Time-Difference-of-Arrival (TDoA) Based Wireless Indoor Localization Using an Effective Hybrid Time Synchronization

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Abstract

Wireless indoor localization is a major challenging issue for state-of-the-art technologies and applications which require precise and robust location information. Many restrictions affect the performance of the wireless indoor localization, for instance, intricate building architecture, decorated appliances inside the building, and inaccessibility and unavailability of using GPS in indoor environments. Nowadays, time based indoor localization is considered as a better and popular research trend for wireless networks. The major disadvantage of time based localization techniques is difficulty to attain precise time synchronization. In this paper, Time-Difference-of-Arrival (TDoA) based wireless indoor localization technique is proposed which is based on an effective hybrid time synchronization approach. Python programming language is used for simulation evaluations to highlight the improved localization performance. By using the robust and effective hybrid time synchronization, localization accuracy of the proposed system is considerably high.

1. Introduction

Wireless indoor positioning system is very prominent for real time application areas which need precise and robust position estimation in order to sustain for our environments. For examples, environmental monitoring and controlling sectors, health care sectors, disaster management and recovery sectors and military sector require accurate information for the location estimation. When considering the localization techniques, it is still necessary to take into account of effective localization accuracy, cost for hardware devices, computational complexity, and energy constraints for real time environments. Due to imperfectness of wireless indoor localization in many researches, different localization techniques and wireless technologies such as Wi-Fi, ZigBee, Bluetooth, ultra wide band (UWB), etc. are being applied in researches to get better solution.

Generally, there are two basic approach for localization system, range free approach and range based approach [1], [2]. Of them, only range based approach can be used for indoor localization since localization error may be large by using range free approach. Range based approach can be distinguished into four basic traditional techniques such as Received Signal Strength (RSS), Angle of Arrival (AoA), Time of Arrival (ToA) and Time Differences of Arrival (TDoA). Each technique has its advantages as well as disadvantages. RSS estimates the target position using the received signal strength measurements between two sensor nodes [3]. Although RSS is the most cost effective method but its localization accuracy is significantly low. In AoA, target position can be estimated using direction of amplitude or phase response of the receiver antenna [4]. By using AoA, localization accuracy is absolutely high, but implementation cost may be high because directional antenna is required. Estimated target position is calculated in ToA using time of arrivals between receiver node and target node [5]. ToA needs precise time synchronization for both receivers and target nodes to get high localization accuracy. TDoA calculates the location of target using measurements of time differences of a transmitted signal from a target node at two receivers respectively [6]. For TDoA, only receiver nodes are needed to synchronize which may reduce computational complexity and power consumption [7]. In TDoA, accurate time synchronization among receiver nodes is crucial for achieving higher localization performance. But, some researches applied unsynchronized TDoA for localization [8].

It is recommended to consider for precise synchronization before applying TDoA technique to get higher localization accuracy. Various time synchronization protocols have been proposed by several researches to promote synchronization accuracy [9]. In Reference Broadcast Synchronization (RBS), time synchronization is based on receiver-receiver synchronization in which timing message is firstly broadcasted and exchanges this message among receiver nodes [10]. For RBS, an extra node is required for broadcasting. Timing-Sync Protocol for Sensor Network (TPSN), including two phases; level hierarchy and pairwise synchronization, is described in [11]. Flooding Time Synchronization Protocol (FTSN) is proposed in [12] in which an ad-hoc network structure is used in order to synchronize the clocks of all other nodes by using the global time set dynamically by root node. An energy-efficient clock synchronization scheme, Pairwise Broadcast Synchronization (PBS) is based on sender-receiver synchronization which has advantage over energy consumption for extended sensor nodes [13].In PBS, two reference nodes are firstly selected and these two nodes synchronize their time to each other. After synchronizing between these two nodes, all other nodes receive this synchronized timing information and they also synchronize with one another. To get precise time synchronization with low computational complexity, low energy use and low hardware cost is still a huge challenge for time-based wireless indoor localization techniques [14].

In this paper, an effective TDoA-based wireless indoor localization scheme is proposed which is based on hybrid time synchronization. The proposed scheme reduces the number of timing messages and improves the localization accuracy. The rest of the paper is organized as follows. In section II, the proposed wireless indoor localization scheme is discussed in details. Then, evaluations and performance analysis are described in section III. Finally, conclusion and further extension are described in last section.

