IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received May 22, 2018, accepted June 4, 2018, date of publication June 27, 2018, date of current version July 12, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2850660

A Model on Indoor Localization System Based on the Time Difference Without Synchronization

YUAN XUE, WEI SU, HONGCHAO WANG, (Member, IEEE), DONG YANG, (Member, IEEE), AND JIAN MA

National Engineering Laboratory for Next Generation Internet Interconnection Devices, Beijing Jiaotong University, Beijing 100044, China

Corresponding author: Hongchao Wang (hcwang@bjtu.edu.cn)

This work was supported by the Natural Science Foundation of China under Grant 61701018 and Grant 61771040.

ABSTRACT Localization has emerged as an attractive solution to enable new business models that rely on location-based services in wireless networks for communication, sensing, and control. In particular, time difference-of-arrival (TDOA) is one of the widely used localization models. However, the conventional TDOA requires precise time synchronization between a target node and anchor nodes for measuring the time difference, which leads to a large number of packets for communication. To reduce packet transmission, we propose a model for measuring the time difference without time synchronization called ASync-TDOA. Different from the conventional model, ASync-TDOA can measure the time difference in a one-way-based ranging by introducing the reference node. Specifically, the time difference between the target node and anchor nodes can be directly measured by the server based on the timestamps from the reference node. After that, the target node is accurately located using least squares and brute force for the time difference. We implement the ASync-TDOA model on a localization system with ultra-wideband signals to estimate the localization of the target node, which is easy to operate in practical engineering. The experiments show that the proposed ASync-TDOA is efficient in reducing the packet transmissions and improving the TDOA measurement and localization precision.

INDEX TERMS Localization, time synchronization, time-difference-of-arrival (TDOA), timestamp.

I. INTRODUCTION

With the improvement of wireless technology, localization is a key aspect of emergent applications in wireless sensor networks and the internet of things [1]–[3]. One of the important localization systems is GPS which has been widely used in outdoor environments. However, such systems cannot work well in indoor environments due to the signal attenuation. Fortunately, ultra-wideband (UWB) has emerged as a promising technique to address this issue. Numerical indoor localization systems have been proposed by leveraging the advantages of UWB, such as a nanosecond timestamp, low power consumption, strong penetrability and a high transfer data rate [4]–[6]. This paper focuses on an indoor localization system based on UWB.

Indoor localization systems can be divided into two categories, range-based and range-free. The most commonly used localization is the range-based system. Many methods for range-based localization have been proposed [7], such as received signal strength (RSSI) [8], time-of-arrival (TOA) [9], time-difference-of-arrival (TDOA) [10], and direction of arrival (DOA) [11] to calculate the distance for the signal from target node to the anchor nodes. As discussed in [12], the accuracy of TOA and TDOA is better than that of RSS-based localization. In TOA, all nodes should use a common synchronous clock reference and participate in the localization process. However, the TDOA-based localization technique only needs time synchronization between the anchor nodes. Thus, TDOA is the most popular method with the high accuracy and low demand on the transmission times. In the conventional TDOA method, a target node can be located by a set of anchor nodes that measure the time difference as shown in Fig. 1. The anchor nodes are first synchronized with each other, and then the time difference between a target node and different anchor nodes is measured to locate a target node. Since the time difference measure is affected by multiple factors such as the accuracy of synchronization, harsh environments, the Non-Line-of-Sight (NLOS) error and so on [10], [13], [14], it is hard to be measured accurately via the conventional TDOA method. Among the factors, the accuracy of synchronization is one of the main

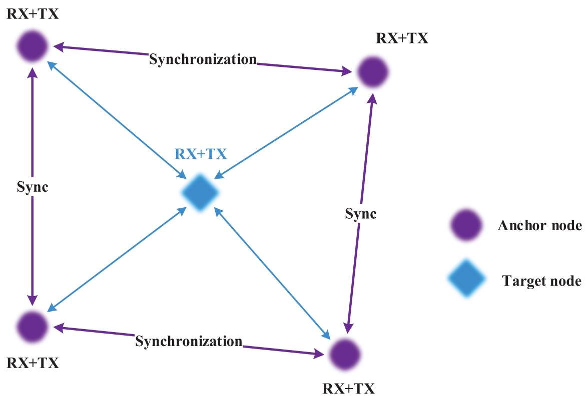

FIGURE 1. TDOA measurement requires synchronization between all nodes or anchor nodes.

impact factors affecting the TDOA measurement. There are many studies that focus on the time synchronization, such as RBS [15], TPSN [16], FTSP [17] and GTSP [18]. However, due to clock skew and drifting, none of the existing works has approached synchronization problems perfectly [19]–[21]. Time synchronization is generally achieved by massive message exchanges among a set of anchor nodes which can result in a heavy network traffic. In addition, this significantly increases the burden of network.

To solve these issues with the synchronization of TDOA measurement, many difference approaches have been proposed to measure the time difference without synchronization [22]–[31]. Localization approaches based on acoustic signals with a speaker, a microphone, and some forms of device-to-device communication were proposed in [23] and [24], respectively. Since the complication of an industrial environment creates many difficulties in transmitting the signals and requires retransmission of lost packets, these approaches cannot be implemented. Reference [25] exploits opportunistically signals and packets for the TOA localization system, which relies exclusively on the measurement of reception times. Though some approaches can obtain a high accuracy of the TDOA measurement in [26]–[31], they often need expensive equipment and rely on a combination of transmission and reception timestamps or require their own protocols. This makes the high-accuracy localization extremely challenging, especially for low-cost devices in complicated industrial environments and with large-scale wireless network localization.

In this paper, we propose ASync-TDOA, a model for TDOA localization without time synchronization, which achieves the time difference in a one-way-based ranging by introducing the reference node. In the proposed ASync-TDOA, anchor nodes first record timestamps that come from the target node and the reference node, and then send them to the server. By using an interpolation method, the server can measure the time difference between the target node and anchor nodes directly based on the timestamps from reference node. Finally, the target node can be accurately located using the least squares and brute force for the time difference. ASync-TDOA can receive more redundant information for localization and thus, improves the accuracy of localization. ASync-TDOA can also reduce the packet transmissions and create high-accuracy localization in low-cost devices. In addition, ASync-TDOA is easy to be implemented in the practical engineering.

The rest of this paper is organized as follows. In Section II, we review the studies on TDOA localization related to our work. Section III describes and analyzes the details of ASync-TDOA. The implementation of our prototype system and the performance are provided in Section IV. Finally, the conclusions are drawn in Section V.

II. RELATED WORK

In range-based localization systems, to achieve an accurate measure for the transmission time of the signal, many range-based localization models have been proposed which can be roughly classified into two types: synchronous and asynchronous.

A. SYNCHRONOUS

Generally, the accuracy of the time difference is influenced by time synchronization among anchor nodes. In the literature, some sutdies use a precise synchronization to measure the time difference. Reference [32] uses radio frequency (RF) and ultrasonic signals to measure the time difference with their own CPU timestamps between difference anchor nodes. Reference [33] proposed and validated a novel multi-user TDOA-based localization system using wireless clock synchronization based on IEEE 802.15.4a. Reference [34], [35] design and implemented a digital receiver and transmitter board called the SMart integrated Localization Extension (SMiLE) with distributed a single frequency over the network via Ethernet clocking. The clock offsets were determined in the SMiLE boards for synchronization. While the accuracy of these synchronous models is very good, the synchronization method is not easy to be implemented and increases the burden of network.

