IR-UWB-based localization for indoor applications: Principles and challenges

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***Abstract*—Impulse radio ultrawideband ranging has recently received significant attention in industrial applications due to the high accuracy of localization and the simplicity of deployment and integration in an existing environment. This new technology and the use of established methods for processing brings up a variety of problems and challenges that need to be taken into account. This paper will give an insight on newly developed approaches used to overcome the challenges that arise with the use of ultrawideband localization.**

***Index Terms*—Impulse radio ultrawideband (IR-UWB), tracking, RIOT, non-line-of-sight (NLOS), localization, industrial, ranging, IEEE 802.15.4a, clock synchronization, wireless;**

I. Introduction

In recent years, there has been a rising demand for indoor localization systems providing accurate and reliable information on the positions of people and objects in different environments. The variety of use cases and applications is steadily increasing and therefore systems with an ease of use, a high degree of integration and comparably low costs are needed. The IEEE 802.15.4a standard [1] (UWB PHY [2] from 2011) and the development of modern ultrawideband integrated transceivers like Decawave's DW1000 ScenSor integrated circuit (IC) [3] have enabled the use of platforms that meet these needs.

In order to provide precise localization, the underlying distance measurements need to be as accurate as possible. IR-UWB is capable of delivering centimetre accuracy, highly depending on the amount of fixed nodes, the constellation of node placement, the ranging method and environment specific non-line-of-sight and multipath effects. Due to the wide band of propagated signals, resulting in short pulses with very narrow edges, IR-UWB is able to deliver accurate time measurements with a resolution of up to dozens of picoseconds. The same property leads to robustness in multipath environments, high precision ranging, unlicensed operation and low power transmission. Due to the large bandwidth used for signal generation, UWB signals can penetrate a variety of materials [4]. Therefore IR-UWB signals are particularly suitable for indoor tracking due to the ability to operate in other than strictly Line-of-Sight (LOS) conditions.

Common system architectures consist of a single to a multiplicity of nodes that need to be localized (tags), infrastructure consisting of fixed positioned nodes (anchors) and a system controller for computing.

There are several different approaches that can be used to perform the ranging measurements. The most commonly used are Time of Arrival (TOA), Time Difference of Arrival (TDOA) and Angle of arrival (AoA). Localization is mainly done within a Bayesian framework and the use of trilateration. The main methods are based on variations of Kalman filtering (KF) and particle filtering (PF). To be able to handle non-linear relationships and non-Gaussian uncertainties, extended Kalman filtering (EKF) and PF are preferred.

The rest of this paper is organized as follows: Section II discusses the background of indoor positioning with IR-UWB and the underlying techniques. Section III describes methods that can be used to overcome problems with NLOS conditions. Section IV will show the impact of system clock and a common time domain and how to deal with it using clock synchronization approaches. In Section V the channel utilization in typically deployed systems and the scalability will be discussed. Lastly, Section VI concludes the paper and discusses some future work regarding the use of IR-UWB technology.

II. IR-UWB Ranging

Electromagnetic (EM) waves propagate at the speed of light and therefore time measurements of the emitted signals can be easily converted into distance (i.e. range) measurements. Ranging gives an estimate of the distance between two nodes. The accuracy of the ranging measurements depends mainly on the ability of the system to estimate the correct time of flight (ToF) of the exchanged signals between two nodes.

ToF-based protocols compute the ranging by multiplying the ToF with the propagation speed of the EM waves. For ranging with IR-UWB different concepts are used to calculate the positions and to estimate the ToF and the range measurements.

A. TOA and TWR

With TOA, the mobile node is transmitting messages containing the emission time on a common time domain. Once received by an anchor, the reception time will be marked and sent back to the mobile node. The two timestamps then will be subtracted and the ToF can be calculated on both nodes. With the known position of the anchors and the estimated range between the tag and every single anchor, the localization can be performed with trilateration (Fig. 1). A common notion of time or in other words, a synchronization between nodes'

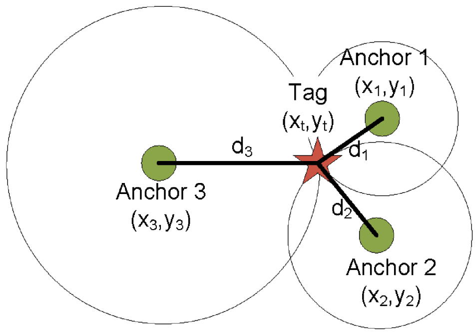
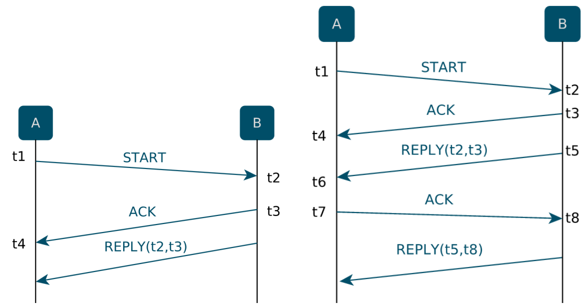


