A TDOA Measurement Technique for Asynchronous Indoor Localization System using UWB-IR

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***Abstract*—In this paper we have proposed a Time Difference of Arrival (TDOA) measurement scheme for practical asynchronous systems using low cost low power target nodes (called tags). The system performs localization of transmit only tags using an ultra wide band Impulse radio (UWB - IR). We use a known location reference node for synchronization between the receiving (or anchor) nodes. The clock of the reference node is considered to be a perfect clock whereas clocks of all other nodes, anchor nodes as well as target node, is assumed to imperfect. We formulated the equations to synchronize the clocks of the anchor nodes and estimate the TDOA range measurements between the anchor nodes. The equations were analyzed with the practical measurement results.**

***Index Terms*—UWB-IR, Indoor Positioning, Wireless Sensor Networks, Clock Synchronization**

I. INTRODUCTION

A very accurate indoor positioning can be achieved by using ultra wide band impulse radio. High accuracy is achieved due to its high temporal resolution and multipath immunity i.e. ability to resolve multipath [1], [2]. Typically, a general localization system consists of some anchor nodes (i.e nodes with fixed location) and the target node/s whose position is to be determined. Range measurements are conducted between anchor nodes and target nodes and based on range measurement information, location of the target node can be determined. Some of the methods which can be used to determine the range are: Time of Arrival (TOA), Time Difference of Arrival (TDOA), Received Signal Strength (RSS) and Angle of Arrival (AOA) [2].

A high accuracy of target node location can be achieved using TOA based positioning for the system having line of sight (LOS) and high signal to noise ratio (SNR). However, TOA method can be affected by the participating nodes clock oscillator offset imperfection. In order to reduce the affect of clock imperfections, in the systems using TOA, two way ranging (TWR) [2] between the target nodes and anchor nodes is generally preferred. The TWR in turn results in more overheads between the target nodes and the anchor nodes, as the nodes need to transmit more messages in order to get the synchronized ranging information. Therefore, TWR may not be feasible in energy constrained target nodes such as low cost low power tags in the system. In order to resolve the problem of clock offset imperfection, as well as to reduce the number of overheads between the tags and the nodes, TDOA based positioning has been proposed and explained in several literature [3]-[5].

Although, TDOA based positioning can mitigate the effect of clock offset imperfections between the tags and the anchors, as well as reduce the number of ranging signal overheads, it still suffers from clock skew imperfections, which is the rate of variations in the local clock compared to real time. Since the participating nodes have their own autonomous clocks, the clock synchronization between the nodes is a challenging task for TDOA based positioning systems.

Several authors in the past have proposed various clock synchronization techniques for TOA and TDOA based localization. Authors, in [6] - [9] have considered TOA based technique for joint synchronization and localization whereas authors in [5], [10] - [13] used TDOA technique for clock synchronization and localization. A low complexity asynchronous TDOA localization method using ultra wideband signals is proposed in [9]. In the method proposed author localizes the target node when all the nodes are asynchronous, however the assumption that all the nodes are under the coverage of each anchor is not generally feasible in practical scenarios. The authors in [11] follows TDOA localization approach of a target node, where an asynchronous target node self localizes itself by computing TDOA measurements. However, in this work the author has assumed that all the anchor nodes are synchronized with a reference clock and transmit their signal at a common time instant. In [14], a practical indoor localization system based on UWB-IR and TDOA principle has been proposed and analyzed with hardware constraints. However, they also consider the anchor nodes to be synchronized with each other.

Adding more to the above contributions, in this paper we have proposed a TDOA range measurement technique for an indoor localization system using UWB-IR, where the target node/s as well as the anchor nodes are asynchronous. Specifically, the algorithm is developed for low cost low power tags (target nodes) using UWB-IR transmit only for ranging.

The rest of the paper is organized as follows: Section II describes the system model and protocol description of TDOA based range measurement techniques, along with mathematical formulations. Section III explains the experimental setup, with section IV discussing the experimental results followed by a conclusion and acknowledgement in section V and section VI respectively.

