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Research Article

Cooperative Scheme ToA-RSSI and Variable Anchor Positions for Sensors Localization in 2D Environments

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To rich good accuracy in the 2D area for wireless sensor network (WSN) nodes, a localization method has to be selected. The objective of this paper is first to select which localization technique is required (Received Signal Strength Indicator (RSSI)) or (Time of Arrival (ToA)) against anchors placement in a 2D area. Depending on whether the anchor nodes are spaced or not and inspired by the idea of using the RSSI method for small distances and the ToA method for greater distances, we will show which method should be used for the positioning process which mainly guarantees a minimal localization error. Second, a two-dimensional localization scheme for WSN which is called Combined Advantages of ToA-RSSI (CA ToA-RSSI), hereafter, ranging methods, is designed in this work, to make the accuracy better during the positioning process. Results provided through MATLAB simulations show that our new technique improves considerably the positioning accuracy compared with the traditional RSSI and ToA ranging method. The proposed scheme can be run under Line of Sight and (LOS) and Nonline of Sight (NLOS) conditions taking into account a difference in the measurement error.

1. Introduction

The current development of Micro- and Electromechanical Systems (MEMS) and computational technologies has caused the emergence of wireless sensor networks, which can be made up [1] of hundreds of thousands of nodes. Each node is able to listen to the environment, perform simple calculations, and communicate with its neighboring sensors. To deploy sensor networks, it is important to disperse the nodes in the positions of interest. This makes the network topology optimal. These networks are widely used for multitasking [2].

The majority of applications using wireless sensor networks rely on the large number of microsensors which are placed randomly; this requires fine position computation, i.e., to calculate their positions in a system with fixed coordinate. As a result, location algorithms become more than essential, not only for the functioning of the network but also to better exploit the collected data. Some sensor nodes know their own positions; these nodes are called anchors. All other nodes are located using the location references received from these anchors.

Technically, the location algorithm is the most important part of the location system. It defines the way in which the available information (distances, angles, positions of already located nodes) is manipulated so that most or all of the nodes can estimate their positions.

From the point of view of researchers' interest, much attention has been given to the location accuracy in sensor networks and to the computational efforts. The importance of the smart deployment of reference nodes is often known but rarely discussed in a study. From another side view, the choice of the positioning method with respect to the topology of the reference nodes remains a very little discussed subject in the previous research work.

In this work, we will start first by showing the right choice to use RSSI or ToA with respect to the anchor nodes' locations. Secondly, by combining the advantage of standards RSSI and ToA ranging methods, a new scheme which is called (CA ToA-RSSI) is designed and discussed in terms of location accuracy and compared with standards RSSI and ToA techniques.

The remaining parts of this paper are organized as follows. Related works will be discussed in Section 2. The third section discusses the suitable choice (RSSI or ToA) depending on the topology of the anchors in the 2D area. RSSI and ToA error positions taking into account the topology of the anchors are shown in Section 4. The design and evaluation of a new scheme which is called CA ToA-RSSI will be detailed in Section 5. Finally, the conclusion of this work will be presented in Section 6.

2. Related Work

In the current literature, most of the positioning methods for sensor networks can be classified into two categories, as discussed in [3–6]. The most remarkable difference between these two categories is that the first category handles the physical behaviors of the arrival signal to calculate the 2D distance which separates two sensor nodes, while the second estimates nodes' locations solely on the basis of the network connectivity information.

In the range-based techniques, RSSI [7], ToA [8], (TDoA) [9], and angle of arrival (AoA) [10] are the main frequently exploited methods. However, the localization process still suffers from many weaknesses in real scenario cases. In this context, we can cite as an example that the RSSI determination of distances is strongly linked to the existing disturbances, signals interactions, and frequently switching of wireless channels, which gives rise to the incredible measurement.

ToA localization method is often affected, in indoor environments, giving rise to multipath effects, and needs the use of exact time synchronization between communicating devices, making it unsuitable for employment in high disturbance networks.

Many works have been accomplished in theoretical analysis and laboratory testing in recent years [3, 4] having the fight against noise and dynamic variations in communication channels as objectives.

Concerning the range-free positioning techniques, they have low-cost characteristics and can be implemented on hardware targets [11, 12].

