF-based methods: ToA, time difference of arrival (TDoA), two-way ranging (TWR) [12] etc. The first two have strong requirements for synchronization of the anchor nodes (fixed RF nodes/access points with known locations), in a network used for localization.

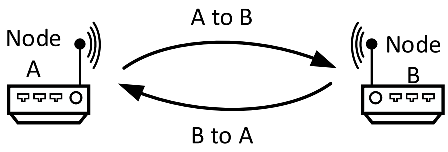

Fig. 1. Basic TWR approach

These nodes should be synchronized with nanosecond precision, which is a challenging task. The TWR method is in this sense more relaxed, i.e. the anchor nodes must not be tightly synchronized. They can deploy a frame arrival detection, or implement a coarse synchronization algorithm that needs to provide a microsecond precision synchronization. This is possible with all of today's widely used wireless data communication systems.

A. TWR: algorithm description

TWR is performed between two wireless nodes (devices) in order to estimate the distance between them. A basic TWR approach is shown in Fig. 1. The first device, node A, initiates the TWR algorithm by sending a frame to the second device, i.e. node B. The second device receives the frame and sends a reply frame to the first device. The first device estimates the round trip time, t_{rtt}, and the second device estimates the reply time t_{rt}. The time of flight, t_{tof}, is found as

$$t_{tof} = \frac{t_{rtt} - t_{rt}}{2}. \quad (1)$$

Having the ToF, the distance can be easily calculated by multiplying it with the speed of light. The time of arrival at both nodes is estimated in two steps. First, the frame arrival is detected and samples are acquired and stored in the memory. Second, an algorithm for precise estimation of the frame arrival is executed on these samples. The frame arrival can be detected in two ways. First, a synchronizer, which detects the frame arrival can be used. Second, if the system already supports data transmission, the MAC layer usually can schedule the frame transmissions with high precision (i.e. microsecond precision). In this case, the MAC processors in both nodes can schedule transmission of ranging frames and reception windows for the arriving frames.

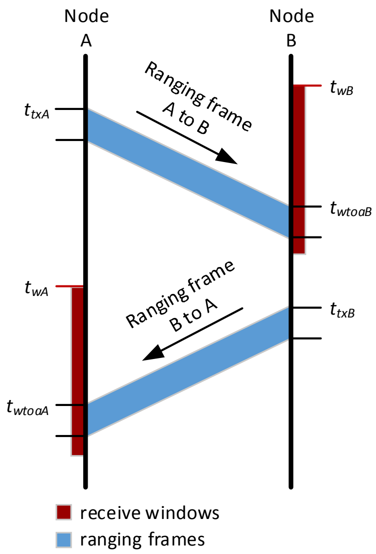

Fig. 2. Time diagram of TWR with time windows

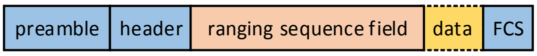

Fig. 3. Ranging frame structure

The received frames are stored in memory and the ToA is estimated offline. This approach is shown in Fig. 2. In both cases, after estimation of the ToA, the round trip time and reply time are calculated and exchanged between the nodes. From these times, both nodes can estimate the ToF and, therefore, the distance. The second approach reuses the functionality of the existing data transmission system, i.e. physical (PHY) and MAC layers.

B. ToA estimation

To precisely estimate ToA, the ranging frame must be carefully designed. The frame can keep the same preamble and header as the data frames used in data transmission system. However, it should contain an additional field, consisting of a modulated pseudo-random (PR) sequence (ranging sequence field). This PR sequence must inherently feature specific autocorrelation properties. The structure of the frame is shown in Fig. 3.

By estimating the ToA of this sequence, the ToA of the ranging frame can be easily estimated. This is performed by cross-correlating the samples of the received frame with those from a locally generated version of the PR sequence. This sequence is usually BPSK modulated. To precisely detect the time of arrival of this sequence, the sequence needs to have a strong correlation peak for $\tau=0$ and weak side lobes for $\tau\neq0$. This is important to precisely detect the cross-correlation peak in the presence of noise. Additionally, the cross-correlation peak can be interpolated to achieve better ToA estimation. Usually quadratic interpolation is sufficient. Many different PR sequences have the required properties and can be used for this purpose. The usual choice are m-sequences or Gold sequences [18].