II. SYSTEM MODEL

We consider a two-dimensional (2-D) system model as shown in fig.1. The system consists of $N+1+1$ nodes. Suppose N are the number of anchor nodes located at known positions $\mathbf{n_i} = [\mathrm{n_{i,1}}\,\mathrm{n_{i,2}}]^{\mathbf{T}} \in \mathbb{R}^2$ where $i = 1, 2......N$. 1 node is the reference node which is situated at the known location $\mathbf{r_1} = [\mathrm{r_1}\,\mathrm{r_2}]^{\mathbf{T}} \in \mathbb{R}^2$. The last node is the target node which is placed at an unknown location $x = [x_1\, x_2]^T \in \mathbb{R}^2$. The reference node is assumed to have the perfect clock, while the clock of all other nodes are not synchronized. The following clock model is used for the local clocks of the target nodes as well as for the anchor nodes.

$$t_i = \omega_i t + \phi_i \tag{1}$$

where t_i denote the local time of a particular node and t denote the reference time. ω_i and ϕ_i denotes the clock skew and clock offset of i^{th} node respectively. The above equation can also be represented as

$$t = \alpha_i t_i + \beta_i \tag{2}$$

where $\alpha_i = \omega_i^{-1}$ and $\beta_i = -\omega_i^{-1}\phi_i$ are the synchronization parameters of i^{th} node. The overall system model can be seen to be divided in two portion, say two portion of a big room. The system is equipped with anchor nodes deployed on the walls of the room. These anchor nodes are used to localize a target node in the room. Some of the anchor nodes are connected to a common analog to digital converter locator box 1(LB1), whereas others are connected to similar locator box 2(LB2). The clock parameters of LB2 are different from that of LB1 and hence they are unsynchronized. However, the anchor nodes connected to the same LB have the same clock parameters. The target node can be localized by selecting the anchor nodes based on the received signal to noise ratio. The problem is to synchronize the nodes, selected from different locator boxes, and calculate the TDOA measurement, to accurately determine the location of the target node. In order to synchronize and find the TDOA measurements, we select a reference node which is in the range of all the asynchronous nodes participating in the localization process. The synchronicity between different clocks is being accounted with the reference clock transmits signal continuously while mobile tag transmits UWB positioning signal upon request. Both the reference node and the target node signal is captured at the respective receiver anchor nodes of different LB as shown in fig.2.

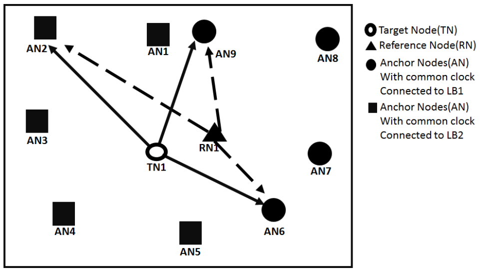

Figure 1. System Model

The following notations will be used while formulating the equations for TDOA estimation. The time duration of the signal between the target node and the i^{th} anchor node, connected to the l^{th} locator box, is given by $\tau_{ti}^{(l)}$. For simplicity, in this paper we assume $l = 1, 2$. The time duration of signal between the reference node and the i^{th} node connected to the l^{th} locator box is given by $\tau_{ri}^{(l)}$, where $l = 1, 2$. Consider an arbitrary anchor node i connected to l^{th} LB. This node will receive the signals from the target node as well as the reference node which transmits the signal at the same instants. Using the received waveform we formulate the TDOA equation at this node. When signal is transmitted from target node to anchor node i, timing equation at anchor node i, captured at time frame k, can be written as,

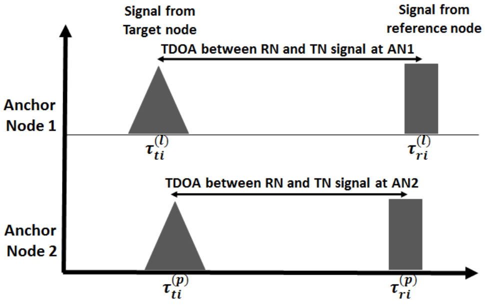

Figure 2. Signal Capture in one time frame

$$\alpha_i T_{ti}^{(k)} + \beta_i = \alpha_t T_t^{(k)} + \beta_t + \tau_{ti}^{(l)} + n_{ti}^{(k)} \tag{3}$$