2. Proposed TDoA-based Wireless Indoor Localization Scheme

The proposed localization scheme consists of two main tasks; (1) synchronization phase and (2) location estimation phase. For synchronization phase, an effective hybrid synchronization approach with two-way message exchange method is introduced based on the ideas of existing RBS and PBS protocols. After synchronization, time difference of arrival (TDoA) measurements are computed and the target position is estimated using multilateration in location estimation phase.

2.1. Synchronization Phase

The main task of this phase is to estimate accurate timing parameters, time offset and time skew for synchronization. Time offset and time skew are the phase difference and frequency difference between two wireless clocks respectively. To synchronize time among wireless nodes, one of these nodes is firstly considered as reference node to define standard time for synchronization. Time synchronization between two nodes can be computed as in (1).

$$t(n_1) = \tau * t(n_2) + \theta \qquad (1)$$

where, $t(n_2)$is reference node and $t(n_1)$ is the node at which time synchronization to be performed. θ and τ are the respective time offset and time skew.

At first, a wireless network is configured with four anchor nodes, O, P, Q, and R (nodes with known location information) placed at four corners of the area of interest for localizing target. As shown in Figure 1, communication range is considered as 50 m. Anchor nodes (O and P, O and Q, O and R) are located 40 m, 40m and 50 m apart from each other respectively. Target node is supposed to be moving dynamically. One of the anchor nodes is defined as a common node to broadcast timing information. By doing so, requirement of one extra node for broadcasting can be eliminated as in RBS.

After all other nodes have received timing information from common node, they all reply messages to common node including their timing information. By using two-way message exchange method for timing information between all other nodes and common node, accuracy of estimating timing parameters in proposed hybrid synchronization may be considerably high.

Figure 2 shows the broadcasting and transmission of timing information between common node and all other nodes. Node O is selected as a common node and sends the first broadcast message containing its current timestamp $T_{s,1}^{O}$. When other three anchor nodes, P, Q and R accept this message at their local timestamps, $T_{r,1}^{P}$, $T_{r,1}^{Q}$ and $T_{r,1}^{R}$, respectively, they record their local arrival time of broadcast

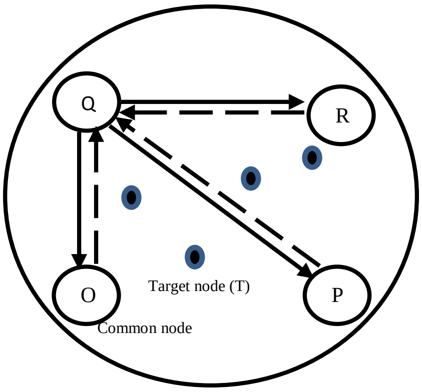

Figure 1. Configuration of a wireless network

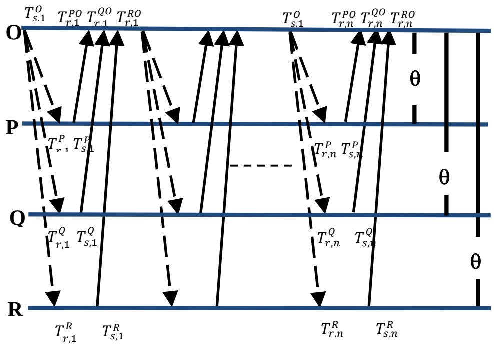

Figure 2. Proposed synchronization approach

message. Next, they resend the timing messages by adding the arrival time of broadcast message and their current sending timestamps, $T_{s,1}^{P}, T_{s,1}^{Q}$ and $T_{s,1}^{R}$ to the common node. Node O notes the arrival time of reply messages from the receiver nodes, $T_{r,1}^{PO}, T_{r,1}^{QO}$ and $T_{r,1}^{RO}$ respectively. After that, all necessary timing information is received by node O to calculate the timing parameters between its local time and each receiver's local time. Node O repeats broadcasting the timing message n times to increase the calculation accuracy of timing parameters [15].