In DV-Hop [13], as being a range-free technique, to estimate distances to anchors, the algorithm determines the Average Jump Progress (AJP) for each sensor node and anchor to finally deal with the multiplication of hop counts by the AJP. In an almost identical way, LAEP [14] is based on statistics to calculate the Network Expected Jump Progress (NEJP). To calculate approximately the distances and anchors to the sensor, LAEP multiplies hop counts by the recorded EHP. This can be done under the condition that the nodes in the network obey the Poisson law, which made LAEP difficult to reach accuracy localization.

Received Signal Strength Indicator (RSSI) technology [15] can be considered a vital solution for estimating distances in sensor networks. It considers the power losses of a signal between its transmission and reception sensors as the main key to predict point-to-point distance. This loss varies depending on the distance between the two sensors; the further the sensors are (resp. Close), the greater the loss (resp. Low). This loss will then be translated into a distance.

Since they are simple and of low cost, many positioning techniques already available in the published works use RSSI to approximate the sensor coordinates [16]. To mention, but not limited to, in [17], the input signal strength to the sensor node is almost employed to determine losses due to propagation and estimate the range between two sensors using an empirical or conceptual equation of path loss [18].

Generally, the RSSI ranging method does not use complementary components and can be integrated on wireless devices with few resources since they do not need either a back and forth timing process or exact synchronization between sensors. RSSI process is challenging, and the major ambiguity lies in determining the signal level.

The precision of localization-based RSSI depends principally on how a wireless channel-based RSS model can translate reliably the real noise inferred from the fundamental signal. The RSSI schemes proposed in the existing literature generally consider that the received signal is proportionate to the direct path between the communicating sensors and that the errors caused by the fluctuations of the RSSI values follow a Gaussian distribution. However, in real cases, measurements using wireless sensors prove that the assumptions mentioned above do not reflect reality [16, 19, 20].

As aforementioned, four standard techniques are used, such as RSS, ToA, AoA, and TDoA [21–23]. Nevertheless, determining the node location is not an obvious process, for the reason that the measurements have nonlinear correspondence with the source location. From the clock synchronization side of view, the four ranging techniques have rigorous demands. Therefore, positioning an unknown sensor node is a significant challenge. In addition, these schemes cannot provide high localization accuracy. In order to conduct better the positioning system, a few combined ranging methods and some deviation negligence techniques have been proposed in [24–27].

Recently, several combined schemes that merge two types of positioning methods have been proposed. To mention, but not limited to, the idea in [28] merged RSS and AOA techniques. The paper [29] studied the node positioning problem in combined and noncombined three-dimension WSN, respectively. From the cooperative WSN side of view, it was evident to assemble RSS propagation channel modeling with its geometry relationship. Ho et al. [28] and Sun and Ho [30] proposed a combined TDOA-FDOA node localization scheme in three-dimension positioning scenarios. A simple TDOA-AOA has been proposed in [31] with two targets. The study in [31] was carried out by making a novel geometric source position-sensor relationship, which is very simple to be conducted.

ToA (Time of Arrival) technology considers that the sensors of the network are synchronous. The distance separating two sensors is deduced from the difference between the times when the message is sent and received and the signal propagation speed. This technology is used by the GPS system (Global Positioning System) [32].

Often, authors choose the placement of anchors at random positions and discuss the network topologies based on their own empirical data. In [33, 34], the authors chose anchors in their studies randomly within the network. However, in [33], the authors mentioned that they chose a collinear set of anchor nodes in one of the examples, without supporting evidence as to why this is not a random choice.

Previous work [35] requires that reference nodes should be located ideally at the corners of the network. In this configuration, the proposal is facing a problem with a simple and single constraint and still requires that all unknown sensors should be located in the convex envelope of the anchor points, and accordingly, better positioning results are obtained when the anchors are in the corners.

In January 2011, a study [36] was done on the impact of anchor sensor coordinates, emphasizing a series of hypotheses presented. Each assumption centers on a metric that can be calculated from the anchor nodes themselves, where network designers might have other data before deploying the network or analyzing the location results.