where α_i, β_i are the clock skew and clock offset, respectively, of anchor node i. α_t, β_t are clock skew and clock offset, respectively of target node. $n_{ti}^{(k)}$, is the zero mean Gaussian measurement noise. When signal is transmitted from a reference node to same anchor node i, timing equation can be written as,

$$\alpha_i T_{ri}^{(k)} + \beta_i = \alpha_r T_r^{(k)} + \beta_r + \tau_{ri}^{(l)} + n_{ri}^{(k)} \tag{4}$$

where α_r, β_r are clock skew and clock offset, respectively, of the reference node. Subtracting equation (3), (4) gives the TDOA equation at anchor node i . Therefore, we get,

$$\begin{aligned} \alpha_i[T_{ti}^{(k)} - T_{ri}^{(k)}] &= \alpha_t T_t^{(k)} + \beta_t + \tau_{ti}^{(l)} + n_{ti}^{(k)} - \\ &\quad (\alpha_r T_r^{(k)} + \beta_r + \tau_{ri}^{(l)} + n_{ri}^{(k)}) \end{aligned} \tag{5}$$

This can also be written as,

$$\begin{aligned} \alpha_i \Psi_{i-LB(l)}^{(k)} &= \alpha_t T_t^{(k)} + \beta_t + \tau_{ti}^{(l)} + n_{ti}^{(k)} - \\ &\quad (\alpha_r T_r^{(k)} + \beta_r + \tau_{ri}^{(l)} + n_{ri}^{(k)}) \end{aligned} \tag{6}$$

where $\Psi_{i-LB(l)}^{(k)}$ represents the $TDOA_{tr\rightarrow i}^{(l)}$ at node i, connected to l^{th} locator box, for the signal from target node and reference node to node i.

Similarly, we formulate the TDOA equation, from the signals received from target node and reference node, at anchor node

$j\,(\neq i)$ connected to other locator box $p\,(\neq l)$

$$\begin{aligned}\alpha_j T_{tj}^{(k)} - \alpha_j T_{rj}^{(k)} &= \alpha_t T_t^{(k)} + \beta_t + \tau_{tj}^{(p)} + n_{tj}^{(k)} - \\ &\quad (\alpha_r T_r^{(k)} + \beta_r + \tau_{rj}^{(p)} + n_{rj}^{(k)}) \qquad (7)\end{aligned}$$

$$\begin{aligned}\alpha_j \Upsilon_{j-LB(p)}^{(k)} &= \alpha_t T_t^{(k)} + \beta_t + \tau_{tj}^{(p)} + n_{tj}^{(k)} - \\ &\quad (\alpha_r T_r^{(k)} + \beta_r + \tau_{rj}^{(p)} + n_{rj}^{(k)}) \qquad (8)\end{aligned}$$

Likewise, we formulate the initial TDOA equation at all the nodes selected for localization of the target node. Therefore, for m nodes which participate in localization, we have m such TDOA values.

Subtracting (8) - (6), we get the TDOA equation between node i connected to locator box 1 and node j connected to locator box 2. Therefore, we get,

$$\alpha_i \Psi_{i-LB(l)}^{(k)} - \alpha_j \Upsilon_{j-LB(p)}^{(k)} = (\tau_{ti}^{(l)} - \tau_{tj}^{(p)}) + (\tau_{ri}^{(l)} - \tau_{rj}^{(p)}) + n^{(k)} \qquad (9)$$

where the term $\tau_{ij=}\tau_{ti}^{(l)} - \tau_{tj}^{(p)}$ represents the time difference of arrival between the target node and two anchor nodes, which is finally used to calculate the localization of the target node. The term $\tau_{ri}^{(l)} - \tau_{rj}^{(p)}$ denotes the TDOA between the reference node and the two anchor nodes which can be calculated from the known positions of the reference node and the anchor nodes. $n^{(k)}$ in the above equation is the zero mean Gaussian measurement noise. α_i and α_j can be adjusted by taking the difference of arrival time of the received signal, transmitted at $(k+1)^{th}$ and k^{th} instance from the reference node, at different receivers.

