A Crowdsourcing-based Localization Scheme with Ultra-Wideband Communication

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***Abstract*—With the development of mobile computing, crowdsourcing has become one of the key technologies supporting collaborative tasks. It has been widely used in areas of real-time localization, such as data collection and fingerprint calibration. Currently, crowdsourcing-based localization are mainly designed for WiFi signals. However, due to the excellent performance on real-time positioning, Ultra-Wideband (UWB) has attracted the attention of major smart device makers. It is highly expected that UWB will be supported by smart devices in the near future. Considering this situation, a crowdsourcing localization scheme is introduced based characteristics of UWB signals. Compared to existing positioning technologies, the proposed scheme does not require direct connection between UWB anchors and smart devices. Instead, the smart devices collaborate with peers to complete the positioning process. Finally, a simulation example is provided as a demonstration and to evaluate the performance.**

***Index Terms*—Localization, Crowdsourcing, Ultra-Wideband, mobile Computing**

I. Introduction

Crowdsourcing has successfully drawn the attention of both industry and academia. With an open framework, crowdsourcing enables decentralized devices/individuals/groups to collaborate efficiently [1] for a common purpose, such as information retrieval, natural language processing, and machine learning [2]. Compared to centralized technologies, crowdsourcing has a series of advantages, including low-cost, flexibility, scalability, diversity, etc.

The popularity of smart devices, such as smart phones and tablets, further drives the development of crowdsourcing in business [3], public services [4], etc. One of the most successful applications is real-time localization. With the large amount of data collected from smart devices, crowdsourcing is used for positioning purpose, such as map construction, fingerprint calibration, etc. Currently, crowdsourcing-based localization is mainly implemented with the ubiquitous WiFi signals, such as [5]–[9].

Compared to WiFi, the emerging UWB technology significantly improves the accuracy of real-time localization, as a result of the ultra-narrow wireless signal at the level of nanoseconds or even less in time domain [10]. Due to this unique feature, UWB has drawn strong interests of major smart device makers, such as Apple Inc, SAMSUNG, and Huawei Technologies Co.,Ltd. In fact, the recently announced iPhone 11 has supported UWB with an embedded chip for positioning purpose. It is expected that UWB will be commonly supported by smart devices in the near future.

With the consideration of the promising future of UWB, this study presents a crowdsourcing-based localization scheme for UWB-enabled smart devices. Referring to a limited number of devices as UWB anchors, smart devices collaborate in a crowdsourcing manner for positioning purpose. In this way, it is not necessary to have a centralized unit for computation and smart device is not required to have direct connection with UWB anchors. It not only reduces the cost of deployment, but also expands the coverage area of the positioning system. In the end, simulation experiments are conducted to evaluate the performance of the proposed scheme.

This paper is organized as follows. Section II offers an insight into distance measurement scheme with UWB. Section III introduces the proposed crowdsourcing-based localization scheme, including the system model and an algorithm for each smart device to obtain the physical location. This is followed by Section IV with simulation analysis of the proposed scheme. Section V concludes this study.

II. Distance Measurement with UWB

This section offers an insight into the distance measurement with UWB technology, on which the crowdsourcing-based localization scheme is built. The notations and symbols used in this study are summarized in Table. I.

TABLE I
NOTATIONS AND SYMBOLS.

c	Speed of light.
d	Propagation distance of the UWB signal.
t	Physical time.
T_{reply}	Processing delay after receiving ranging requests.
T_{round}	Total flight time of the UWB signal.
T_{prop}	Signal propagation time.
A_i	The ith UWB anchor.
D_j	The jth smart device.
$S_{r,i}$	Set of neighboring reference devices.

For distance measure between two UWB devices, several

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approaches are available. In this study, the time-of-flight (ToF) [11] approach is assumed. The key idea of ToF is to firstly measure the propagation time of UWB signal between transmitter and receiver, after which the distance is obtained by multiply with the light speed. Fig. 1 shows an example of obtaining the propagation time between two UWB devices.

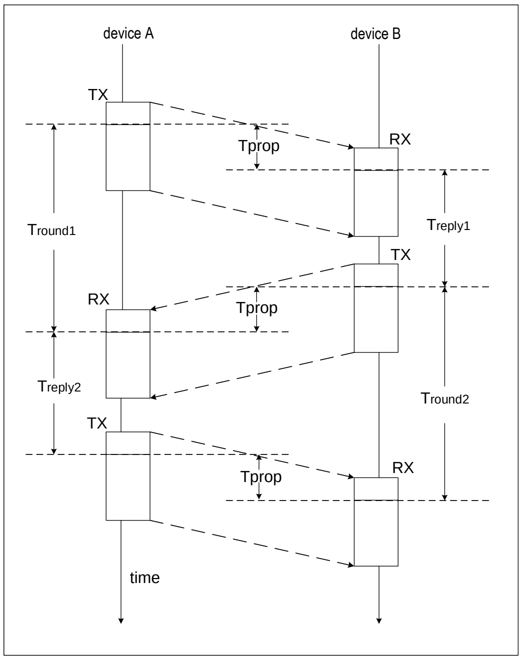

Fig. 1. Distance Measurement with UWB.