The time interval for exchanging timing information between common node O and anchor node P, defined as T^{OP}, is provided in (2).

$$T^{OP} = \frac{(T_{r,1}^{P}-T_{s,1}^{O})+(T_{r,1}^{O}-T_{s,1}^{P})}{2} \quad (2)$$

$$T_{r,1}^{P} - T_{s,1}^{O} = \theta_{OP} + \tau_{OP} + \beta_{OP} + \omega_{OP} \quad (3)$$

$$T_{r,1}^{O} - T_{s,1}^{P} = \theta_{PO} + \tau_{PO} + \beta_{PO} + \omega_{PO} \quad (4)$$

in which $T_{r,1}^{P} - T_{s,1}^{O}$ is the interval of broadcasting between two nodes O and P, and $T_{r,1}^{O} - T_{s,1}^{P}$ is the time taken for replying phase from node P to O. θ_{OP} and τ_{OP} are time offset and time skew between the two respective nodes. β_{OP} is defined as fixed or deterministic delay which is supposed as transmission and propagation delay. β_{OP} can be computed as follows.

$$\beta^{OP} = \frac{Packet\ size}{Bandwidth} + \frac{Distance}{Propagation\ speed} \quad (5)$$

ω_{OP} is considered as random or nondeterministic delay between node O and P respectively. Random delay is defined as send, access and receive time of two nodes which cannot be computed accurately but it can be estimated using various distribution models.

Time skew, τ, may alter according to time pass even after synchronization and thus, we need to estimate this value every some interval of time. However, transmission speed of radio frequency in wireless networks is as fast as the speed of light that timing messages can transfer before requiring resynchronization to estimate time skew. So, the occurrence of time skew is ignored in this proposed scheme. The value of time offset can be estimated more accurately using two-way approach as in (6),

$$\theta_{avg}^{OP} = T^{OP} - \beta^{OP} - \omega_{avg}^{OP} \quad (6)$$

where, $\beta^{OP} = \beta^{PO}$ and $\omega_{avg}^{OP} = (\omega_{OP} + \omega_{PO})/2$. Time offset values for n number of broadcast messages are used to compute the optimal time offset in (7) in which i is the number of broadcasting times.

$$\theta_{est} = \frac{1}{n}\sum_{i=1}^{n} \theta_{avg}^{OP}(i) \quad (7)$$

In accordance with above equations, time offset between all other anchor nodes and common node can be estimated for time synchronization. Besides, all anchor nodes can synchronize with each other by substituting the estimated time offset value in (8).

$$\theta_{PQ} = \theta_{OQ} - \theta_{Op} \quad (8)$$

2.2. Location Estimation Phase

In location estimation phase, time difference of arrival (TDoA) values between common node and each of other anchor nodes are computed. For example, between common node O and anchor node P, the following equation is used to calculate TDoA values,

$$\Delta t = |t(\mathrm{O}) - t(\mathrm{P})| \quad (9)$$

where time synchronization is not yet considered. To improve localization accuracy, TDoA values using timing parameters from synchronization phase are derived by substituting (1) in (9) as follows.

$$\Delta t_{OP} = t(O) - (\tau_{OP} * t(P) + \theta_{OP}) \quad (10)$$

where, τ_{OP} is neglected in synchronization phase, and (10) becomes,

$$\Delta t_{OP} = t(O) - t(P) - \theta_{avg}^{OP} \quad (11)$$

After measuring TDoA values between anchor nodes, the next step is to change TDoA measurements to range difference values using the relationship between time and distance illustrated in (12).

$$\Delta t_{OP} = \frac{1}{v}(d_{OT} - d_{PT}) \quad (12)$$

where, v is the rate of transmission speed and d_{OT} and d_{PT} are the distance between target node T and anchor node O and P respectively.

$$(d_{OT} - d_{PT}) = \left|\sqrt{(x_t - x_o)^2 + (y_t - y_o)^2} - \sqrt{(x_t - x_p)^2 + (y_t - y_p)^2}\right| \quad (13)$$

Then, position of target node is predicted based on the value of range difference measurements using multilateration scheme [16]. In multilateration scheme, target position is estimated using at least two hyperbolic functions. In this step, three hyperbola functions for four anchor nodes O, P, Q, and R are modeled and position of target node T is calculated using these hyperbola functions [17], [18]. For node O and P, O and Q, and O and R, their hyperbolic functions are considered in (14), (15) and (16). Approximately,

$$\frac{(x-h)}{a^2} - \frac{(y-k)}{b^2} = 1 \quad (14)$$

$$\frac{(y-k)}{a^2} - \frac{(x-h)}{b^2} = 1 \quad (15)$$

$$(x-h) * (y-k) = c \quad (16)$$

where, x and y are coordinates of target node and h, k, a, b and c are variables that can be computed by using mathematical concept of hyperbolic function. Accuracy of estimated location depends on the precision of estimated time offset value.