B. ASYNCHRONOUS

Although the time synchronization could improve the measure precision, it also heavily increases the burden of communication network. This is mainly because the time synchronization technique requires a large amount of communication bandwidth and a high network throughput. However, the communication links and the data transmission are increasing. Some slightly different perspectives on the problem of the time difference in asynchronous models were addressed in [36]. Reference [37] measured the time difference between two signals from distinct transmitters arriving at the same receiver based on DTDOA. The received signals should be in sequence to reconstruct the time difference, but the clock drift problem has not been overcome. To calibrate the clock skews of the anchor nodes in asynchronous networks, [31], [38], and [39] proposed the time-based localization strategies, which rely exclusively on a combination of transmission and reception timestamps to calculate the real distance between two nodes. However, the node transmissions are bidirectional and increase the packet transmission and the system complexity.

Many difference approaches have been proposed to measure the time difference without synchronization to reduce complexity. A new TDOA model was proposed in [26], which can measure the time without the synchronization to overcome the disadvantages of TDOA. However, it needs to know the initial coordinates of the target first. The initial coordinates are hard to ensure in practice. Reference [27] proposed Whistle, a novel TDOA localization without time synchronization, which achieves high accuracy by two techniques: Two-signal sensing and sample counting. This model is implemented with a high computation performance and a wide bandwidth. Reference [30] proposed a procedure to estimate the pseudo-ranges between the target and anchor nodes by measuring the time between the participating nodes. The method proposed in [40] uses DTDOA in conjunction with oscillator frequency offset compensation in large-scale asynchronous WLANs. It needs to be amended with other devices capable of hardware timestamping IEEE802.11b frames.

With the cooperation of GPS-enabled mobile terminals, an approach to opportunistic positioning based on timing measurements was presented by [28], proposing that the asynchronous radio transmissions from fixed stations and from mobile GPS-equipped nodes are jointly exploited to cooperatively localize a blind node. Reference [29] proposed an approach to compensate the GPS synchronization offset with DTDOA in the operating environment (e.g.. indoors). These ideas were combined with TDOA or DTDOA methods and require additional infrastructures.

III. LOCALIZATION MODEL

TDOA-based localization needs to measure the time difference between the target and any pair of anchor nodes. In this contribution, we present a localization model, namely, ASync-TDOA, to measure the time difference by introducing a reference node that does not require time synchronization between anchor nodes.

A. STRUCTURE OF THE ASYNC-TDOA APPROACH

In the proposed ASync-TDOA, we choose a UWB signal with nanosecond accuracy for sample-based timestamps, and a reference node was introduced which could emit a UWB signal lasting for a specified period. A few anchors were designed to receive the UWB signal form target and reference nodes. In ASync-TDOA, we assume that the target node can emit a UWB signal to demonstrate its existence, the localization of all anchor nodes and reference node are known.

The basic idea of ASync-TDOA is as follows: An anchor node needs to record timestamps that come from the target node and the reference node, and then send them to the server. According to the record, the server can locally detect the interval of the arrival time of these two signals. By using an interpolation method, the server calculates the mapping values, without referring to the clock of any other anchor. The server can measure the time difference between the target node and anchor nodes directly based on the mapping values, still without any time synchronization. Finally, the target node can be accurately located by the least squares and brute force for the time difference.

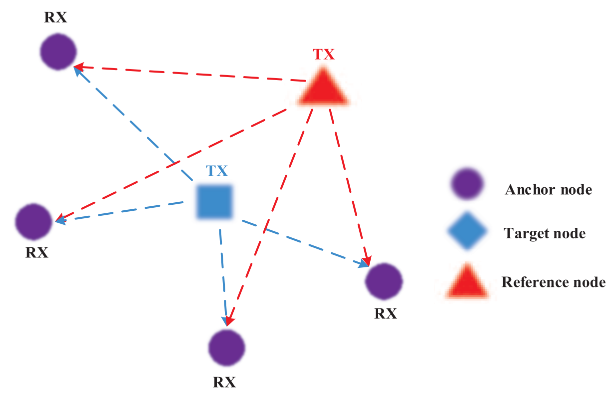

FIGURE 2. TDOA measurement without synchronization.

We use a simple scenario to illustrate the ASync-TDOA model as shown in Fig. 2. The target node could send localization signals at any time and its position is denoted by $\boldsymbol{X_S} = [x_s, y_s]$. The reference node sends the signal periodically, where its position is denoted by $\boldsymbol{X_R} = [x_r, y_r]$. The anchor nodes receive signals from the target node and the reference node, and these positions can be denoted by $\boldsymbol{X_{AN}} = [x_{an}, y_{an}]$. During the measurement process, all anchor nodes record the timestamp and take turns passing parameters to a central server to execute the computation tasks. Ignoring the measurement noise, the distance between the target node and the ith anchor node can be computed by

$$d_{AN_i} = cT_{AN_i} = \|\boldsymbol{X_S} - \boldsymbol{X_{AN_i}}\|, \quad \text{for } i = 1, \ldots, M \tag{1}$$

where c is the signal transmission speed, T_{AN_i} is the transmission time between the target node and the ith anchor node, $\|\cdot\|$ denotes the L2 norm, and $\boldsymbol{X_{AN_i}}$ is the localization of the ith anchor node. The time difference between AN_i and AN_j can be given as

$$\begin{aligned} T_{AN_{i,j}} &= T_{AN_i} - T_{AN_j} \\ &= \frac{\|\boldsymbol{X_S} - \boldsymbol{X_{AN_i}}\| - \|\boldsymbol{X_S} - \boldsymbol{X_{AN_j}}\|}{c} \end{aligned} \tag{2}$$

With multiple TDOAs as well as locations of anchors, we can deduce the location of the target node. It is notable that to locate the target, we need to solve a set of equations for TDOA measurements such as Equation (2). Obviously, the solution of the TODA measurement affects the precision of the localization. Therefore, ASync-TDOA concentrates on how to accurately measure the TDOA values between any pair of anchors.

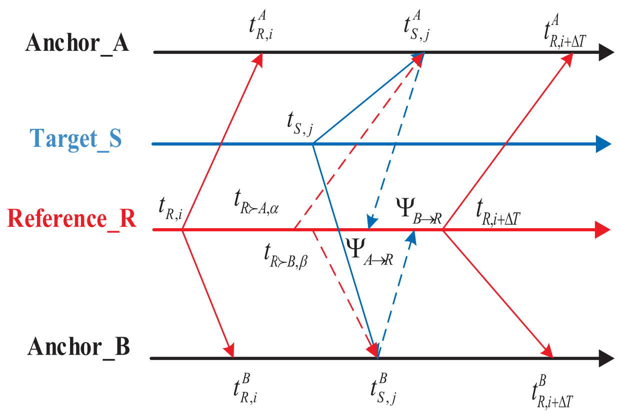

FIGURE 3. ASync-TDOA to measure TDOA.

B. MEASURING TDOA BY MAPPING VALUES

Without time synchronization between anchor nodes, the conventional TDOA cannot exactly express the TDOA value directly. Here, we describe how to accurately measure TDOA values by the ASync-TDOA model. The symbols used in our approach are defined in the notation list:

- $t_{k,i}$: The transmission time when node k emits the signal at t_i.
- $t^m_{k,i}$: The reception time of the packet that is sent by node k to node m at t_i.
- $t^{m,n}_k$: The time difference between node k to node m and node n.
- d^m_k: The distance between node k and node m.
- $d^{m,n}_k$: The distance difference between node k to node m and node n.
- c: The signal transmission speed.

To measure the time difference between asynchronous anchors, we introduce the reference node to calculate the mapping values, without referring to the clock of any other anchor.

