UWB positioning accuracy and enhancements

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***Abstract*—Requirements of different applications and usage scenarios on a wireless positioning system is very different. A single positioning system is unlikely to meet all the requirements. UWB based positioning systems offer a solution which would meet all the indoor usage requirements. Though, the theoretical positioning accuracy offered by such systems is very good, in actual implementation, their accuracy is dependent on clock accuracy, anchor location, anchor time synchronization and other errors in Time-Difference of Arrival (TDoA) based method. In this paper, we analyze the advantages and problems of the TDoA method. Extensive simulations are given to show the location errors of TDoA method with respect to clock errors, time synchronization errors and anchor locations. Furthermore, we propose two system solutions for enhancing the location accuracy in UWB based positioning systems.**

Keywords—UWB; Indoor Positioning; Location Accuracy; TDoA; Localization

I. INTRODUCTION

Global Navigation Satellite Systems (GNSS) [1] such as GPS, GLONASS, etc… have existed for long time and have been used as default systems for outdoor positioning. With increasing use of smartphones, advent of Internet of Things (IoT) and in industry 4.0 [2] for tracking inventory and tools, the need for indoor localization has increased in recent years. Many systems have been developed for indoor positioning [3]-[6] based on RFID, Bluetooth Low Energy (BLE), Wi-Fi based positioning, etc… They all determine the position information through triangulation techniques based on the received RF signal strength which is converted back to the distance information. Some other solutions with dedicated hardware measure Time-of-Flight (ToF) and Time-of-Arrival (ToA) of signals to determine the position through lateration techniques. Lateration techniques are somewhat robust but still provide limited positioning accuracy due to narrowband nature of the signals. Angulation techniques using angle of arrival (AoA) provide better accuracy but require multiple antennas and complex hardware. Ultra-wideband (UWB) based systems have the advantage of higher bandwidth [6][7]. With recent standardization activity in UWB systems, IEEE 802.15.4-2011 standard [8], which includes Chirp Spread Spectrum (CSS) and UWB PHY layer, incorporates short impulse transmission based UWB. This has created positioning systems [9] which offer measurement of AoA, ToF or ToA or Two-Way Ranging (TWR) even in multipath environments such as indoor scenarios. Traditionally, UWB systems have been used for high throughput communications, but in the current standard, communications capability is brought down to less than 8Mbps with more emphasis to satisfy positioning requirements. Location information in UWB positioning can be derived through measurement of RSSI or ToA or Time-Difference of Arrival (TDoA). Though RSSI based method does not require accurate clocks and synchronization, it needs to know the exact channel model to translate signal attenuation to distance. As the wireless channel can vary fast with time, the accuracy of such a method is usually quite low. Moreover, RSSI based distance measurement does not make use of the wideband nature of UWB signals to translate it to high positioning resolution. On the other hand, ToA based distance measurement is based on determining the time of arrival of a signal at a particular node. Generally, a mobile tag's transmissions are received by multiple stationary anchor nodes whose position information is already known. By determining the exact time of arrival of the signal at a particular anchor, the distance between the anchor and tag is determined. To determine the 2-D position of the mobile tag, distance information from at least 3 anchor nodes would be required. The accuracy of time of arrival estimation is aided by wide bandwidth of the UWB signals. Furthermore, with 802.15.4-2011 standard signals, it is possible to resolve the different multipath signals to determine the exact time of arrival of the signal. Figure 1 shows 3 anchors with their distances to the tag.