C. Implementation

In order to test TWR in the 60 GHz band and to acquire qualitative results for the ranging precision and/or accuracy, the TWR algorithm was implemented and evaluated. A diagram of the 60 GHz setup used for the ranging experiments is shown in Fig. 4. A commercial off-the-shelf (COTS) analog front-end (AFE) was used. The baseband unit [5] is used to acquire and generate baseband signals needed for the AFE. This unit works in a so-called SDR mode.

For simplicity in our investigations, a TWR algorithm with receive windows is implemented (see Fig. 3). The ranging frames are expected to arrive in these receive windows and, therefore, only samples from these windows are stored in memory and processed later. Since these receive windows must be synchronized with the transmissions, a separate synchronization cable is used, as shown in Fig. 4. For this algorithm, no strict synchronization of the nodes is needed and, therefore, the use of the cable is not affecting the generality or the quality of our results. Similar solution can be found in [13].

The ranging frames to be transmitted are prepared in MATLAB and stored in the memory of the two baseband units. A command to start TWR is issued to the master (node A) baseband unit. A ranging frame is sent while, at the same time, a receive window start is triggered at the slave (node B) using the synchronization cable. After the sample acquisition process in the receive window terminates, a new ranging frame is transmitted from the slave to the master. Again, a receive window at the master is triggered using the synchronization cable. At the end of the TWR process, both nodes have the samples acquired in the receive windows as well as the timestamps indicating when the ranging frames were transmitted and the timestamps when the receive windows were triggered. Both nodes perform ToA estimation by correlating the received samples with the locally generated PR sequence. This is the same PR sequence residing in the ranging field of the ranging frame. Having the ToA estimation, both nodes exchange the estimated ToAs together with the corresponding timestamps. Using this data, both nodes can estimate the ToF and, therefore, the distance as

$$t_{tof} = \frac{1}{2}(t_{wA} + t_{wtoaA} - t_{txA} - t_{wB} - t_{wtoaB} + t_{txB}), \quad (2)$$

where t_{txA} and t_{txB} are the ranging frame transmission times (timestamps), t_{wA} and t_{wB} are the receive window start times and t_{wtoaA} and t_{wtoaB} are ranging frame time of arrivals with respect to the start of the receive windows. The time of flight, t_{tof}, is calculated as a half of the difference between the round trip time measured in node A, $t_{wA}+t_{wtoaA}-t_{txA}$, and the reply time measured in node B, $t_{wB}+t_{wtoaB}-t_{txB}$. Multiplying the estimated ToF with the speed of light gives the resulting distance.

IV. Experiments and Results

In this section, we present the measurement results of the implemented TWR approach in the 60 GHz band. First, we describe the hardware components used in the testbed, which has the same architecture as in Fig. 4. Then, we present results of the measurements. Ranging results are given for each reference position and the precision of the ranging measurements are analyzed by means of the cumulative density function (CDF) of the distance errors. Finally, the measurement results are analyzed by means of distribution of the ranging errors.

A. Testbed component description

The setup used for the ranging measurements is show in Fig. 4. The baseband unit is a SDR FPGA platform called *digiBackBoard* [5]. This is a universal platform intended for mmWave applications, equipped with high performance FPGA-ARM-SoC (Zynq-7045), 2.16 Gsps data converters and Gigabit Ethernet transceivers.