The authors in [37, 38] proposed their localization algorithm based on RSSI data, which used the received power at the node from the reference anchor resulting in the position estimation of the unknown sensor node. In [39], the authors proposed a target positioning technique by using both ToA and RSSI input signals in the case of NLOS conditions. In the same context, the sensors' positions already calculated can be used to determine the sensors' location not yet determined, thus minimizing the number of anchors needed by the localization process [40]. To better reduce the localization error, we will propose in this present work the suitability (localization method/anchors topology) which will somehow provide a positive gain in terms of the exact position.

In this work, the localization problem of multiple sensors' nodes is considered. To improve the positioning process, a new combined ToA-RSSI positioning scheme is proposed. Firstly, we will show the importance of the proper placement of anchors nodes in improving the localization accuracy for unknown sensor nodes (USNs). Thereby, the advantage and disadvantage of ToA and RSSI will be well exposed. Secondly, a two-dimensional localization scheme for WSN which is called Combined Advantages of ToA-RSSI (CA ToA-RSSI) ranging methods will be proposed, to better improve the accuracy during the positioning process. Results provided through MATLAB simulations show that our proposed algorithm improves considerably the positioning accuracy compared with the traditional RSSI and ToA ranging method.

3. RSSI and ToA against Working Environment

3.1. Position Estimation from RSSI Measurements. In the literature, the most used model using RSSI is based on log-normal shadowing [41–46].

$$RSS\,(dBm) = P_0 - 10n\log\left(\frac{d}{d_0}\right) + X_\sigma, \quad (1)$$

where

(i) P_0 is the received power on the receiver antenna (dBm)

(ii) d_0 is a reference distance from the transmitter (m)

(iii) n is the path loss factor that characterizes the working environment (without unit)

(iv) d is the actual distance separating two sensors antenna (m)

(v) X_σ is a Gaussian centered random variable with variance σ^2_{RSS}, which also depends on the working environment (without unit)

For IEEE 802.15.4 standard, σ_{RSS} can vary between 0.5 dB and 6 dB [47, 48] while n varies in the range [1.9, 4.75] depending on the working environment [47–52].

As a general rule, short ranges and/or visibility situations (resp. long ranges and nonvisibility) naturally give the lowest (resp. strong) values for σ_{RSS} and n. For example, in the IEEE 802.15.4 standard, if the distance between sensors is less than 8 m (resp. greater than 8 m), it gives rise to $n = 2$ (resp. $n = 3.3$). An evolution of this basic model, which takes into account the NLOS conditions, has already been proposed in [53, 54]. Other experimental parameters were also found in [55–59].

3.2. Position Estimation from ToA Measurements. Another widely used metric for location techniques is Time of Arrival (ToA). Literally, this metric would correspond to the Time of Arrival of the transmitted signal, defined according to the receiver's local clock and relative to its own observation window. Measuring the Time of Arrival (round trip), which is more directly linked to the distance between two asynchronous devices, would require exchanging several consecutive packets at the protocol level (n-way ranging) and making an estimation of ToA for each of these packages. In the ToA technique, the distance between sensors and their required time of flight are linked by the following equation:

$$D = c \times t\left(c = 3 \times 10^8 \frac{m}{s}\right). \quad (2)$$

The IEEE 802.15.4 standard proposes the Symmetric Double-Sided Two-Way Sending (SDS-TWS) scheme for the ToA localization process [60] as depicted in Figure 1.

In the positioning scheme, the Time of Arrival technique requires the nodes of the source and the destination to transmit signals at the same time. This requirement makes the ToA process considerably restricted in practical scenarios. The IEEE 802.15.4 standard proposes the Symmetric Double-Sided Two-Way Sending (SDS-TWS) scheme for the