3. Simulation Evaluations

To demonstrate the performance improvement of the proposed wireless indoor localization scheme, simulation evaluations are carried out using Python programming for both synchronization phase and location estimation phase of the proposed scheme.

3.1. Evaluations for Synchronization Phase

Regarding the first phase, number of timing message exchanges among wireless nodes, and time offset error values are compared for RBS, PBS and proposed hybrid RBS-PBS synchronization approach. By using the different number of wireless nodes, l, and broadcasting times, m, the number of message exchanges, N, required for these approaches may be distinct.

For RBS, we use $N = m + m * \{l * (l - 1)/2\}$ to know the number of message exchanges. $N = 2 * m$ is applied for PBS and $N = m + m * (l - 1)$ is used for proposed hybrid approach. By reducing the number of timing message exchanges, energy consumption of wireless nodes can be saved.

Figure 3 illustrates the comparisons of number of timing message exchanges over different number of wireless nodes. As well, Figure 4 shows the number of exchange messages over various number of broadcasting times. The proposed scheme requires considerably less number of message exchanges than RBS, but slightly greater than PBS.

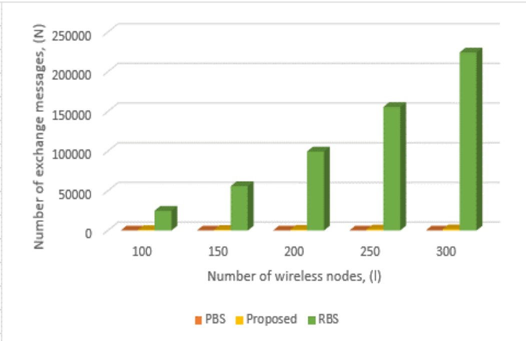

Figure 3. Number of exchange messages over l wireless nodes

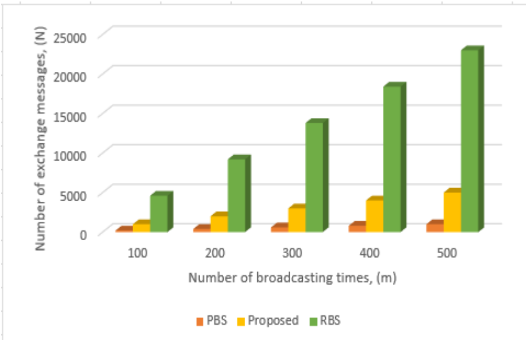

Figure 4. Number of exchange messages over m broadcasting times

To increase the synchronization accuracy, nondeterministic or random delays are estimated using different distribution models, Uniform distribution, $f(x) = \frac{1}{b-a}$, Gaussian random variable series model, $z[i] \sim N(\mu\sigma)$, and Log-normal distribution $\ln(X) \sim N(\mu, \sigma^2)$, so that time offset error can be calculated by using the estimated random delays. As comparison, random delays are calculated with time information getting from one-way and two-way exchange approaches using these three distribution models.

As to the results of these comparison, random delays can be estimated almost accurately by using Gaussian distribution. By applying the random delay values of uniform and log-normal distribution, estimated time offset error values are up to around

12ms and 15ms respectively which may cause high synchronization error. So, these values are neglected.

For simulation, we assign some time offset values (500ms, 50ms, and 5ms) between each of two anchor nodes (O and P, O and Q, and O and R) first.

Table 1. Time offset error, θ_{err} for RBS, PBS and proposed scheme

θ	θ_{err}		
	RBS	PBS	Proposed
5ms	490.62 μs	490.62 μs	183.24 μs
50ms	23.98 μs	23.98 μs	20.78 μs
500ms	14.61 μs	14.61 μs	10.39 μs

Table 1 describes the time offset error, θ_{err} , which is the difference between the assigned time offset values and estimated time offset values. Time offset error, θ_{err}, is calculated by using the estimated random delays using Gaussian model for RBS and PBS which is based on one-way timing information message exchange method and the proposed hybrid synchronization based on two-way method. Time offset error for RBS and PBS are equal because timing information is obtained by one-way transmission. Time offset error rate for proposed approach can be averagely reduced to 35% compared with existing approaches. Thus, synchronization accuracy of proposed scheme is absolutely higher than RBS and PBS.