Fig. 3 shows a typical time sequence for all nodes. The target node S sends a localization signal at $t_{S,j}$. Anchor nodes A and B receive the reference signals at $t^A_{S,j}$, $t^B_{S,j}$, respectively. The TDOA value between receiver A and B, denoted by $T_{A,B}$, is expressed with $\left(t^A_{S,j} - t^B_{S,j}\right)$ if both anchors are time synchronized. The reference node R sends reference signals at $t_{R,i}$ and $t_{R,i+\Delta T}$. Then, reference signals arrives at anchor node A at $t^A_{R,i}$ and $t^A_{R,i+\Delta T}$ and that receives at anchor nodes B at $t^B_{R,i}$ and $t^B_{R,i+\Delta T}$, respectively. For all nodes, the TDOA is measured by the nodes' CPU timestamps, and there is no identical timestamp in a short time. Hence, $t^A_{S,j}$ is in the range of $t^A_{R,i}$ and $t^A_{R,i+\Delta T}$, $t^B_{S,j}$ is in the range of $t^B_{R,i}$ and $t^B_{R,i+\Delta T}$.

We define the mapping values on the reference node, that the time of the anchor node receives the localization signal. We denote the mapping values of $t^A_{S,j}$ and $t^B_{S,j}$ by $\Psi_{A\to R}$ and $\Psi_{B\to R}$, respectively. Then, the TDOA between A and B using mapping values is modeled by

$$T_{A,B} = \left(t^A_{S,j} - t^B_{S,j}\right)_{sync} \overset{mapping}{\Rightarrow} \Psi_{A\to R} - \Psi_{B\to R} \tag{3}$$

Clearly, we only need to calculate $\Psi_{A\to R}$ and $\Psi_{B\to R}$ to measure the TDOA value. Moreover, the mapping value of a receiver can be obtained by the reference node, without any synchronization with the others. With the help of the reference node, we develop a method to measure the TDOA by the mapping values. Thus, we use Equation (3) to measure the TDOA between two anchors.

C. CALCULATING MAPPING VALUES

To calculate the mapping values, we introduce the time of $t_{R\succ A,\alpha}$ and $t_{R\succ B,\beta}$. In Fig. 3, we assume that reference node R sends a signal at $t_{R\succ A,\alpha}$ and $t_{R\succ B,\beta}$, and then anchor nodes A and B receive these signals at $t^A_{S,j}$, $t^B_{S,j}$, respectively. We assume that $t_{R\succ A,\alpha}$ and $t_{R\succ B,\beta}$ are the send time, denoted by $\lambda(0), \lambda(1), \cdots, \lambda(m)$, and $t^A_{S,j}$, $t^B_{S,j}$ are the corresponding reception time, is denoted by $\Phi(0), \Phi(1), \cdots, \Phi(m)$, respectively. Suppose the corresponding relationship between the send time λ and the corresponding reception time Φ is existing, but too complex to evaluate efficiently. We can achieve the comparison expression Φ to calculate $t_{R\succ A,\alpha}$ and $t_{R\succ B,\beta}$.

By using the interpolation method, a few known data points from the original function can be used to create an interpolation based on a simpler function. Now, we take anchor A as an example. At the time of θ, λ_θ is the send time from R to A and $\Phi(\lambda_\theta)$ is the corresponding reception time of A. We construct $\gamma_\theta(\lambda)$ as a special n-th-order polynomial that meets the requirement:

$$\begin{aligned} \gamma_\theta(\lambda_0) &= \cdots = \gamma_\theta(\lambda_{\theta-1}) = 0 \\ \gamma_\theta(\lambda_\theta) &= 1 \\ \gamma_\theta(\lambda_{\theta+1}) &= \cdots = \gamma_\theta(\lambda_m) = 0 \end{aligned} \tag{4}$$

Obviously, $\gamma_\theta(\lambda_0), \cdots, \gamma_\theta(\lambda_{\theta-1}), \gamma_\theta(\lambda_{\theta+1}), \cdots, \gamma_\theta(\lambda_m)$ are the null point of $\gamma_\theta(\lambda)$. Then,

$$\gamma_\theta(\lambda) = \Lambda_\theta(\lambda - \lambda_0)\cdots(\lambda - \lambda_{\theta-1})(\lambda - \lambda_{\theta+1})\cdots(\lambda - \lambda_m) \tag{5}$$

According $\gamma_\theta(\lambda_\theta) = 1$, Λ_θ can be calculated by

$$\Lambda_\theta = \frac{1}{\prod\limits_{\substack{j=0\\ j\neq\theta}}^{m}(\gamma_\theta - \gamma_j)} \tag{6}$$

According to equation (5) and (6), we obtain equation:

$$\gamma_\theta(\lambda) = \frac{\prod\limits_{\substack{j=0\\ j\neq\theta}}^{m}(\gamma - \gamma_j)}{\prod\limits_{\substack{j=0\\ j\neq\theta}}^{m}(\gamma_\theta - \gamma_j)} = \prod_{\substack{j=0\\ j\neq\theta}}^{m}\frac{(\gamma - \gamma_j)}{(\gamma_\theta - \gamma_j)} \tag{7}$$

$\gamma_\theta(\lambda)$ is a special n-th-order polynomial, λ_θ is the send time, and $\Phi(\lambda_\theta)$ is the corresponding reception time.

By using the interpolation method, the comparison expression $\Phi(\lambda)$ can be given as:

$$\Phi(\lambda) = \sum_{\theta=0}^{m} \gamma_\theta(\lambda)\,\Phi_\theta \tag{8}$$

To determine the function of $\Phi(\lambda)$, we construct the polynomial $P_m = a_0 + a_1x + a_2x^2 + \cdots + a_mx^m$, $P_m(x_\theta) = \Phi_\theta$, where $\theta = 0, 1, \cdots, m$. Φ_θ can be calculated by

$$\begin{cases} a_0 + a_1x_0 + \cdots a_mx_0^m = \Phi_0 \\ a_0 + a_1x_1 + \cdots a_mx_1^m = \Phi_1 \\ \vdots \\ a_0 + a_1x_m + \cdots a_mx_m^m = \Phi_m \end{cases} \tag{9}$$

The coefficient determination of the Equation (8) is

$$D = \begin{vmatrix} 1 & x_0 & x_0^2 & \cdots & x_0^m \\ 1 & x_1 & x_1^2 & \cdots & x_1^m \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & x_m & x_m^2 & \cdots & x_m^m \end{vmatrix} = \prod_{0\le j\le\theta\le m}(x_\theta - x_j) \tag{10}$$

D is a Vandermonde determinant. As $x_\theta \neq x_j$, $D \neq 0$, $\theta = (0, 1, \cdots, m)$, $j = (0, 1, \cdots, m)$, the coefficient of Equation (9) has only one solution $(a_0, a_1, \cdots, a_m)$. According to Equation (10), $\Phi(\lambda)$ can be regarded as a linear function with a unique solution at λ:

$$\Phi(\lambda) = \Phi(\lambda_0)\frac{\lambda - \lambda_1}{\lambda_0 - \lambda_1} + \Phi(\lambda_1)\frac{\lambda - \lambda_0}{\lambda_1 - \lambda_0} \tag{11}$$

That is

$$\frac{\Phi(\lambda_1) - \Phi(\lambda_0)}{\lambda_1 - \lambda_0} = \frac{\Phi(\lambda) - \Phi(\lambda_0)}{\lambda - \lambda_0} \tag{12}$$

Thus, we can achieve the time of $t_{R\succ A,\alpha}$ and $t_{R\succ B,\beta}$ with equation (12):

$$\begin{aligned} \frac{t^A_{R,i+\Delta T} - t^A_{R,i}}{t_{R,i+\Delta T} - t_{R,i}} &= \frac{t^A_{S,j} - t^A_{R,i}}{t_{R\succ A,\alpha} - t_{R,i}} \\ \frac{t^B_{R,i+\Delta T} - t^B_{R,i}}{t_{R,i+\Delta T} - t_{R,i}} &= \frac{t^B_{S,j} - t^B_{R,i}}{t_{R\succ B,\beta} - t_{R,i}} \end{aligned} \tag{13}$$