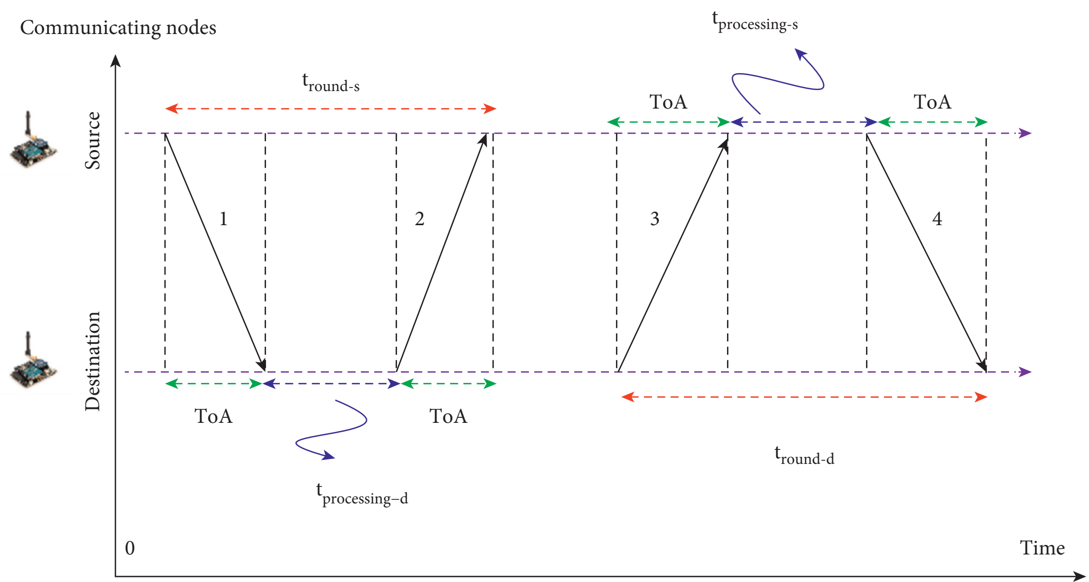

FIGURE 1: ToA measurement between two nodes.

ToA localization process [60]. This can offset the effect of the lag time due to the incapability to meet time synchronization on the ranging results. The SDS-TWS technique makes use of symmetrical sending and receiving to determine ToA in two ways. The specific design process is as follows. (1) In the first TWR, the source serves as a transmitter and the destination serves as a signal receiver. (2) In the second TWR, destination serves as a transmitter and source serves as a receiver. This process of sending and receiving messages can be shown in Figure 1. Thereby, a Time of Arrival (ToA), that is, the considered time measurement output can be formulated as follows:

$$\mathrm{ToA} = \frac{t_{\mathrm{round-source}} - t_{\mathrm{processing-destination}} + t_{\mathrm{round-destination}} - t_{\mathrm{processing-ssource}}}{4}. \quad (3)$$

3.3. Ranging Accuracy versus Distance between Anchors. Based on [61], it has been concluded that the signal loss, when using the RSSI technique, varies strongly due to different parameters in various environments. When operating within a short distance, the transmission and reception of the signal essentially obey log-normal law already integrated into the design of RSSI hardware, and in that condition, the precision is then high. If the unknown sensor is at a certain distance from the reference node (anchor), the received power across the signal decreases quickly, and the positioning error will step up. On the other hand, and based on [62], it has been proven that the ToA process always needs a very precise time synchronization during the transmission/reception cycles and an offset occurs in the small distance communication, which will automatically generate a nonnegligible deviation in the sensor positioning steps. Nevertheless, when the measurement occurs at a considerable distance, it has a small error.

Starting from standard methods (ToA and RSSI), excluding their disadvantages, and keeping only their advantages, an extended algorithm will take place. In this new algorithm, RSSI and ToA algorithms will be executed alternately. To develop this algorithm, an average distance between the anchor and unknown sensors (Threshold Distance: TD) is to be fixed rigorously, and then, the extended localization process is mainly based on this new parameter TD. Roughly speaking, if the actual distance is less (res greater) than TD, then RSSI (res ToA) will be activated and vice versa.

The Distance Threshold which causes the switch from one ringing to another is determined by several simulations and it was approximately fixed to $L/2 = 10/2 = 10\,\mathrm{m}$. L is the length of the sensor network area. More than fifty simulations were done to determine the threshold distance. Results show that beyond $L/2$ RSSI is more efficient in terms of accuracy and that ToA is recommended for distances above $L/2$. The design of the new scheme which is called CA ToA-RSSI is shown in Figure 2. USN in this figure means unknown sensor node.