Fig. 1: TOA based localization [5]



(a) TWR (b) SDS-TWR

Fig. 2: TWR and SDS-TWR [6]

clocks is essential for accurate measurements. This is a big challenge, because crystal oscillators used in nodes for precise time measurements suffer from imperfection. They usually do not operate exactly at the nominal frequency they were manufactured for. They tend to have a clock skew and a clock drift over time, caused by temperature and other environmental factors. These non-ideal characteristics are a source of error in these protocols and need to be minimized or eliminated.

The conventional TWR protocol, as proposed by the standard [1], estimates the distance without a common time reference. According to the protocol (Figure 2a), the mobile node records the departure time t_1 of the START message and the anchor records the arrival time t_2 of this received message. The acknowledgement (ACK) will then be sent back and departure time t_3 will be recorded by the anchor. After receiving the ACK, the arrival time t_4 will again be recorded by the mobile node. It is usually impossible for the anchor to predict the departure time of the ACK and therefore the information of t_2 and t_3 will be sent in a separate REPLY message [6]. With the collected information, the ToF can be calculated by:

$$ToF = \frac{t_4 - t_1 - (t_3 - t_2)}{2} \quad (1)$$

In [7], the authors make use of the advanced functionality of the DecaWave DW1000 and have introduced an improved TWR protocol, named 2M-TWR. This feature of DecaWave's MAC-layer [3] allows to send a message at a precise time, already including the information of the departure time. Now the ACK already contains t_2 and t_3 and a separate REPLY message is not needed.

Clock skew still has a noticeable impact on the accuracy of the ToF measurements using TWR. Since the signals propagate with almost the speed of light, even a very small clock offset can cause a significant ranging error. Therefore the Symmetric Double-Sided Two Way Ranging (SDS-TWR), shown in Figure 2b, has also been included in the IEEE 802.15.4a standard [1]. It basically combines two TWR measurements for each direction and reduces the impact of the clock skew error of both nodes. The ToF can be calculated by:

$$ToF = \frac{t_4 - t_1 - (t_3 - t_2) + (t_8 - t_5) - (t_7 - t_6)}{4} \quad (2)$$

SDS-TWR uses at least four messages per ranging to perform the ToF measurement. Literature offers a variety of variants of SDS-TWR to even further compensate the effect of clock skew or to reduce the channel utilization.

In [8] and [9], the authors propose the SDS-TWR-Multiple Acknowledgement (SDS-TWR-MA) method for increasing overall system accuracy by collecting many samples related to the same anchor, despite of reducing the total amount of packets transmitted. Each ranging is initialized by a request packet of the mobile node. The difference to the standard SDS-TWR is a multiple response containing an ACK and a data request in every response of the fixed node (Fig. 3). Every response is performed after a fixed and predefined reply time. Therefore this method for example only transmits six packets for three performed ranging measurements compared to 12 packets when using standard SDS-TWR [8].

The Double TWR (D-TWR) method is proposed in [10]. The mobile node transmits two consecutive requests and the anchor only replies once. The goal is to reduce overhead and increase system accuracy and enhance processing speed.

The work in [11] introduces the Burst extension of the classic SDS-TWR, where k ranging measurements take place between a mobile node and an anchor but are interweaved with each

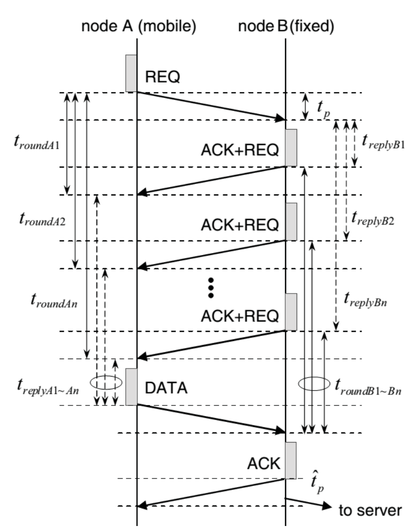


Fig. 3: Ranging procedure of SDS-TWR-MA [9]

other. The mobile node sends the request *k* times, the anchor replies *k* times. Simulations have confirmed that this protocol increases the localization accuracy but also increases the channel utilization.