Recall that on the reference node, $\Psi_{A\to R}$ is the mapping values of $t^A_{S,j}$ and $\Psi_{B\to R}$ is the mapping values of $t^B_{S,j}$. In other words, R sends a signal at $t_{R\succ A,\alpha}$ and $t_{R\succ B,\beta}$, and receives it at $\Psi_{A\to R}$, $\Psi_{B\to R}$, respectively. Hence, the distance between reference node R and anchor node A or B can be written as:

$$\begin{aligned} d^A_R &= c\left(\Psi_{A\to R} - t_{R\succ A,\alpha}\right) \\ d^B_R &= c\left(\Psi_{B\to R} - t_{R\succ B,\beta}\right) \end{aligned} \tag{14}$$

In the ASync-TDOA model, the reference node and anchor nodes are stationary, whose localizations are known. The distance between reference node R and anchor node A or B can be written as:

$$\begin{aligned} d^A_R &= \|\boldsymbol{X_R} - \boldsymbol{X_A}\| = \sqrt{(x_r - x_a)^2 + (y_r - y_a)^2} \\ d^B_R &= \|\boldsymbol{X_R} - \boldsymbol{X_B}\| = \sqrt{(x_r - x_b)^2 + (y_r - y_b)^2} \end{aligned} \tag{15}$$

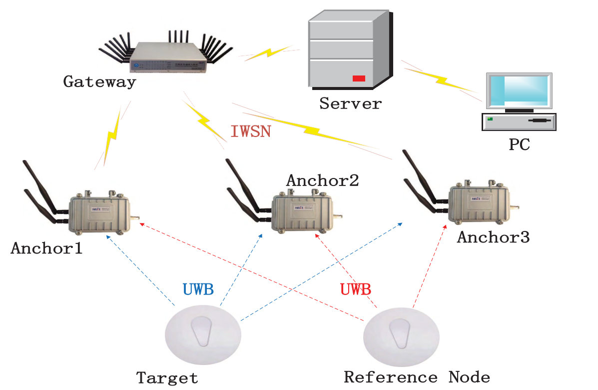

FIGURE 4. System architecture.

According to Equation (14) and (15), the distance difference of the reference node R to anchor node A and B is bound by:

$$\begin{aligned} d^{A,B}_R &= d^A_R - d^B_R = \|\boldsymbol{X_R} - \boldsymbol{X_A}\| - \|\boldsymbol{X_R} - \boldsymbol{X_B}\| \\ &= c\left[\left(\Psi_{A\to R} - t_{R\succ A,\alpha}\right) - \left(\Psi_{B\to R} - t_{R\succ B,\beta}\right)\right] \end{aligned} \tag{16}$$

As a result, $\Psi_{A\to R}$ and $\Psi_{B\to R}$ can be calculated by $t_{R\succ A,\alpha}$ and $t_{R\succ B,\beta}$. According to Equation (3) and (13), the time difference T_{AB} between A and B satisfy the following relation:

$$T_{A,B} = \Psi_{A\to R} - \Psi_{B\to R} = t_{R\succ A,\alpha} - t_{R\succ B,\beta} + \frac{d^{A,B}_R}{c} \tag{17}$$

Note that if such model of ASync-TDOA is used, the time difference will be measured in a one-way-based ranging without the transmission of synchronization packets.

IV. IMPLEMENTATION AND EXPERIMENTS

In this section, we introduce the architecture of ASync-TDOA in hardware first, and then give an example of how ASync-TDOA works. We evaluate the performance of the ASync-TDOA model and the localization accuracy of the ASync-TDOA-based localization system.

A. SYSTEM ARCHITECTURE

To evaluate our proposed model, we designed a system based on the ASync-TDOA model, which can overhear IEEE 802.15.4 signals, and mark the captured messages with a timestamp accurately. As shown in Fig. 4, the system can estimate the localization of the target node by measuring the time difference between the target node and any pair of anchor nodes in real time. The system is comprised of five main components, a target node, a reference node, anchor nodes, a gateway and a server.

In the ASync-TDOA-based localization system, we use the DecaWave DW1000 as radio transceivers, which is compliant with the IEEE802.15.4-2011 standard as shown in Fig. 5. The controlling framework of transmitting or receiving the timestamp was actualized by an STM32f105 chip with Contex-M3 as shown in Fig. 6.

We integrated these nodes into a low-speed industrial wireless multi-hop network. The network not only enlarged

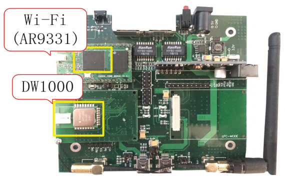

FIGURE 5. Transport module.

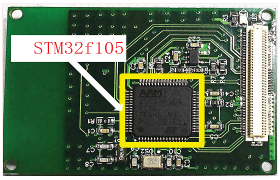

FIGURE 6. Control module.

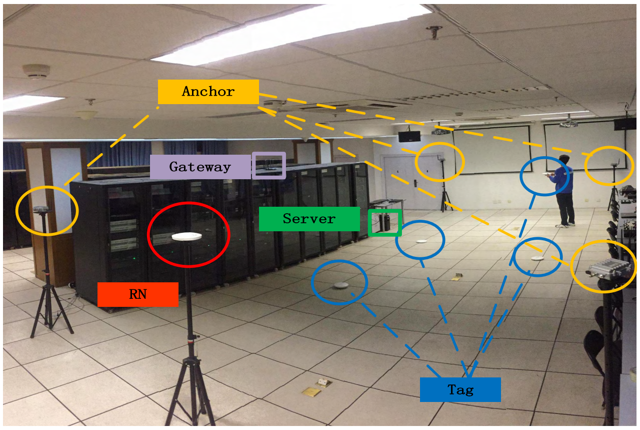

FIGURE 7. Experimental environment.

the system coverage scope but also greatly improved the flexibility of system networking. The gateway adopted our industrial sensor network protocol, which had the features of high density, anti-interference, high efficiency, low consumer and so on.

The server ran on a PC, which could estimate the localization of the target node by measuring the time difference and pushing the result to the Web. We could see the localization and the trajectory on the Web.

B. MEASUREMENT SETUP

Herein, we give an example to show the working process of the ASync-TDOA.

In the localization process, the target node and reference node periodically broadcasts packets. First, all anchor nodes were connected to the server by an industrial wireless multi-hop network. Second, the server starts to send a command to the anchors and determines the number of activity nodes by counting the ACK messages replied from these anchors. After successfully connecting, as the anchor has received the packet from the target or reference, it retransmits the packet. The packet contains the information of all nodes, such as the types of the nodes, the IP of the anchor, the ID of the target, and so on. This information can be collected and managed by the server. Finally, the server receives and stores all the data, and estimates the localization as follows:

(a) Find the mapping interval in the original data.

(b) Measure the time difference between the target node and any pair of anchor nodes by the mapping value.

(c) Use the TDOA values to estimate the localization of the target node by least squares and brute force.

(d) Store the localization of the target node in the database, and display it on the Web in real-time.

C. EXPERIMENT SCENARIO

We performed extensive experiments to examine the feasibility of ASync-TDOA working for localization in a large-scale wireless network. As shown in Fig. 7, we used a laboratory to simulate the factory environment. For the sake of simplicity, we considered a $2D$ localization model to compare with other models. We measured the time difference and estimated the localization in this environment to evaluate the proposed model.