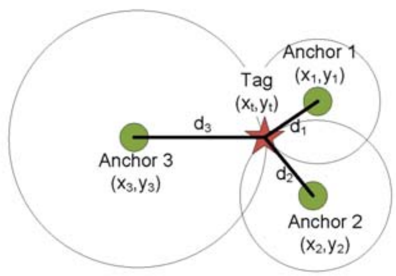

Fig. 1. ToA based positioning.

$$d_1 = \sqrt{(x_1 - x_t)^2 + (y_1 - y_t)^2} \quad (1)$$

$$d_2 = \sqrt{(x_2 - x_t)^2 + (y_2 - y_t)^2} \quad (2)$$

$$d_3 = \sqrt{(x_3 - x_t)^2 + (y_3 - y_t)^2} \quad (3)$$

The distance estimates $(\widetilde{d_1}, \widetilde{d_2}, \widetilde{d_3})$ are derived as $(c.T_x)$, with T_x being the time of flight to anchor 'x' and 'c' the speed of travel of RF signals. The 2D co-ordinates of the tag can be derived based on the distance estimates and (1), (2) and (3). However, the accuracy of range estimation is dependent on the clock accuracy and the synchronization between the anchors and tag, which affects the reference time based on that the ToF is estimated. In practice, accurate clock synchronization between a mobile tag and anchor is very difficult, which makes the ToA based method less attractive. Apart from the geometrical positioning techniques such as AoA, ToA, TDoA, etc…, Statistical approaches [7], which basically are a combination of multiple geometrical approaches are also being used for positioning.

With IEEE 802.15.4-2011 signals, TWR based positioning is proposed for Real Time Location System (RTLS), as in OpenRTLS [10]. In such a system, each anchor queries the tag and estimates the distance based on the time taken for the reply from tag to reach the anchor. Since the range estimation is based on query and reply, they do not need precise synchronization between the tag and anchor. Even on this approach's accuracy is dependent on the location accuracy of the anchor. This also requires that the tag be able to communicate with the anchor, which is not guaranteed in indoor situations, especially in environments where there are lots of obstructions with no clear Line of Sight (LoS) path.

TDoA is another approach which is used for determining the position. In this paper we first briefly explain the approach. Then we analyze the advantages and problems of the method, and present the positioning accuracy with extensive simulations. Especially, the simulations show the relationship between the position estimation error and the clock accuracy, position of the anchors and location accuracy of the anchors. We further present a scheme for improving the positioning accuracy in UWB based systems. The remaining of the paper is organized as follows. In Section II, we present the TDoA approach as applicable to UWB systems and in section III we present the simulation setup and results of the positioning error due to clock accuracy and anchor location. In Section IV, we present two schemes for improving the positioning accuracy.

II. System Model

In TDoA scheme each tag transmits a signal which is received by multiple anchors, at least 3 for 2D positioning. All the anchors are assumed to be synchronized and are linked to a positioning engine. Figure 2, shows a TDoA based positioning scenario in which a mobile tag is positioned/localized with four anchors in the 3-dimensional coverage area.

The time of arrival of the signal from the mobile tag at each anchor is made available at other anchors or to a centralized positioning engine. The time difference of arrival between different anchor pairs is calculated to determine their distances $(\widetilde{d_{12}}, \widetilde{d_{13}}, \widetilde{d_{14}}, \widetilde{d_{23}}, \widetilde{d_{24}}, \widetilde{d_{34}})$. We can write the distance-difference equations, which form a hyperbolic region as shown in Figure 2, d_{ab} for between anchors 'a' and 'b' is

$$d_{ab} = \sqrt{(x_a - x_t)^2 + (y_a - y_t)^2 + (z_a - z_t)^2} - \sqrt{(x_b - x_t)^2 + (y_a - y_t)^2 + (z_b - z_t)^2} \quad (4)$$

With known anchor locations, (x_a, y_a, z_a) of anchor 'a', an estimate of mobile tag's location $(\widetilde{x_t}, \widetilde{y_t}, \widetilde{z_t})$ is determined through a solution of (4) with multiple anchors.

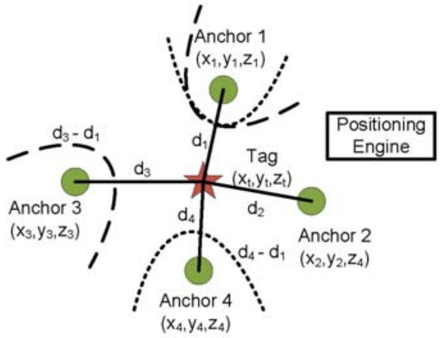

Fig. 2. TDoA based positioning.