With the standard SDS-TWR the assumption of identical reply times of both nodes participating in a ranging measurement is taken. In reality this is not always applicable, because the nodes could be designed differently, or have a different performance or current system delay. A small variation of the reply times, leads to an error in the ranging measurement. In [10] the authors introduce Double TWR (D-TWR) for ToF estimations, reducing the impact of clock skew without the assumption of identical reply times. A fixed reply time is used. The number of packets used for ranging has also been reduced in comparison to standard SDS-TWR.

All TWR protocols have in common, that they need at least two to four packets per ranging for each tag within the system [12]. Each packet sent out by a tag will be received by every anchor within reception and requires time for processing [13]. Since ranging is performed with every individual anchor, the channel utilization is also multiplied with each anchor and TWR is not ideal for systems with a significant amount of tags [8].

B. TDOA

The idea behind TDOA is to determine the relative position of the tag, by computing the time-differences of the received packets, that arise between the anchors, rather than the absolute times of arrival. TDOA therefore uses the time-difference of the received packets to eliminate the local clock error of the tag. Due to the missing time stamp of the tag, an additional anchor is required to compensate for this unknown and to be able to perform the localization. Each ranging determines that the transmitter must be located on a hyperboloid with a constant range difference between two anchors [14]. The position estimation turns into a problem of solving a set of hyperbolic equations (Fig. 4), that can be solved by many methods like Taylor-series expansion [15] or CH method [16]. For 2D localization at least three anchors are needed to obtain the intersection of two hyperboloids, which corresponds to the location of the tag. For 3D localization at least four anchors are required [17].

The synchronization between the anchors is critical, due to the use of a common time domain and the individual clock drifts. With ATLAS [18], the authors introduced an open-source TDOA-based localization system with wireless clock synchronization. They use a clock model for every single anchor clock and update this model dynamically during runtime with synchronization frames. With this method the error from clock drifts can be reduced significantly and the system is capable of delivering good accuracy comparable to TWR.

In [19], the authors introduced TDOA with a reference tag. The reference tag with a known position transmits a wideband signal for localization and starts the ranging. The tag that needs to be localized then sends another signal. The anchors capture the two signals and are able to perform the ranging measurements. With the known position of the reference tag, it is shown that the system is able to cancel the front end delay of the nodes. This delay is commonly measured after calibration and assumed to be stable over time, but it varies with environmental parameters like temperature and aging. It also results in a big workload at system deployment, which should be avoided.

III. NLOS

EM waves do have the ability to penetrate all kinds of materials except for metals and liquids. Errors caused by factors impacting the wireless signal propagation include multipath effects, direct path (DP) excess delay and DP blockage. These effects belong to the NLOS propagation which may have significant negative impact on the localization accuracy, especially in complex indoor environments. Therefore it is of great importance to find a way to mitigate them.

Multipath effects consist of IR-UWB signals that have been reflected by various obstacles and a DP component is not clearly visible any more. This often causes multiple measurement results for a single ranging performed and leads to errors. Excess delays accrue when the signal is able to penetrate an obstacle within the LOS and generally causes a positive biased TOF. Whereas a DP blockage leads to a missing measurement due to a completely blocked signal propagation between two nodes.

There exist many techniques for dealing with the NLOS problem in IR-UWB ranging and localization [20]. Commonly the goal is to identify a NLOS condition, which usually depends on the features analysis of the received waveforms, such as mean excess delay (MED), kurtosis, root mean delay spread (RMS), strong path energy (SPE), etc. An identified NLOS condition can then be mitigated by trying to reduce the range estimate bias introduced by delayed propagation of the signal.

In [21] the authors proposed a combination of identifying and compensating NLOS measurements. They recorded the waveforms of different propagations in a specific environment and classified them with the use of a set of features. With this method they are able to identify a NLOS condition and can even classify the type of obstacle/material causing it and can

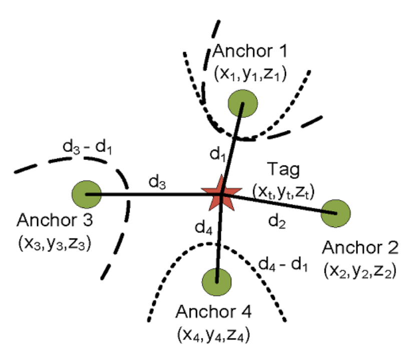


Fig. 4: TDOA based localization [5]