We tested the performance of the proposed model in a 9.6∗4.8 m^2 areas in an indoor lab space. The implemented system is consisted of four anchor nodes and a reference node. Evaluation measurements were conducted at two scenes, which had different layouts as shown in Fig. 8(a) and Fig. 8(b), respectively. The coordinates of anchor nodes were $A = (9.6\,m, 0)$, $B = (0, 0)$, $C = (0, 4.8\,m)$, $D = (9.6\,m, 4.8\,m)$. The coordinates of the reference node were $R_1 = (4.8\,m, 2.4\,m)$ in scene 1 and $R_2 = (9.6\,m, 2.4\,m)$ in scene 2. The theoretical coordinate of the target node was $(2.1\,m, 2\,m)$ in scene 1, and $(2.1\,m, 2.2\,m)$ in scene 2. In all experiments, the target node was static and transmitted a packet every 300 ms. The localization of each was conducted many times. The reference node and target node sent broadcast signals.

D. PACKET TRANSMISSION

The conventional TDOA model requires anchor nodes to be synchronized. Generally, this is the main reason for increasing the packet transmission between anchor nodes.

Fig. 9 shows the number of packets for a single target node located in the conventional TDOA model and ASync-TDOA model., respectively. The system needs at least 3 anchor nodes to estimate the localization of the target in a 2-Dimensional area. At the beginning of the test, the conventional TDOA model needed 7 groups of packets, but ASync-TDOA only needed 3 groups of broadcast packets. The reason is that the conventional TDOA-based localization needs to synchronize first and then estimates the localization. While ASync-TDOA-based localization only needs two broadcasts to measure the time difference and estimate the localization.

After the test began, the number of packets increased in the conventional TDOA model in Fig. 9. However, the number of packets did not increase in ASync-TDOA. With the increase

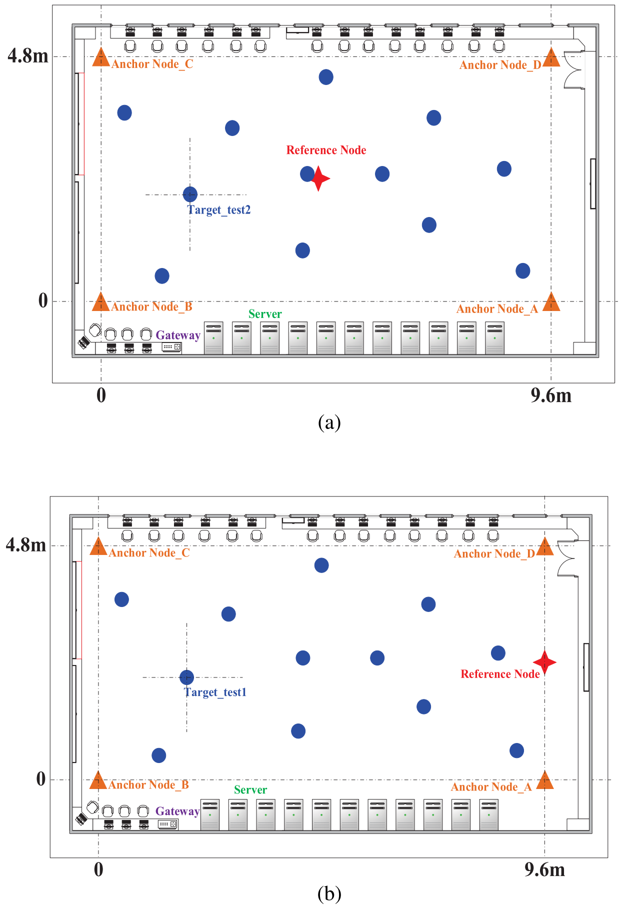

FIGURE 8. Experiment Scenario. (a) Scene 1: Reference node in the middle of the area. (b) Scene 2: Reference node is stochastic in the area.

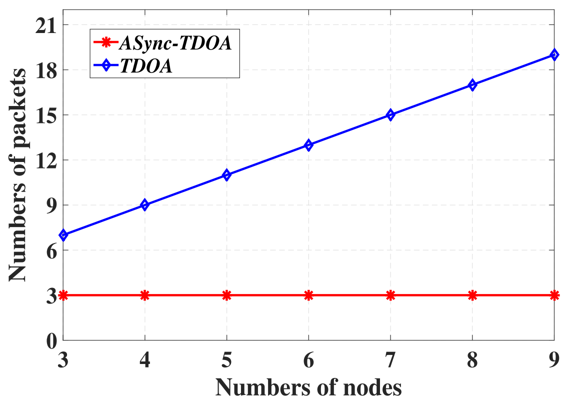

FIGURE 9. Packet transmission, as TDOA measurement in different models.

of the anchor nodes, the synchronization packets increased in the conventional TDOA model. The number of packets is increased by $(2n - 2)$ than ASync-TDOA model, n is number of anchor nodes.

Fig. 10 shows the overall number of packets transmitted in a certain moment. The number of packets transmitted between the anchor nodes increased in the conventional TDOA model; however, it was constant in the ASync-TDOA

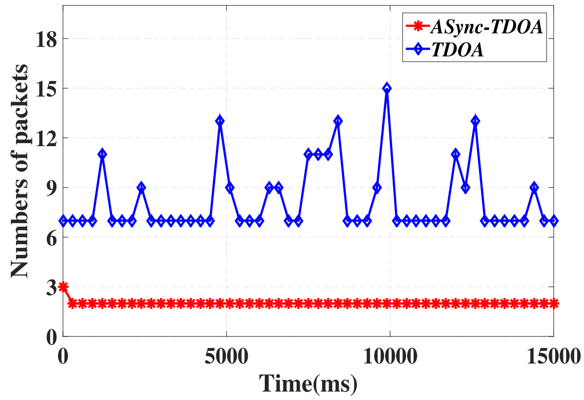

FIGURE 10. Packet transmission, as the synchronization packets are losing.

model. The reason is that when the synchronization failed, the synchronization packets needed to be retransmitted. ASync-TDOA can use the historical data to measure the time difference. Thus, the number of retransmitted packets was significantly reduced compared to the conventional TDOA model. As a result, packet transmission was much lower when compared with the conventional TDOA model.

Note that, the synchronization process of the conventional TDOA model is occupied bandwidth. Channel conflicts could occur and result in the loss of localization packets when the number of targets and anchors increased. In a large-scale area with a plenty of anchor nodes and target nodes, ASync-TDOA can reduce the cost to the network and bandwidth.

E. MEASUREMENT PERFORMANCE

For a localization system, the TDOA measurement is an important factor affecting the localization accuracy. Through the experiments, we examined the performance of the ASync-TDOA model.

To analyze the accuracy of the time difference, we obtained the $TDOA_{i,j}$ between the target node and any pair of anchor nodes in scene 1 and scene 2. Substituting $TDOA_{i,j}$ into the Equation (2), we can computed the distance difference $d_{i,j}$. We compared the Root Mean Square Error (RMSE) of the distance difference with different periods of the reference signals and plotted RMSE in Fig. 11 and Fig. 12. The RMSE was calculated as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(d_{measure,i} - d_{model,i}\right)^2}{n}} \tag{18}$$

where, n is the times of the measurement, $d_{measure,i}$ is the measurement value and $d_{model,i}$ is the theoretical value. To compare the performance of the ASync-TDOA and TDOA, we set the synchronization frequency of the conventional TDOA as 5 HZ. In Fig. 11 and Fig. 12, we can see that the RMSE of the ASync-TDOA closely approximates the conventional TDOA. We found that the RMSE decreased as the reference node sent signals more frequently. Our experiments, for instance, showed that there exists a close relationship between