The major difference between TDoA method and ToA method is: TDoA uses the time difference of arrival while ToA uses the actual time arrival. Using only the time difference of arrival, TDoA does not need time synchronization between the mobile tag and anchor, which is a major obstacle in ToA method. In fact, in mathematics, TDoA method treats the time information of the mobile tag as another unknown variable to be solved. For both methods, time synchronization among anchors is required. The impact of time synchronization errors among anchors will be discussed in detail in Section III.

The mobile tag's location estimate is based on the availability of the anchor location and the time of arrival estimate of the mobile tag's signal at each of the anchors. Actual anchor location for the coverage area and the error in clock which is used to represent the time of arrival at each anchor, will lead to the inaccurate estimate of mobile tag's location. In the following section we determine the extent of the error based on the anchor location and clock accuracy. Further we will propose two schemes to minimize and eliminate these errors.

III. Simulations and Discussions

A. *Simulation settings and algorithm details*

For the purpose of simulation we have considered a 3-dimensional area of size (-100,100) × (-100,100) × (-5,5) meters. The anchors and tags are assumed to be randomly distributed in the area, and there are no tags outside this area. In order to model the time synchronization error among the anchors, let T_0 be the average time of the anchors considered for one location implementation and T be the actual time of an anchor. $\Delta T = T - T_0$ is the clock error of this anchor. We model ΔT as a random variable with zero mean uniform distribution. It is assumed that the clock errors of different anchors are independent. Similarly to model the TDoA error due to the clock mismatch of the tag and anchors, Let T_{tag} be the time of the tag and then the TDOA error is $\Delta T_{tag} = T_{tag} - T_0$. In the location algorithm, ΔT_{tag} is treated as an unknown and is estimated.

The Bancroft's algorithm [11] is used to solve the range equations. As the equations normally give two solutions, we use the following rules to resolve the ambiguity.

(1) For over-determined system ($N \geq 5$), choose the one with the best match to the measured TDoAs of all the anchors.

(2) In general, choose the one within the specific area. If both solutions are within the area, use the average of them.

(3) If there is no real solution (the solutions are complex numbers due to noises), choose the real part of it.

(4) If the resultant is out of the specific area, choose the point in the specific area that is the closest to the resultant as the solution.

As the tag may not be synchronized to the anchors and the tag clock accuracy may not be high, in our simulations we do not constrain the range of TDoA error ΔT_{tag}. That is, the results are valid for any TDoA error.

B. Simulation results

With arbitrary locations of anchors and tags, the location estimation error with respect to the maximum clock accuracy error is given in Figure 3. The results show that the smaller the clock error, the less is the location estimation error. Moreover, when we increase the number of anchors from 4 to 6 the location estimate improves as expected. Figure 4 presents the percentage for which the location error exceeds 3 meters. As we increase the number of anchors, the performance improves. Leading to a solution, with lower clock accuracy we are able to get better performance with larger number of anchors. For the chosen coverage area, when we fixed the location of the anchors, instead of random locations, we see a remarkable improvement in performance even with lower number of anchors. The fixed locations chosen are given in Table I. The simulation results for these fixed locations are shown in Figure 5 and Figure 6. It is seen that with careful selection of 4 anchor locations it is possible to achieve the performance of 6 anchors or even better.

TABLE I. FIXED ANCHOR LOCATIONS

Location Identifier	Anchor 1	Anchor 2	Anchor 3	Anchor 4	Anchor 5
Location 1	x = 0 y = -50 z = 2	x = 0 y = 50 z = 2	x = 50 y = 0 z = -2	x = -50 y = 0 z = -2	-
Location 2	x = -100 y = 100 z = -5	x = -100 y = -100 z = -5	x = 50 y = 50 z = 5	x = -50 y = 50 z = 5	-
Location 3	x = -100 y = 100 z = -5	x = -100 y = -100 z = -5	x = 50 y = 50 z = 5	x = -50 y = 50 z = 5	x = 0 y = 0 z = -5

C. Observations and discussions

From the simulations, we have the following observations.