III. EXPERIMENTAL SETUP

The experimental test set up is shown in fig.3 with an area coverage of about 8.25 x 15 m. The experiment was performed at Delta-EEE lab on Internet of things at NTU, Singapore. We consider 6 anchor nodes namely, AN1, AN2, AN3, AN4, AN5, AN6, one reference node and one mobile tag. The location of the anchor nodes, reference nodes and mobile tag are shown in fig.3 with their respective coordinates. We select the 4 anchor nodes, AN2, AN4, AN5 and AN6, out of the 6 available based on their received signal to noise ratio. AN2 and AN4 are connected to locator box 1 whereas AN5 and AN6 are connected to locator box 2. As mentioned earlier two locator boxes run a separate clock oscillator that are not in sync with each other. The experiment is done in 2-D with all the receivers (anchor nodes) fixed at the same height. The reference node is used to continuously transmit IR ranging signal, which has a unique waveform when compared to the mobile node waveform as shown in fig2. It is implemented in such a way so that when both signals appeared simultaneous on the same frame, both the signals are distinguishable. In the experiment, we choose the AN2 instead of AN1 so as to capture the direct line of sight from the mobile tag. The signal to the AN5 is partially blocked by a metallic pillar as shown in fig.2.

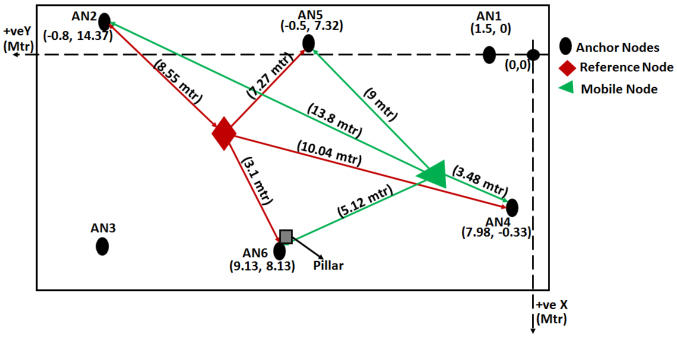

Figure 3. Experimental Setup of the system

The mobile tag transmit IR signal at pulse repetitive frequency (PRF) of 1.625MHz. Due to the presence of long distance multipath in the environment, and in order not to misinterpret it as weak direct path lower PRF value is chosen. On the other end, sub-sampling mechanism [14] is used to sample the IR signal at locator box and at the time of the experiment being done, the ADC sampling clock frequency is set at about 1.6245MHz. The equivalent resolution of sampling is determined by the sample number to reconstruct one periodic impulse signal, which is around 0.1763ns. Hence, with uncertainty of 10 sample points, it can be translated to be about 20 cm errors. However, resolution can be increased with manipulation of the frequency of sampling clock.

Furthermore, for simplicity, we consider AN4 as the base anchor node for calculation of independent TDOA among all the anchor nodes since it is the nearest as well as in direct line of sight from the target node. However, in dynamic environemnt the base node will be seleted based on the received signal to noise ratio. We denote TDOA24 as the range difference between AN2 and AN4, TDOA54 denotes the time difference between AN5 and AN4 and TDOA64 denotes the time difference between AN6 and AN4.

IV. SIMULATION RESULTS AND DISCUSSIONS

Fig.4, fig.5 and fig.6 shows the distribution of the measured distance difference of arrival between receiver 2 and receiver 4 (the combination of receiver 2 and receiver 4 is represented as R24), receiver 5 and receiver 4 (R54), receiver 6 and receiver 4 (R64), respectively. The actual distance difference from mobile to receiver 2 and receiver 4, receiver 5 and receiver 4, and receiver 6 and receiver 4 is 10.1252 m, 1.5591 m and 5.3615 m respectively. The mean value for each of the distribution is 10.2756 m, 2.0929 m and 5.4975 m for R24, R54 and R64 respectively. The standard deviation obtained is 0.2969, 0.3375 and 0.33 for R24, R54 and R64 respectively. As calculated from the values, the difference between the true value and the estimated is in the range of 15 cm, 53 cm and 13 cm for TDOA24, TDOA64 and TDOA54, respectively. The large difference of 53cm can be accounted by the fact that the receiver anchor node 5 is not directly receiving the signal from the target node due to the presence of metallic pillar as shown in fig3. However, the error achieved can be reduced to an extent by increasing the resolution of sampling by manipulating the frequency of the sampling clock. The distance difference between the estimated and accurate value can also be reduced by using accurate TO estimation techniques. The above analysis shows that it is feasible to synchronize the nodes by the method introduced in this paper.