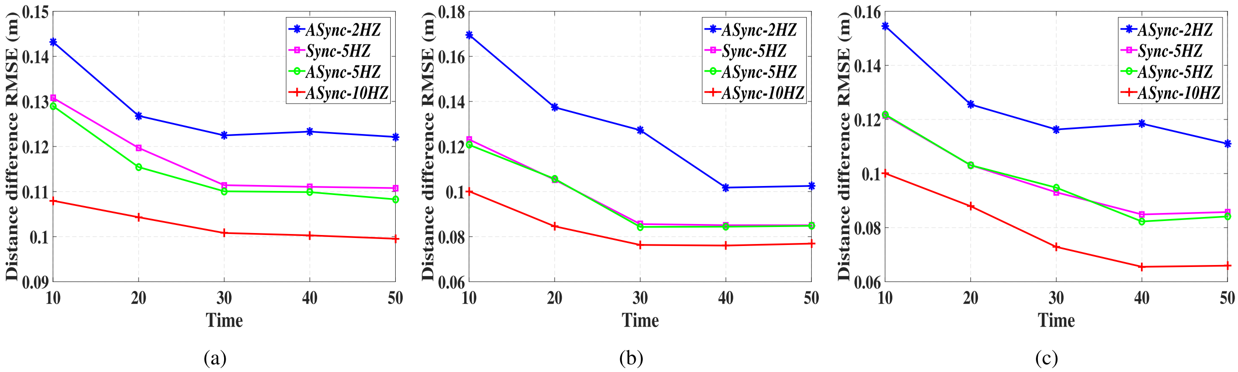

FIGURE 11. Distance difference RMSE in scene 1. (a) RMES $\epsilon_{A,B}$. (b) RMES $\epsilon_{A,C}$. (c) RMES $\epsilon_{A,D}$.

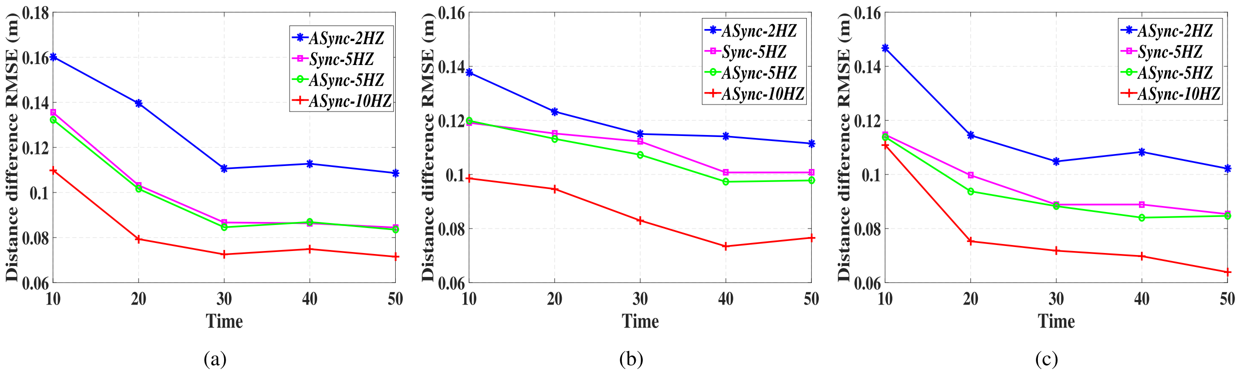

FIGURE 12. Distance difference RMSE in scene 2. (a) RMES $\epsilon_{A,B}$. (b) RMES $\epsilon_{A,C}$. (c) RMES $\epsilon_{A,D}$.

TABLE 1. TDOA measurement error.

Types	Scene	Mean(m)	Standard Deviation(m)
AB	scene 1	0.0678	0.0861
	scene 2	0.0674	0.0856
AC	scene 1	0.0711	0.0891
	scene 2	0.0770	0.0940
AD	scene 1	0.0699	0.0834
	scene 2	0.0668	0.0897

the TDOA measurement and the sending frequency of the reference node. In other words, if the reference node sends signals more frequently, the time difference is more accurate.

Fig. 13 plots the distribution of the distance difference error $Error_{i,j}$ between the measurement values and theoretical values in different scenes. The frequency of the reference node sends signals was 5 HZ. It is obvious that there were only very few poor values for most configurations. The $Error_{i,j}$ was less than 0.2 m in different configurations. Table. 1 shows the distance difference measurement error results, including their mean error and standard deviation. These deviations mainly resulted from the error in calculating the mapping values, and the localization of the reference node or anchor nodes were inaccurate.

It can be clearly seen that the proposed model can offer better performance and the higher precision of the distance difference measurement. Overall, ASync-TDOA can achieve relatively high accuracy on the time difference.

F. LOCATION ESTIMATION USING ASYNC-TDOA

By collecting the related information about the localization with wireless measurement technology, we can obtain the localization of the target by estimation technology. Based on the model of ASync-TDOA, the method is essential to obtain the intersection point of a set of hyperbolas. Here, the localization of the target node was calculated by the least squares and brute force to improve the accuracy of localization.

Each coordinate contains rational X and Y. These numbers represent horizontal and vertical coordinates. We compared the coordinate error calculated by ASync-TDOA in scene 1 and scene 2. We plotted the distribution of the coordinate error $Error_{coordinate,scene}$ in Fig. 14. The graph shows the error of the coordinates in two scenes. It is clearly seen that for two scenes with different configurations, most of the results of the coordinate error were less than 0.1 m.

Fig. 15 summarizes the cumulative distribution function (CDF) of localization errors in the ASync-TDOA-based system and TDOA-based system. Obviously, the CDFs of the localization errors increased rapidly, and the ASync-TDOA-based system had higher performance than the conventional TDOA-based system in 2- Dimensional area. The reason is that ASync-TDOA can reduce packet transmission and receive more redundant information instead of using the process of synchronization. The localization of the target node is calculated by the least squares and brute force to improve

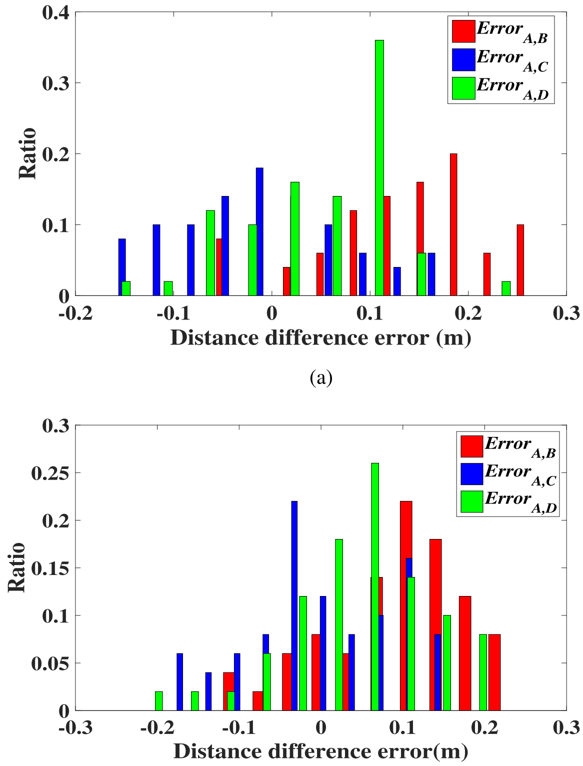

FIGURE 13. Distribution of the distance difference error. (a) Distance difference error in scene 1. (b) Distance difference error in scene 2.