compensate the positive bias caused by penetrating different types of materials.
A method based on a map that needs to be generated for a specific environment is proposed in [22]. A map with a coarse grid of measurements taken at reference points has to be generated, which then consists of the NLOS characteristics (TOF bias) at every position measured. When a new localization is performed during runtime of the system, this information is used by a next-neighbour-approach, to compensate for the error at this specific position. The performance of this approach depends on the number of measurements taken beforehand.
These methods typically require prior knowledge of the system environment and do need a significant amount of reference measurements. In reality this is often not practicable or not even possible and increases the cost of deployment and decreases the flexibility. Therefore other methods like [23] or [24] were introduced, that do not need a prior knowledge of the environment. By analysing the waveform of a IR-UWB signal, it is possible to determine the first path (FP) component and to identify a LOS or NLOS condition. In [23] the authors correct the bias caused by a NLOS by subtracting an evaluated mean value with a standard deviation. Additionally the method consists of lowering the significance of NLOS ranging in the underlying localization algorithm. A predefined threshold for the difference between the received signal power and the FP component is used in [24] to identify a NLOS ranging. This method does not require any prior training or reference measurements and is capable of real-time NLOS identification.
A machine learning (ML) approach for feature processing was used by the authors in [25]. An environment specific database with a number of measurements in LOS and NLOS conditions was created. The set of feature parameters has been extracted for every measurement and included in the database. To identify a NLOS condition of a performed ranging, the ML algorithm was trained with a variety of different features of the beforehand created database. After this training the algorithm is able to identify a NLOS condition with a very high probability, depending on the amount of features used. A detected NLOS ranging can then be compensated with a mean bias and the overall localization accuracy can be increased.

IV. Clock Synchronization

Since ranging with IR-UWB is based on time measurements, clock synchronization between nodes has got an big impact on localization accuracy. When centimetre precision is required, errors in the order of 1 nanosecond or less must be met. Especially if TDOA or TOA methods are used for localization, a common time domain is very important for accurate position estimations.
The problem of synchronization with typical localization systems can be split up into two main issues [26]:

- Inter node synchronization - performed between anchors, tags and a system controller, to maintain a common time base
- Node drift compensation - temperature and other environmental changes can cause clock drifts of up to single microseconds

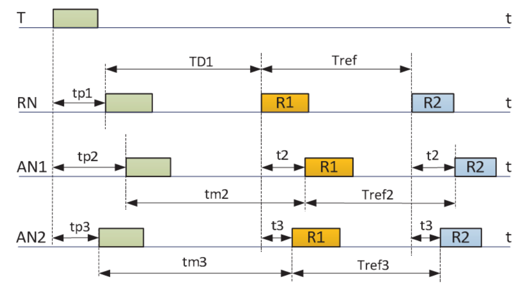


Fig. 5: Transmissions for reference anchor [29]

There exist a few methods for solving this problems. The easiest is to provide cable connections between all the anchors, like used by Ubisense [27]. This solution, however, needs the deployment of cabled infrastructure, which can be problematic in industrial or wide spread areas with a significant amount of nodes. Therefore a wireless solution is often more desirable and cost effective.
In [26] the authors introduced a zone supervisor for wireless synchronization. It transmits packets periodically, which are then received by all nodes which note their reception times. Additionally all anchors sequentially transmit packets with a predefined delay, which are only received by the tags. All timing related data is then collected in the system controller and used for estimating the positions.
Another method uses a reference tag placed in a fixed and predefined position. It periodically transmits packets, received by the anchors. The propagation times between the reference tag and the anchors are constant and known, so they can be used to synchronize arrival times at the anchors and establish a common time domain for localization [28].
A method using an anchor as a reference node instead of a tag was introduced with [29]. The transmission scheme (Fig. 5) is initiated by a packet transmitted from a tag. The packet is received by all anchors and the reference node and triggers a timer in the latter. After the delay TD1, the node sends packet R1 and repeats another transmission of packet R2 after the reference period Tref. With the use of a moving average for reference period measurement errors correction, the compensated TDOAs can be calculated in the system controller.
In [30] the authors propound a method similar to the concept of clock synchronization used in [28]. A localization engine with a wired backbone connected to all anchors of the system is used. A special synchronization node (one of the anchors) is transmitting a precisely timed periodic frame. All anchors receive this frame and note the timestamps of reception of their local clocks and communicate this information to the localization engine. With the known timing increment and the local reception timestamps, the engine is able to reconstruct the synchronization node's clock as a timing reference. A

model for the clock drift based on experiments conducted on the anchors is used to compensate for local clock drifts on every individual anchor. The engine keeps track of the anchor clocks and is therefore able to perform the localization with synchronized clocks.