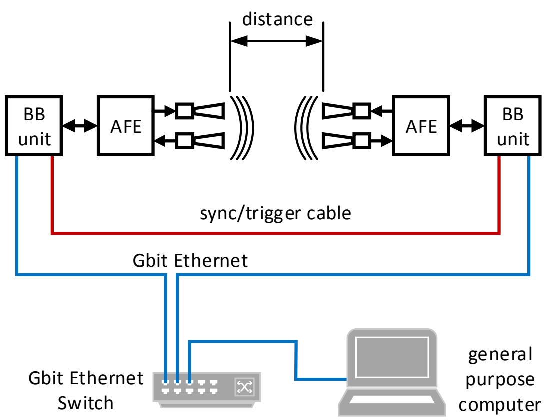

Fig. 4. 60 GHz TWR evaluation test setup

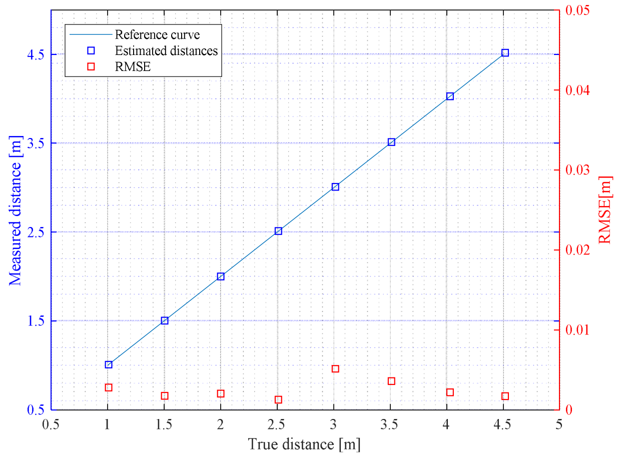

Fig. 5. Estimated distances versus true distances with the room mean squared error

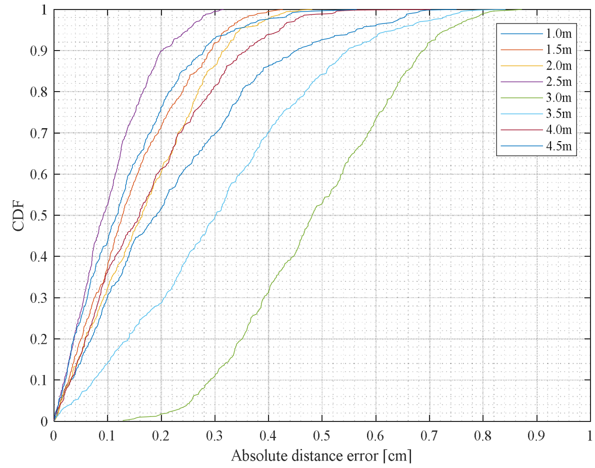

Fig. 6. CDF of the absolute distance error

The AFEs are 60 GHz transmitter and receiver chips from Analog Devices (HMC6300 and HMC6301, respectively). Standard rectangular horn antennas of 20 dBi gain and 15° beam width from SAGE Millimeter, Inc. are used.

Measurements were performed in a lab environment. The distance between devices was varied starting from 1 meter to 4.5 meters with a 0.5 meter step size. For each distance 500 measurements were taken.

The waveform used for the ranging tests is an m-sequence of length $L = 2^{10}-1 = 1023$. The sequence is BPSK modulated and filtered using a square-root-raised-cosine (SRRC) pulse-shaping filter with a roll-off factor of 1. The 3-dB bandwidth is 1 GHz.

B. Ranging results

The estimated distance vs. true distance is shown in Fig. 5, together with the root mean squared error (RMSE). It can noticed that the distance estimates fit accurately the reference curve. The RMSE is below 5 mm.

Additionally, the precision of the distance estimation is analyzed by calculating the CDF of the distance errors. The empirical cumulative distribution function (ECDF) of the distance estimates is shown in Fig. 6. It can be observed that the absolute distance error is below 9 millimeters for all test distances. Additionally, the CDFs of the distance estimates measured at the distances of 3.0 and 3.5 meters are shifted to the right compared to the ECDF of the remaining reference distances. The reason for this might be the existence of side reflections from the test setup.