(1) The equations almost always give two solutions while only one solution is the desired one. This causes location ambiguity especially when the timing error is large. Although we have used a few rules (discussed in Section III.A) to solve the problem, there are still cases in which the ambiguity cannot be resolved. The area and anchor topology, history of the tags, and prediction of the tags could also be used to further reduce the ambiguity.

(2) Anchor locations have impact on the robustness of the location estimation with respect to errors/noises and also affect the ambiguity resolving. Hence the anchor deployment locations are important.

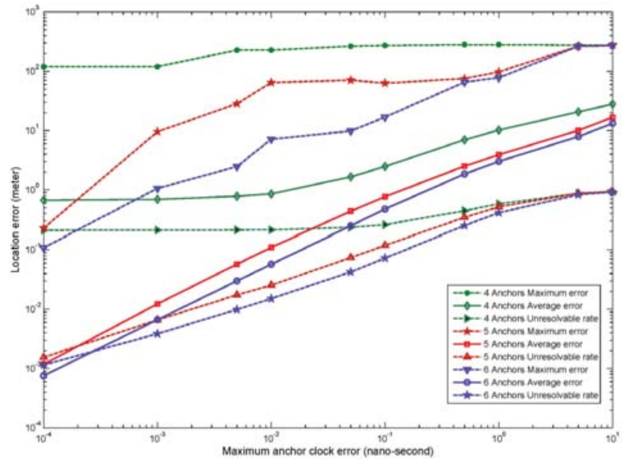

Fig. 3. Location estimation error with respect to clock accuracy, random anchor locations.

(3) The anchor time synchronization has substantial impact to the positioning accuracy. It is crucial to synchronize the anchor clocks with as close to within each other as possible. The anchor clock errors are usually independent at different anchors, which cannot be solved via the range equations. The synchronization error must be kept at least below nano-second scale for robust sub-meter level accuracy.

(4) There are other possible factors such as multipath, MAC delay, communication bandwidth (sampling rate), and noise, which also cause ToA errors. Such TOA errors may be different at different anchors, which cannot be solved via the range equations. Such errors have the same impact as the anchor clock error and can severely degrade the location performance. Thus the impact of such errors can be readily seen from the Figures with increased anchor clock errors.

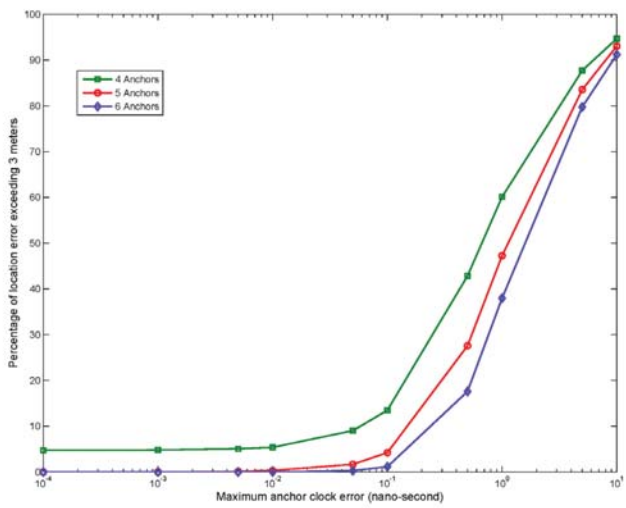

Fig. 4. Percentage location error exceeding 3 meters with respect to clock accuracy, random anchor locations.