Four anchors in a workspace of $20\,\mathrm{m} \times 20\,\mathrm{m}$ will be the main key of this proposal, and a two-dimensional positioning process for blind nodes is then designed, which

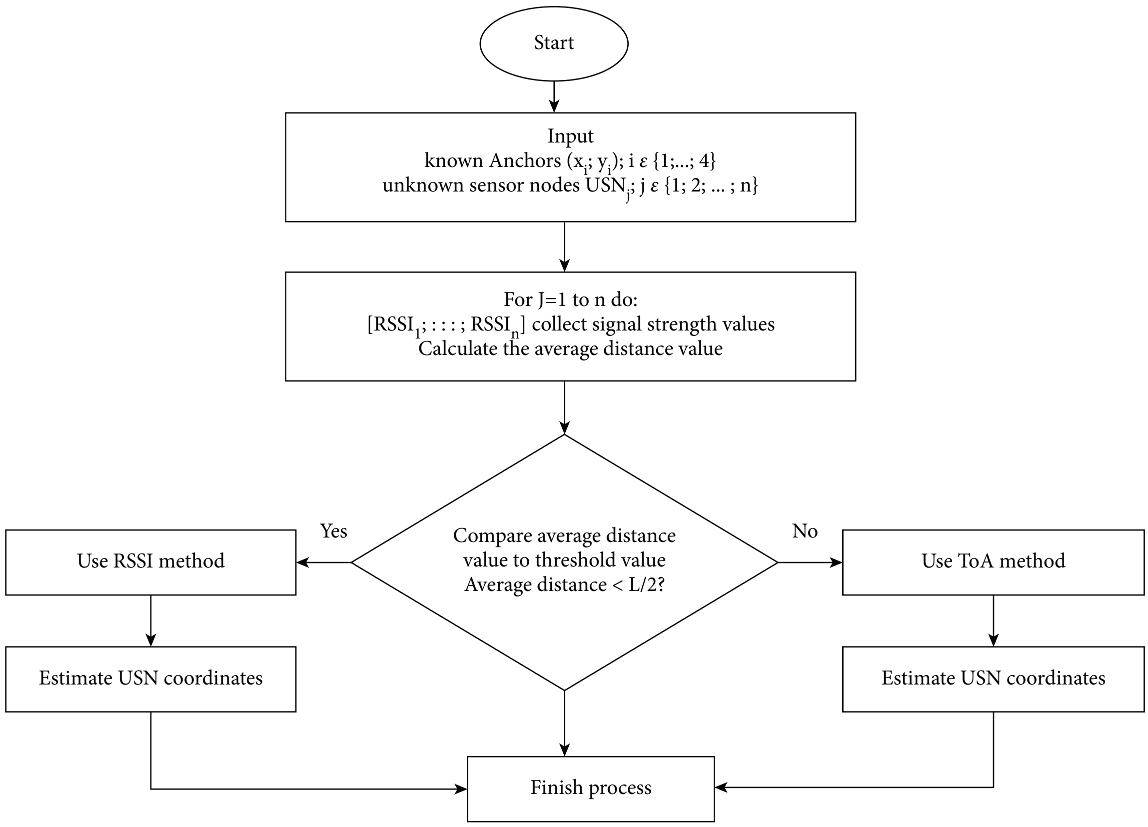

Figure 2: Proposed CA ToA-RSSI for coordinates estimation.

merges RSSI and ToA advantage points. The implementation phases are as follows.

3.3.1. Data Input

(i) A workspace of 20 m × 20 m will be covered by hundred unknown sensors randomly placed

(ii) Four anchor nodes will be placed for each scenario at known positions

(iii) It is supposed that all communicating sensors have the same radius (R) of communication

3.3.2. RSSI Method

(i) Standard RSSI is executed to compute the actual distance of the required sensor from each Anchor, and (1) is used to obtain the attenuation value of the received signal

(ii) In the WSN workspace, if the actual distance between the reference node and the unknown sensor is below the Threshold Distance ($L/2$), the distance value is taken into account

3.3.3. ToA Method

(i) Standard ToA is executed to compute the actual distance of the required sensor from each Anchor extracted by (2)

(ii) In the WSN workspace, if the actual distance between the reference node and the unknown sensor is above the Threshold Distance ($L/2$) and less than R, then the actual distance value is taken into account

3.3.4. Coordinates Computations

(i) At the node localization phase and regardless of the distance calculation method (ToA or RSSI), the wireless sensor node can estimate its coordinates by the RSSI or ToA technique according to the actual distance already calculate

(ii) Finally, CA ToA-RSSI ranging method will provide the unknown sensor node coordinates much better than ToA or RSSI alone

4. Simulation and Analysis

To perform our simulations, we used MATLAB software. A choice motivated by the fact that localization can be seen as a purely geometric problem.