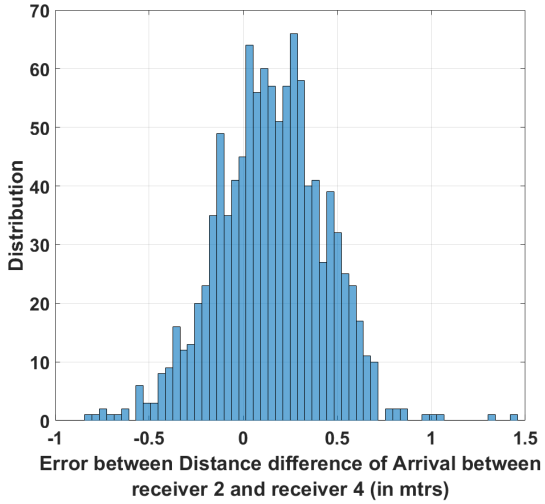

Figure 4. Distribution plot of TDOA between receiver 2 and receiver 4

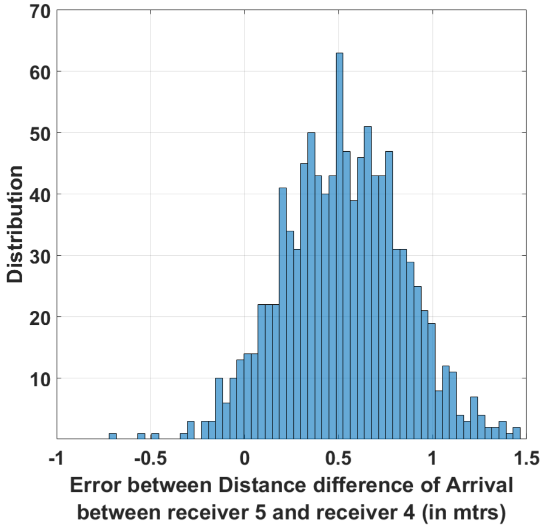

Figure 5. Distribution plot of TDOA between receiver 5 and receiver 4

V. CONCLUSIONS

A time difference of arrival measurement scheme for an asynchronous indoor localization system using ultra wideband impulse radio has been proposed in this paper. The scheme can be useful in low power and low cost transmit only target nodes based on UWB-IR. A fixed position reference node is used to calculate the time difference of arrival, at the anchor nodes selected for localization, between signal received from mobile node as well as reference node. These time difference of arrival are further used to synchronize the different anchor nodes. The proposed scheme has been verified with practical measurements in an indoor environment. The proposed scheme results in sub cm accuracy for line of sight scenario.

VI. ACKNOWLEDGMENTS

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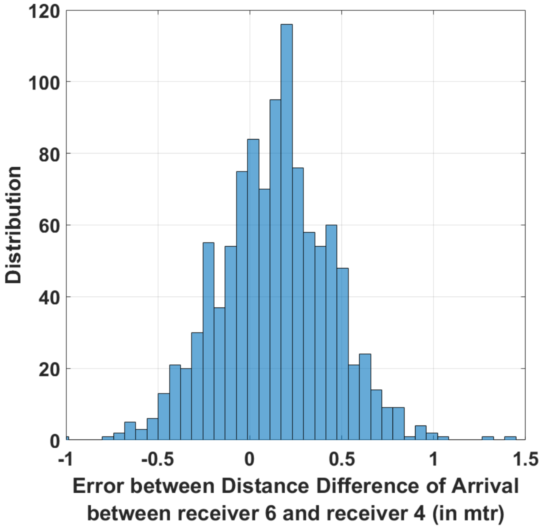

Figure 6. Distribution plot of TDOA between receiver 6 and receiver 4

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