3.2. Performance Comparisons in Location Estimation Phase

For location estimation phase, 4 anchor nodes are placed in 50 x 50 m^2 area and location of target node is estimated by using RBS and the proposed scheme. For all simulations, time offset value of 5ms is applied.

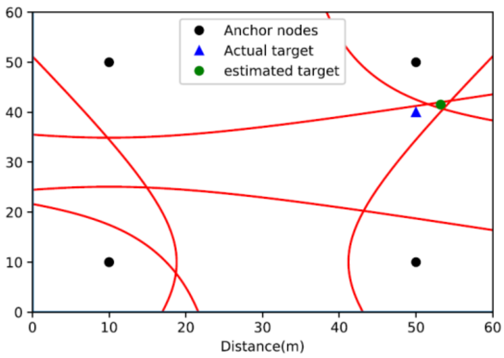

Figure 5. Location estimation using RBS (Err_{rms}=3.56 m)

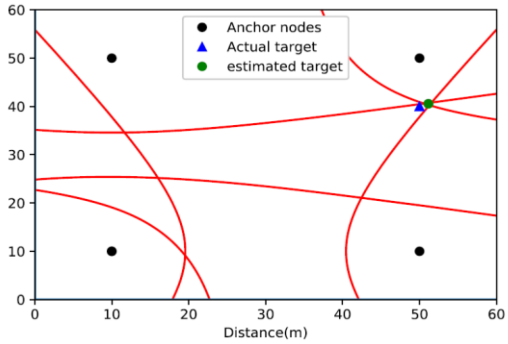

Figure 6. Location estimation using proposed scheme (Err_{rms}=1.27 m)

Figure 5 and 6 illustrate the position estimation of one target node by using RBS and the proposed scheme. Additional simulations are carried out with 10 target nodes placed inside the same network scenario. Localization accuracy is calculated by using (17).

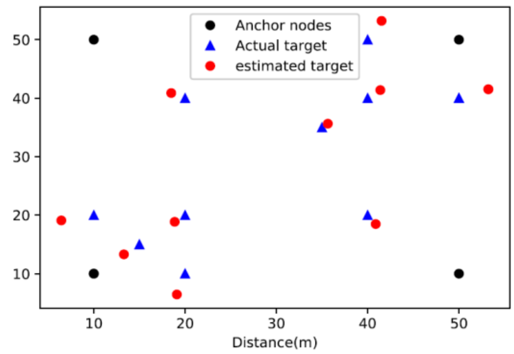

Figure 7. Comparison of real and estimated target positions (Err_{rms}=2.67 m)

$$Err_{rms} = \sqrt{\frac{1}{n}\sum_{j=1}^{n}(|P_r - P_{es}|^2)} \quad (17)$$

where, P_r is the actual coordinates of target and P_{es} is the estimated values.

In accordance with the result in Figure 7 and 8, the localization accuracy increases 67% by using the proposed scheme.

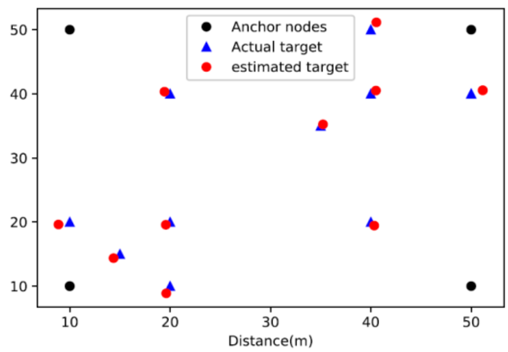

Figure 8. Comparison of real and estimated target positions (Err_{rms}=0.88 m)

4. Conclusion

This paper proposes a TDoA based wireless indoor localization using an effective hybrid time synchronization approach classifying two phases. By combining the merits of two existing wireless time synchronization protocols, synchronization performance becomes improved by reducing number of timing messages and getting more precise time synchronization. Consequently, localization accuracy in location estimation phase is getting higher. Evaluations also reveal that the proposed system is robust and effective one for wireless indoor localization. Additionally, experimental evaluations will be carried out for real time wireless indoor localization applications.

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