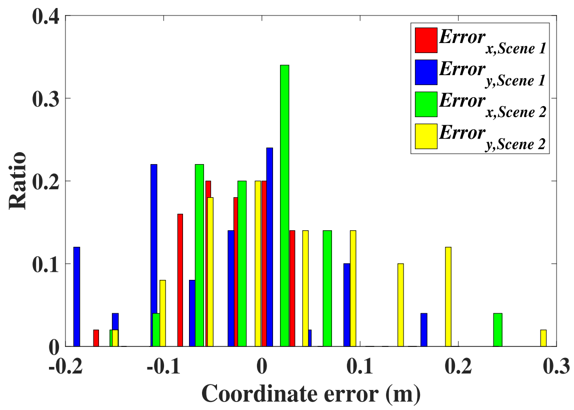

FIGURE 14. Distribution of the localization error.

the accuracy of localization. Similar to the observations on the mean error, the ASync-TDOA-based model achieved similar performance in scene 1 and scene 2. The localization error was less than 0.25 *m*. The result of the localization was a precision of 50% within 0.05 *m* and more than 90% within 0.15 *m*. The main reasons for the error were the error of the distance measurement, and the absolute accuracy of the reference node and anchor nodes could not be determined.

In addition, we compared the proposed model with some existing indoor UWB localization systems proposed and the results are summarized in Table. 2. Compared with the

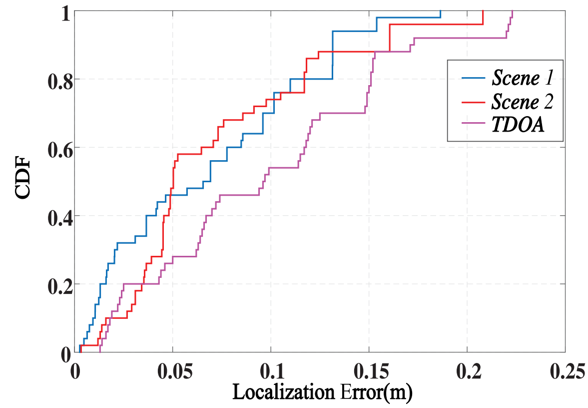

FIGURE 15. CDF of the localization error.

TABLE 2. Comparison with the existing platforms.

Technique	System	Accuray	Test Area	Complexity
TDOA	[41]	0.3 m	8 m*6 m	High
A-TDOA	[42]	0.21 m	5 m*5 m	Medium
TD2S	[27]	0.29 m	9 m*9 m	Low
ASync-TDOA	This work	0.21 m	9.6 m*4.8 m	Low

existing platforms, the implemented ASync-TDOA platform can offer better performance with a compact structure and low fabrication cost.

Based on the above results, we can conclude that, first, the localization of the target node can be correctly estimated with the ASync-TDOA model. Second, during the same period of time, ASync-TDOA can receive more redundant information for localization and thus, improve the accuracy of localization.

V. CONCLUSION

In this paper, we presented the ASync-TDOA model for the time difference measurement between the target node and anchor nodes without time synchronization and implemented it on a platform with UWB signals, which is easy to operate in the practical engineering. In the TDOA-based localization, the accuracy of synchronization affected the precision of the localization, and the process of time synchronization between anchors used more bandwidth. Compared with the existing literature, we investigated the feasibilities of ASync-TDOA for UWB system by extensive experimentation. The results showed that ASync-TDOA can measure the time difference by introducing the reference node and provide available accurate measurements. During the process of the localization, ASync-TDOA can reduce packet transmission with plenty of nodes active and obtain more localization information to estimate the localization in real time to improve the localization precision.

REFERENCES

[1] L. M. Borges, F. J. Velez, and A. S. Lebres, "Survey on the characterization and classification of wireless sensor network applications," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 4, pp. 1860–1890, 4th Quart., 2014.

[2] Q. Li, W. Li, W. Sun, J. Li, and Z. Liu, "Fingerprint and assistant nodes based Wi-Fi localization in complex indoor environment," *IEEE Access*, vol. 4, pp. 2993–3004, 2016.

[3] J. Zhang, G. Han, N. Sun, and L. Shu, "Path-loss-based fingerprint localization approach for location-based services in indoor environments," *IEEE Access*, vol. 5, pp. 13756–13769, Jul. 2017.

[4] J. Tiemann, F. Eckermann, and C. Wietfeld, "ATLAS—An open-source TDOA-based ultra-wideband localization system," in *Proc. Int. Conf. Indoor Positioning Indoor Navigat. (IPIN)*, Oct. 2016, pp. 1–6.

[5] Y. Xu, Y. S. Shmaliy, Y. Li, and X. Chen, "UWB-based indoor human localization with time-delayed data using EFIR filtering," *IEEE Access*, vol. 5, pp. 16676–16683, Aug. 2017.

[6] V. Djaja-Josko and J. Kolakowski, "A new transmission scheme for wireless synchronization and clock errors reduction in UWB positioning system," in *Proc. Int. Conf. Indoor Positioning Indoor Navigat.*, Oct. 2016, pp. 1–6.

[7] A. Tahat, G. Kaddoum, S. Yousefi, S. Valaee, and F. Gagnon, "A look at the recent wireless positioning techniques with a focus on algorithms for moving receivers," *IEEE Access*, vol. 4, pp. 6652–6680, 2017.

[8] Q. Luo, Y. Peng, J. Li, and X. Peng, "RSSI-based localization through uncertain data mapping for wireless sensor networks," *IEEE Sensors J.*, vol. 16, no. 9, pp. 3155–3162, May 2016.

[9] N. H. Nguyen and K. Doğançay, "Optimal geometry analysis for multistatic TOA localization," *IEEE Trans. Signal Process.*, vol. 64, no. 16, pp. 4180–4193, Aug. 2016.

[10] G. Wang, A. M.-C. So, and Y. Li, "Robust convex approximation methods for TDOA-based localization under NLOS conditions," *IEEE Trans. Signal Process.*, vol. 64, no. 13, pp. 3281–3296, Jul. 2016.

[11] L. Liu and H. Liu, "Joint estimation of DOA and TDOA of multiple reflections in mobile communications," *IEEE Access*, vol. 4, pp. 3815–3823, 2016.

[12] K. Yang, J. An, X. Bu, and G. Sun, "Constrained total least-squares location algorithm using time-difference-of-arrival measurements," *IEEE Trans. Veh. Technol.*, vol. 59, no. 3, pp. 1558–1562, Mar. 2010.

[13] R. Ostrovsky and B. Patt-Shamir, "Optimal and efficient clock synchronization under drifting clocks," in *Proc. 18th Annu. ACM Symp. Principles Distrib. Comput.*, 1999, pp. 3–12.

[14] S. Leugner, M. Pelka, and H. Hellbrück, "Comparison of wired and wireless synchronization with clock drift compensation suited for U-TDoA localization," in *Proc. 13th Workshop Positioning, Navigat. Commun. (WPNC)*, Oct. 2016, pp. 1–4.

[15] J. Elson, L. Girod, and D. Estrin, "Fine-grained network time synchronization using reference broadcasts," *ACM SIGOPS Oper. Syst. Rev.*, vol. 36, no. SI, pp. 147–163, 2002.

[16] S. Ganeriwal, R. Kumar, and M. B. Srivastava, "Timing-sync protocol for sensor networks," in *Proc. 1st Int. Conf. Embedded Netw. Sensor Syst.*, New York, NY, USA, 2003, pp. 138–149.

[17] M. Maróti, B. Kusy, G. Simon, and A. Lédeczi, "The flooding time synchronization protocol," in *Proc. 2nd Int. Conf. Embedded Netw. Sensor Syst.*, New York, NY, USA, 2004, pp. 39–49.

[18] P. Sommer and R. Wattenhofer, "Gradient clock synchronization in wireless sensor networks," in *Proc. Int. Conf. Inf. Process. Sensor Netw.*, Apr. 2009, pp. 37–48.

[19] F. Sivrikaya and B. Yener, "Time synchronization in sensor networks: A survey," *IEEE Netw.*, vol. 18, no. 4, pp. 45–50, Jul. 2004.