V. Channel Utilization

Every ranging measurement is based on an exchange of packets, containing different types of information, that need to be transmitted between two nodes. Depending on the method that is used for performing this ranging, a known number of packets will be exchanged. Table I provides a comparison between commonly used TWR methods. SDS-TWR-MA and burst use a higher number of reply packets to increase the system accuracy by calculating a mean value over k measurements within a single ranging (Section II-A). This implies a longer occupation of the channel by a single mobile node and therefore reduces the number of mobiles that can be used within a system. Every mobile node added needs a certain amount of time to perform the required ranging measurements between itself and the anchors deployed within the system.

In order to provide more scalable systems, ranging methods like Parallel Double Sided TWR (PDS-TWR) have been introduced [13]. The goal of these methods is to reduce localization overhead despite keeping system accuracy at an acceptable level. In Figure 6 the comparison of these methods with respect to the number of packets transmitted between a single mobile node and numerous anchors is given. SDS-TWR-MA and burst perform well in respect to system accuracy, but they transmit a high amount of packets compared to the proposed PDS-TWR [13]. This has been accomplished by sending out a start message of the mobile node containing the list of anchors it wishes to perform the ranging with. The anchors reply in a predefined order according to their position in that list (Fig. 7).

TABLE I: comparison of different ranging methods in terms of packets transmitted for ranging [13]

Method	Number of packets used for n anchors
TWR	$n * (REQ + ACK)$
burst	$n * k * (REQ + ACK_{\text{REQ}} + ACK)$
D-TWR	$n * (2 * REQ + ACK)$
SDS-TWR-MA	$n * (REQ + k * ACK_{\text{REQ}} + ACK)$
PDS-TWR	$2 * (REQ + n * Reply)$

A positive side effect of reducing the amount of packets that need to be transmitted is the reduction of power consumption in the mobile nodes. These are most likely battery powered and therefore decreasing their power usage is a very desirable circumstance.

VI. Conclusion

This paper presents principles of IR-UWB technology and shows up a variety of methods used by literature to overcome different challenges that arise when integrating this technology in common environments. It includes basic methods to perform ranging measurements and calculate positions of mobile nodes. A set of different approaches are introduced to increase accuracy, reduce the negative effect of non ideal components, decrease system complexity and lower the barrier for easy integration in existing environments.

Problems like NLOS detection and mitigation are partly addressed, but future work to further improve performance and accuracy in NLOS conditions, especially in complex industrial environments, is desirable. A combination of different approaches for detection and mitigation could be used as a starting point to develop better methods. The use of a self learning system for example based on Machine Learning (ML) could be a very promising method to reduce the effort for system integration and to be able to react on dynamically changing environmental factors.

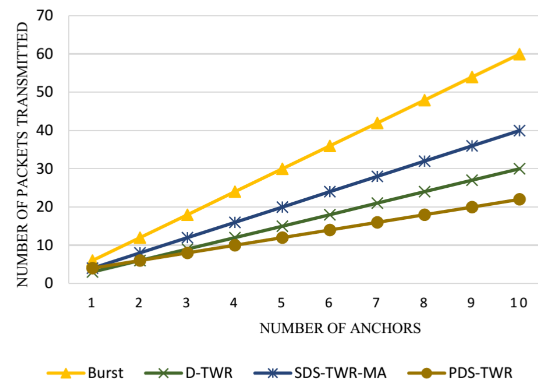
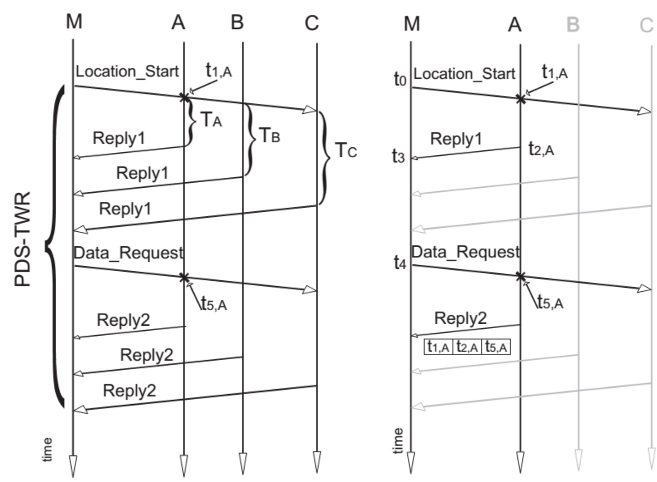


Fig. 6: packets comparison for different ranging methods [13]



(a) PDS-TWR with 3 anchors (b) timestamps for 1 anchor

Fig. 7: PDS-TWR [6]

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