20 m × 20 m is considered a simulation scene. At the beginning of the process, 100 sensors are deployed in a two-dimensional workspace so as to cover the entire surface without knowing their coordinates.

A rectangular surface formed by the four anchors varies over the global area, thus giving rise to four scenarios as shown in Figures 3–6. The communication radius R between every two sensors is fixed to 2.5 m. The speed of light is

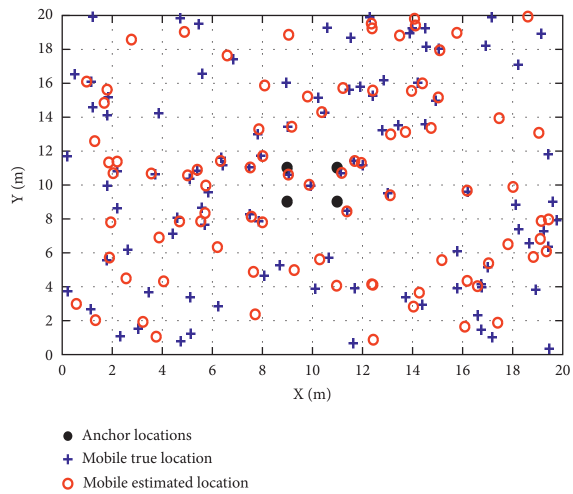

Figure 3: A: Locations estimation with anchors positions at (9, 9), (11, 9), (11, 11), and (9, 11).

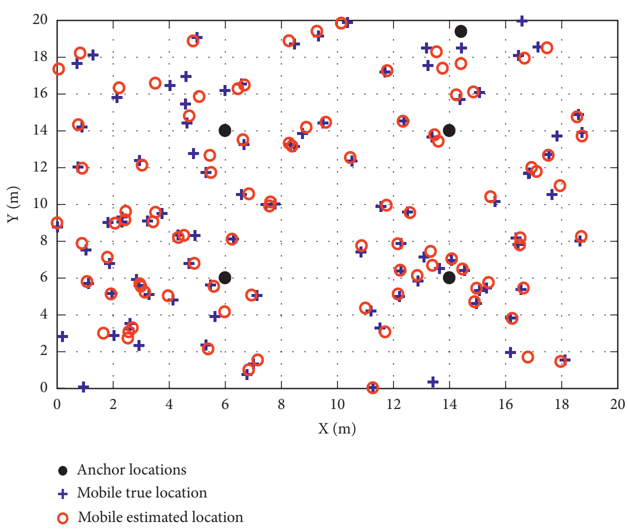

Figure 4: B: Locations estimation with anchors positions at (6, 6), (14, 6), (14, 14), and (6, 14).

known and is to be set to 3×10^8 m/s. The received power P_0 on the receiver antenna in this simulation is fixed to −30.

The path loss factor (n) is 1, and the Gaussian centered random variable X_σ is 2. Figure 7 shows the deployment of the unknown sensor nodes and the four anchors inside the simulation area.

All simulations' outputs are approved on 50 executions time, and then, the mean output value of all experimental tests is considered as the final result.

Simulation results allowed deducing that the metric "Area of anchors' nodes" can be a good indicator of the quality of the localization process. Based on the anchors' node location, the choice of the location (RSSI or ToA) can be retained. In total, four tests were carried out for each of the two measurements ranging (RSSI and ToA) at different anchors locations in order to find out how anchors' positions would affect the positioning error. In each simulation, the coordinates of all nodes were recorded along with the measured RSSI and ToA outputs. Table 1 gives the global network error for each test. We note that the results provided in Table 1 are depending on the simulation parameters such as the number of nodes, number of anchors, and network size. However, anchor positioning relative to such sensors' deployment remains the general idea provided in this paper.

Standard RSSI and ToA results shown in Table 1 are provided according to the WSN two-dimensional space of 20 m × 20 m. When using RSSI ranging alone, the minimum mean location error (3.76 m) is reached at the anchors' coordinates (6, 6), (14, 6), (14, 14), and (6, 14) which correspond to Figure 4. The mean location error increases at the anchors' coordinates (9, 9), (11, 9), (11, 11), and (9, 11) which correspond to Figure 3. However, when using ToA ranging alone, minimum and maximum mean location errors abstain at anchor locations (0, 0), (20, 0), (20, 20), (0, 20), and (6, 6), (14, 6), (14, 14), and (6, 14), respectively which correspond to the Figures 3 and 4. From the existing literature point of view, the results shown in Table 1 are well matching with [61, 62].