[20] M. R. Gholami, S. Gezici, and E. G. Strom, "TDOA based positioning in the presence of unknown clock skew," *IEEE Trans. Commun.*, vol. 61, no. 6, pp. 2522–2534, Jun. 2013.

[21] H. Wang, L. Shao, M. Li, and B. Wang, "A global clock skew estimation scheme for hierarchical wireless sensor networks," *IEEE Access*, vol. 5, pp. 20333–20338, 2017.

[22] F. Dwiyasa and M.-H. Lim, "A survey of problems and approaches in wireless-based indoor positioning," in *Proc. Int. Conf. Indoor Positioning Indoor Navigat.*, Oct. 2016, pp. 1–7.

[23] C. Tan, X. Zhu, Y. Su, Y. Wang, Z. Wu, and D. Gu, "A low-cost centimeter-level acoustic localization system without time synchronization," *Measurement*, vol. 78, pp. 73–82, Jan. 2016.

[24] A. Canclini, E. Antonacci, A. Sarti, and S. Tubaro, "Acoustic source localization with distributed asynchronous microphone networks," *IEEE Trans. Audio, Speech, Lang. Process.*, vol. 21, no. 2, pp. 439–443, Feb. 2013.

[25] D. Spano and F. Ricciato, "Opportunistic time-of-arrival localization in fully asynchronous wireless networks," *Pervas. Mobile Comput.*, vol. 37, pp. 139–153, Jun. 2017.

[26] S. Kim and J.-W. Chong, "An efficient TDOA-Based localization algorithm without synchronization between base stations," *Int. J. Distrib. Sensor Netw.*, vol. 11, no. 9, p. 832351, 2015.

[27] B. Xu, G. Sun, R. Yu, and Z. Yang, "High-accuracy TDOA-based localization without time synchronization," *IEEE Trans. Parallel Distrib. Syst.*, vol. 24, no. 8, pp. 1567–1576, Aug. 2013.

[28] A. Coluccia, F. Ricciato, and G. Ricci, "Positioning based on signals of opportunity," *IEEE Commun. Lett.*, vol. 18, no. 2, pp. 356–359, Feb. 2014.

[29] Z. Li, T. Braun, and D. C. Dimitrova, "A time-based passive source localization system for narrow-band signal," in *Proc. IEEE Int. Conf. Commun.*, Jun. 2015, pp. 4599–4605.

[30] F. Bandiera, A. Coluccia, G. Ricci, F. Ricciato, and D. Spano, "TDOA localization in asynchronous WSNs," in *Proc. 12th IEEE Int. Conf. Embedded Ubiquitous Comput.*, Aug. 2014, pp. 193–196.

[31] Y. Wang, X. Ma, and G. Leus, "Robust time-based localization for asynchronous networks," *IEEE Trans. Signal Process.*, vol. 59, no. 9, pp. 4397–4410, Sep. 2011.

[32] N. B. Priyantha, A. Chakraborty, and H. Balakrishnan, "The cricket location-support system," in *Proc. 6th Annu. Int. Conf. Mobile Comput. Netw.*, 2000, pp. 32–43.

[33] J. Tiemann, F. Eckermann, and C. Wietfeld, "Multi-user interference and wireless clock synchronization in TDOA-based UWB localization," in *Proc. Int. Conf. Indoor Positioning Indoor Navigat.*, Oct. 2016, pp. 1–6.

[34] R. Exel, G. Gaderer, and P. Loschmidt, "Localisation of wireless LAN nodes using accurate TDOA measurements," in *Proc. Wireless Commun. Netw. Conf.*, Apr. 2010, pp. 1–6.

[35] R. Exel, J. Mad, G. Gaderer, and P. Loschmidt, "A novel, high-precision timestamping platform for wireless networks," in *Proc. IEEE Conf. Emerg. Technol. Factory Autom. (ETFA)*, Sep. 2009, pp. 1–8.

[36] M. Maróti, "Radio interferometric geolocation," in *Proc. 3rd Int. Conf. Embedded Netw. Sensor Syst.*, 2005, pp. 1–12.

[37] H. H. Fan and C. Yan, "Asynchronous differential TDOA for sensor self-localization," in *Proc. IEEE Int. Conf. Acoust., Speech Signal Process.*, Apr. 2007, pp. II-1109–II-1112.

[38] N. Facchi, F. Gringoli, F. Ricciato, and A. Toma, "Emitter localisation from reception timestamps in asynchronous networks," *Comput. Netw.*, vol. 88, pp. 202–217, Sep. 2015.

[39] M. Pelka and H. Hellbrück, "S-TDoA—Sequential time difference of arrival—A scalable and synchronization free approach forl positioning," in *Proc. IEEE Wireless Commun. Netw. Conf.*, Apr. 2016, pp. 1–6.

[40] A. Nagy, R. Exel, P. Loschmidt, and G. Gaderer, "Time-based localisation in unsynchronized wireless LAN for industrial automation systems," in *Proc. IEEE 16th Conf. Emerg. Technol. Factory Autom. (ETFA)*, Sep. 2011, vol. 47, no. 10, pp. 1–8.

[41] F. C. Rmerz, A. Blatter, C. Botteron, and P. A. Farine, "An experimental platform for an indoor location and tracking system," *J. Physiol.*, vol. 285, no. 6, pp. 23–38, 2008.

[42] S. He and X. Dong, "High-accuracy localization platform using asynchronous time difference of arrival technology," *IEEE Trans. Instrum. Meas.*, vol. 66, no. 7, pp. 1728–1742, Jul. 2017.

YUAN XUE received the B.S. degree from the University of Jinan, Shandong, in 2012. He is currently pursuing the Ph.D. degree in the professional of communication and information system with Beijing Jiaotong University, Beijing. His specific areas of research interest mainly focus on industrial wireless sensor networks, reliable and real-time networks, and indoor localization.

WEI SU received the Ph.D. degree in communication and information systems from Beijing Jiaotong University in 2008. He is currently a Teacher with the School of Electronics and Information Engineering, Beijing Jiaotong University. He was granted the title of Professor in 2015. He is mainly engaged in researching key theories and technologies for the next generation Internet and has taken part in many national projects such as the National Basic Research Program (also called the 973 Program), the Projects of Development Plan of the State High Technology Research, and the National Natural Science Foundation of China. He currently presides over the research project Fundamental Research on Cognitive Services and Routing of Future Internet and a project funded by the National Natural Science Foundation of China.

HONGCHAO WANG (M'14) received the B.S. degree in communication engineering and the Ph.D. degree in communication and information systems from Beijing Jiaotong University, Beijing, China, in 2005 and 2012, respectively. He is currently with the School of Electronic and Information Engineering, Beijing Jiaotong University. His research interests include Internet architecture, network security, and wireless sensor networks.

DONG YANG (M'11) received the B.S. degree from Central South University, Hunan, China, in 2003, and the Ph.D. degree in communications and information science from Beijing Jiaotong University, Beijing, China, in 2009. From 2009 to 2010, he was a Post-Doctoral Research Associate with Jonkoping University, Jonkoping, Sweden. In 2010, he joined the School of Electronic and Information Engineering, Beijing Jiaotong University. Since 2017, he has been a Professor of information networks with the School of Electronics and Information Engineering, Beijing Jiaotong University. He is currently a Founder and the Director of the Industrial Internet Research Group, National Engineering Laboratory for Next Generation Internet Technologies. His research interests are network technologies, including Internet architecture, industrial Internet, and industrial wireless networks.

JIAN MA received the B.S. degree in communication engineering from Beijing Jiaotong University, Beijing, China, in 2013, where he is currently pursuing the Ph.D. degree in communications and information science. His specific areas of research interest mainly focus on low-power network technologies and industrial wireless sensor networks.