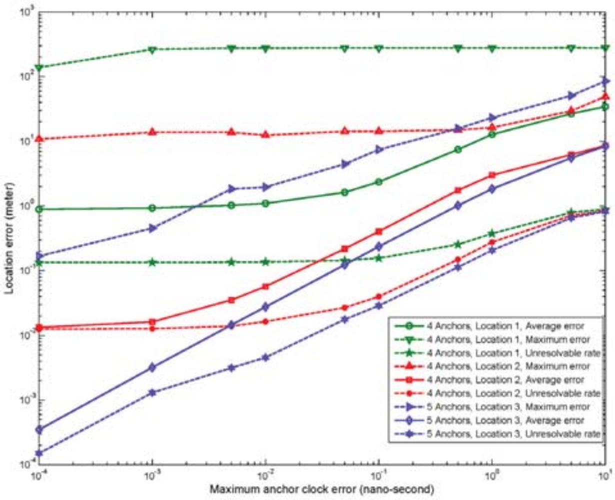

Fig. 5. Location estimation error with respect to clock accuracy, fixed anchor locations.

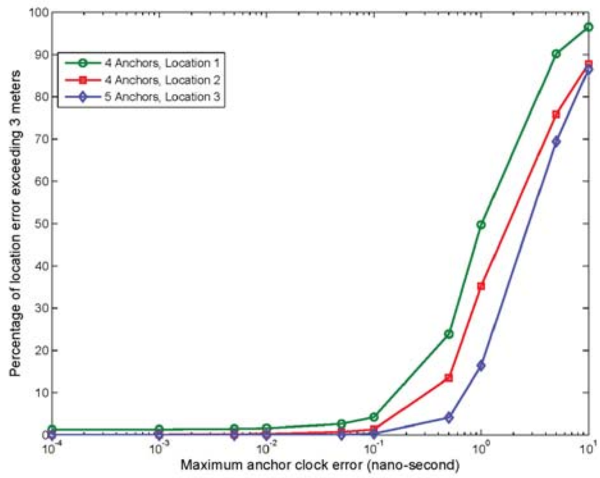

Fig. 6. Percentage location error exceeding 3 meters with respect to clock accuracy, fixed anchor locations.

IV. PROPOSED ENHANCEMENTS

From the simulations we have determined that to improve the robustness of mobile tag location we need to have careful planning of anchor deployment for a given coverage area and timing synchronization between anchors need to be maintained. With larger indoor environments it is difficult to not only plan the anchor deployment with good location accuracy but also maintain LoS RF coverage over the entire area. Here, we detail how this is achieved in a practical deployment. The proposed deployment is based on the UWB transceivers from DecaWave DW1000 [12]. The DecaWave's transceiver uses a bandwidth of 900MHz and is complaint with IEEE 802.15.4a standard [8]. The burst structure of the UWB signal is shown in Figure 7. The preamble can be of 16, 64, 1024 or 4096 symbol length. The longer the preamble, the better is the accuracy of time of arrival estimate. The start-of-frame delimiter (SFD) is the a sequence of 8 or 64 symbols which is used to indicate the end of preamble and start of the physical layer header, which is followed by the data. In IEEE 802.15.4 standard different ranging mechanisms such as Two-Way ToA (TW-ToA), Symmetric Double Sided ToA (SDS-ToA) and a private ranging protocol have been mentioned. These are basically two-way ranging protocols which derive the range estimates based on the round-trip delay for the request and the replied acknowledgement bursts. The SDS-ToA is robust even in receivers with frequency offset errors but requires one additional handshake message transfer [8]. In our proposed approach, the mobile tag's transmit UWB burst is received and decoded at the anchor. The burst's time of arrival is noted transmitted back to the positioning engine. The time of arrival values from different anchors are collated and used in determining the location based on TDoA algorithm.

Figure 8 shows a basic deployment setup with multiple anchor and mobile tag nodes. In the above shown deployment (hyperbolas around T1 are for illustration only), the gateway anchor, which also acts as a positioning engine collects the time of arrival from all the anchors for each of the tags and estimates the location of the tags. It also stores the previous location to resolve any ambiguity arising from the estimate.