The same scenarios (A, B, C, and D) shown in Figures 3–6 were simulated according to standard RSSI, standard ToA, and even the proposed CA ToA-RSSI.

Figure 8 shows the mean positioning errors of the three methods (standards and proposed) under the four scenarios of anchor node locations. It is approved, from Figure 8, that when using CA ToA-RSSI, a minimum error is always guaranteed. On the other hand, it is also shown that in each scenario a large localization error is generated by either standard ToA or standard RSSI. In A and D scenarios, standard ToA can estimate the coordinates of the unknown sensor node with a small error compared to standard RSSI. Opposite results are provided in scenarios B and C. However, in all scenarios, CA ToA-RSSI can estimate the coordinates of an unknown sensor node introducing the smallest error compared with standard ranging methods.

Table 2 summarizes all data and results relative to different scenarios.

Table 2 shows the overall errors obtained by each technique, namely, RSSI, ToA, and the proposed technique

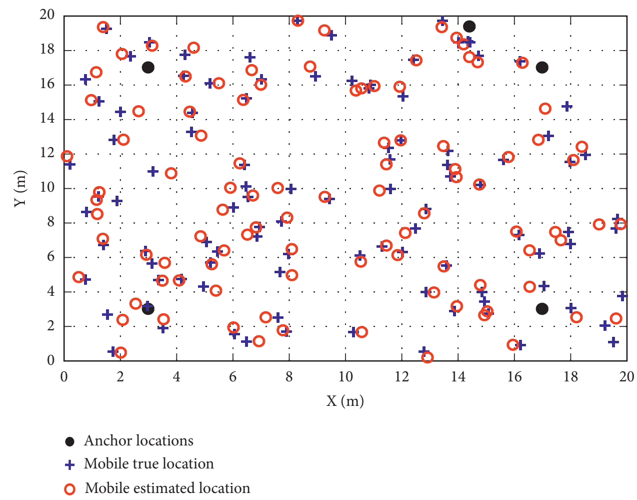

Figure 5: C: Locations estimation with anchors positions at (3, 3), (17, 3), (17, 17), and (3, 17).

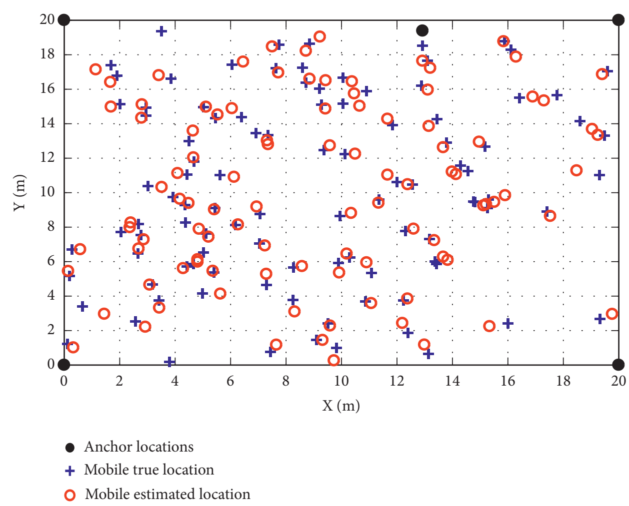

Figure 6: D: Locations estimation with anchors positions at (0, 0), (20, 0), (20, 20), and (0, 20).

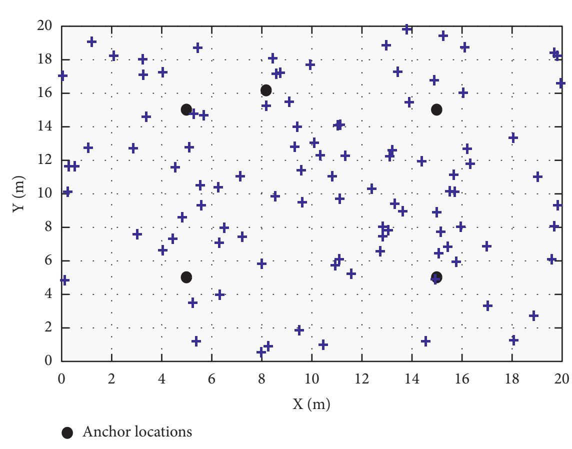

Figure 7: Unknown sensor nodes and anchors deployment in 20*20 m area.