TABLE I. THE BEST FITTED DISTRIBUTION PARAMETERS

Ranging distance [m]	mean μ [cm]	standard deviation σ [cm]
1.0	0.148	0.235
1.5	-0.077	0.158
2.0	0.022	0.200
2.5	0.027	0.122
3.0	-0.490	0.152
3.5	0.302	0.195
4.0	0.082	0.202
4.5	-0.014	0.170

C. Distribution of the distance errors

It is also interesting to analyze the distribution of distance errors at different reference positions. To find the best-fitted distribution, a Kolmogorov-Smirnov (K-S) test [17] is used to examine the "goodness" of the fit. The K-S test is used to find whether the data come from a specific, continuous distribution by quantifying the distance between the empirical CDF of the data and the CDF of the reference distribution.

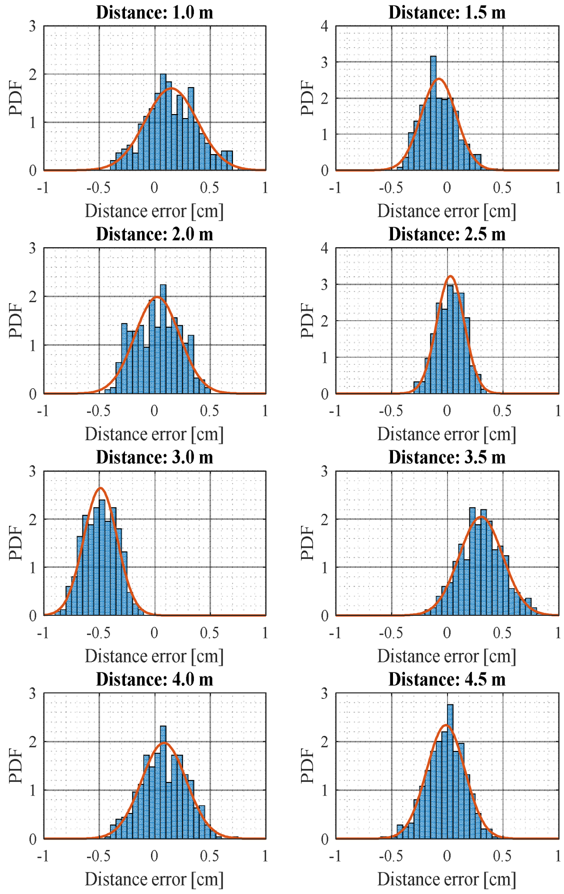

Fig. 7. Distribution of the distance error at the reference positions.

TABLE II. COMPARISON WITH SIMILAR HIGH PRECISION RANGING/POSITIONING APPROACHES

	Band	Bandwidth	Precision	Remarks
This work	60 GHz	1 GHz	<5 mm	single measurement
Fischer et al. [14]	UWB	499.2 MHz	4 cm	filtered/averaged
Schroeer [15]	UWB	499.2 MHz	10 cm	
Indirayanti et al. [10]	60 GHz	6 GHz	2.7 mm	only ToA, no TWR
Ohlemuller et al. [6]	60 GHz	400 MHz	10-30 cm	
Jafari et al. [16]	60 GHz	2 GHz	1 m	TDoA

Fig. 7 shows the histograms of the distance errors at each position and the best-fitted distribution found by the K-S test. For each distance, the Normal distribution was found to be the best-fitted one. Parameters of the fitted distribution are given in Table 1.

Finally, a comparison with other works is given in Table II.

V. CONCLUSION

In this paper, we have presented an approach for implementation of a TWR algorithm in the 60 GHz band using a mmWave baseband processing unit. This unit can be used in SDR mode to simplify the development of new algorithms.

We propose an approach for implementation of TWR algorithms, which requires minimal dedicated hardware and can be easily integrated in data transmission systems. The processing is performed in software, enabling easy implementation of this approach on existing data transmission systems.

The ranging precision and accuracy achievable with this approach were evaluated. The achieved RMS ranging error is better than 5 millimeters. It outperforms all similar systems which use ToF methods and similar channel bandwidth.

The further work will be focused on extending this approach to support localization. TWR localization with multiple anchor nodes will be evaluated, but also ToA approach would be considered.

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