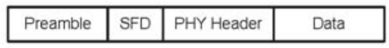

Fig. 7. UWB burst frame structure.

In order to make the deployment robust, we propose 1) A positioning engine with dynamically changing anchor nodes and 2) A time synchronization network.

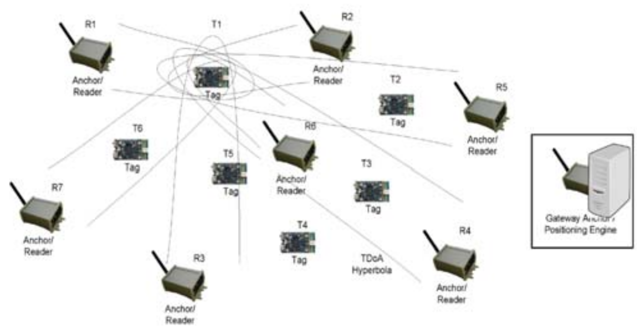

Fig. 8. Deployment scenario of multiple UWB anchors and mobile tags.

A. Positioning engine with dynamically changing anchor nodes.

To enhance the positioning capability, increase the robustness and reduce the number of mobile tags which are in RF shadow, the deployment is designed to allow dynamically changing anchor nodes. With this capability, positioning performance is improved by extending the functionality of reader/anchor nodes to certain or all the mobile tags as well. A Custom MAC implementation will provide the anchor node functionality to mobile tags, and also dynamically identify mobile tags which can be used as anchor nodes. When integrated to the conventional deployment, the overall localization capability of the system is improved. For this purpose, the mobile tag is to be modified to make it transmit as well as receive the UWB pulses from other mobile tags and communicate the time of arrival to the central positioning engine.

B. Anchor timing synchronization and communication network.

The proposed network timing synchronization is based on a platform such as White Rabbit project. By creating suitable interface on the anchor for clock injection, the different anchor units are time synchronized to a single clock. With this the errors due to time synchronization of anchors are eliminated. Figure 9 shows the basic setup of the deployment with the time synchronization network (hyperbolas around T1 are for illustration only). It uses the components from the White Rabbit project, Light Embedded Node (WR-LEN) and Zynq Embedded Node (WR-ZEN) [13].

V. CONCLUSION

Accurate positioning requirement in indoor environments is increasingly demanding with the use of smartphones and Industrial IoT applications. With TDoA being one of the desired approaches to estimate the location, in this paper we have simulated and presented performance of TDoA in estimating the mobile tag locations with multiple anchor nodes. It is shown that the location error in a deployment is dependent on the number of anchors and the location of the anchors for a given coverage area. With indoor environments getting bigger with scenarios such as large shopping malls and factory floors, it is not only difficult to plan the anchor deployment locations it is also difficult to obtain LoS RF coverage. For increasing the robustness so that location errors could be minimized we have presented deployment scenarios where a TDoA positioning engine which estimates the tag's location based on dynamically changing anchor nodes and a timing synchronization network based on components from the White Rabbit project to synchronize all the anchor nodes.

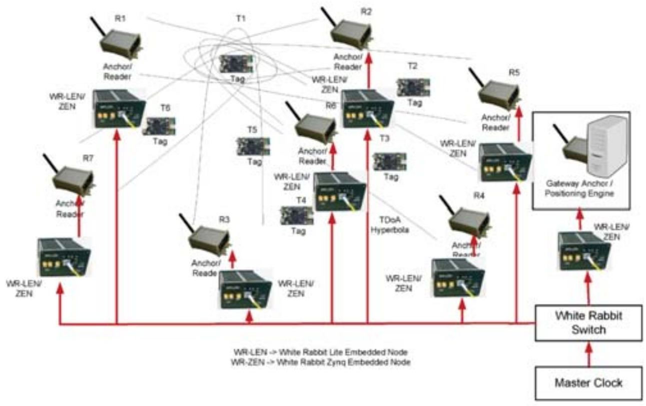

Fig. 9. Anchor timing synchronization network.

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