Table 1: Basic RSSI and ToA mean error relative to anchors location.

Anchors coordinates (m)	Deployed sensor nodes	Mean localization error using standard RSSI	Mean localization error using standard ToA
A: (9, 9), (11, 9), (11, 11), (9, 11)	100	13.91	4.31
B: (6 ,6), (14, 6), (14, 14), (6, 14)	100	3.76	8.62
C: (3, 3), (17, 3), (17, 17), (3, 17)	100	5.72	7.92
D: (0, 0), (20, 0), (20, 20), (0, 20)	100	6.41	3.13

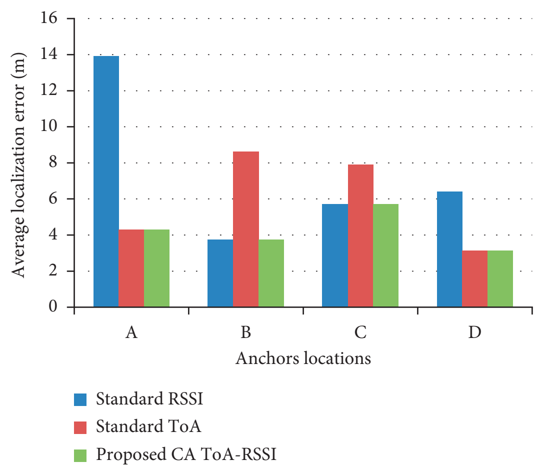

Figure 8: Average localization error versus different ranging methods.

Table 2: Mean error and gain of proposed scheme versus standards ranging methods.

	RSSI	ToA	Proposed	Proposed versus RSSI gain (%)	Proposed versus ToA gain (%)
Scenario A mean error (m)	13.91	4.31	4.31	69.01	0
Scenario B mean error (m)	3.76	8.62	3.76	0	56.38
Scenario C mean error (m)	5.72	7.92	5.72	0	27.77
Scenario D mean error (m)	6.41	3.13	3.13	51.17	0
Mean of means error (m)	7.45	5.99	4.23	43.22	29.38

(CA-ToA-RSSI). If we take, for example, the first line of this table (the same principle for the other lines), RSSI, ToA, and the proposed technique (CA-ToA-RSSI) provide mean errors of 13.91 m, 4.31 m, and 4.31 m, respectively. Thereby, the percentage gain of the proposed technique (CA-ToA-RSSI) with respect to RSSI is calculated as follows.

Percentage gain $= (13.91 - 4.31/13.91)\times 100\% = 69.01\%$. All other percentages are obtained in the same way. From the global side of view and by taking the average of mean errors of the four scenarios, it is clearly shown that the new extended scheme provides the highest accuracy against standard ranging methods. It can allow a significant gain of 43.22% and 29.38% compared with standard RSSI and ToA, respectively.

5. Conclusion

First, the right positioning of anchor nodes is the key to precise localization. Depending on whether the anchor nodes are spaced or not, the localization method can be selected. If the totalities of the unknown sensor nodes are far from the reference nodes (anchors), the positioning error steps up when using the RSSI ranging method; therefore, the positions of the anchors must be modified until we reach the minimum error. On the other hand, it has been proven that the ToA process provides a small error in the opposite scenarios.

Second, a new scheme is proposed that merges the advantages of RSSI and ToA techniques in this paper. The new solution drops the average location errors through the employment of the RSSI or ToA phase. To better optimize the positioning precision, four anchor nodes at different locations are introduced. The results provided by simulations are successful in producing desired objectives of the cooperative CA ToA-RSSI method and provided a better localization process. The proposed scheme can allow a significant gain of 43.22% and 29.38% compared with standard RSSI and ToA, respectively.

In our future works, we are ready to develop and design other cooperative techniques like ToA-TDoA and RSSI-

TDoA taking from their geometric advantages, thus achieving simple and effective techniques suitable for wireless nodes with limited resources.

Data Availability

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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