As shown in Fig. 1, the device requesting distance measurement (A) sends a ranging request to pairing device (B). After receiving the ranging request, device B sends a message to device A after a short processing delay T_{reply1} and records the time locally. After device A receives the response message from device B, it records the round-trip flight time of the UWB signal T_{round1}, sends the response message back to device B, and records the local processing delay, T_{reply2}. After receiving the response message, device B records the round-trip flight time of the UWB signal, T_{round2}, and further forwards T_{reply1} and T_{round2} to device A. After receiving the time values from device B, the distance is calculated according to Eq. (1).

$$\begin{cases} d = c \times t = c \times \bar{T}_{prop} \\ \bar{T}_{prop} = \dfrac{(T_{round1} \times T_{round2} - T_{reply1} \times T_{reply2})}{(T_{round1} + T_{round2} + T_{reply1} + T_{reply2})} \end{cases} \tag{1}$$

III. Crowdsourcing-based Localization Scheme

This section presents a crowdsourcing-based localization scheme with UWB technology, with the system architecture described in Section III.A and a detailed positioning scheme given in Section III.B.

A. The System Model

Fig. 2 shows the system model of crowdsourcing-based localization with UWB. Here, we assume that: i) each smart device is embedded with a UWB transceiver, which has already been supported by iPhone 11; ii) the UWB transceiver is available for message exchange in addition to distance measurement; iii) a small number of UWB anchors with known physical locations are deployed in the system.

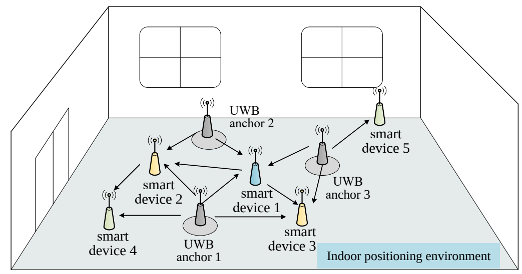

Fig. 2. System model of crowdsourcing localization.

With the known physical location, UWB anchors provide positioning services to neighboring smart devices, while smart devices conduct real-time positioning process in a crowdsourcing manner based on distance measurement and collaborative communication with UWB transceivers. Take the network in Fig. 3 as an example, which consists of four UWB anchors (A_1-A_4) providing positioning services to neighboring smart devices and eight smart devices (D_1-D_8) to be localized. Initially, D_1 is the device with sufficient UWB anchors as neighbors, while the other smart devices do not have sufficient direct connection with anchors. Using the embedded UWB transceiver, D_1 measures the distance with UWB anchors and computes its own physical location based on the positions announced by UWB anchors. After its location is determined, D_1 starts to operate in anchor-like manner and provides positioning services to the rest smart devices. As a result, smart devices D_3 and D_5 are capable of computing their locations utilizing the services provided by D_1. Meanwhile, D_2 uses the same approach to provide positioning services for D_4 and D_6. In this way, a large number of smart devices can get their locations.

However, it is noticeable that some smart devices, such as D_7, still do not have sufficient neighboring devices to determine its location. As it is only neighboring to two devices A_1 and D_3, there are two possible options, namely the physical location and the location indicated by D_7'. In this case, D_7 send a query request to its neighbors, which further broadcast the query request to their neighbors and let them vote for the physical position of D_7. After receiving the query request, D_1 easily finds that D_7' is impossible to be the location of D_7. Otherwise, D_7 would be its neighboring device.

For smart devices that only have direct connection to one device with known location, such as D_8, it is impossible to determine its accurate physical location, but an arc indicating possible locations of the smart device can be determined in a similar way. Since D_8 has only one neighbor A_2, and the distance between them can be measured, the position of D_8 is on the circle with A_2 as the center and the distance between them as the radius. At this time, D_8 adopts the same working mode as D_7, sends a query request to its neighbor, A_2 calculates the intersection point D_8' and D_8'' between the circle where D_8 is located and the circles with neighboring devices D_4 and D_5 as the center and communication distance as the radius. Since D_8 has only one neighboring device, it is not within the communication range of D_4 and D_5. Therefore, although we cannot get the exact position of D_8, it can be sure that D_8 is located on the blue arc.

B. Crowdsourcing Localization Algorithm for smart devices

Algorithm 1 illustrates the crowdsourcing localization algorithm for smart devices in detail. The key idea of the algorithm has been described shows in Section III.A with the network example given in Fig. 3.

Algorithm 1: Crowdsourcing based Localization

1 **Step 1:** Detect neighboring UWB anchors and smart devices with known locations and form Set $S_{r,i}$;
2 **Step 2:** For each device in Set $S_{r,i}$, obtain coordinates and measure the distances collaboratively using UWB;
3 **Step 3:**
4 **if** *The number of elements in Set* $S_{r,i} \geqslant 3$ **then**
5   Estimate the coordinate using Eq.(5);
6   Go to Step 4;
7 **else if** *The number of elements in Set* $S_{r,i} = 2$ **then**
8   Estimate the coordinates using Eq.(5) and get two possible answers;
9   Send query request to neighboring devices;
10   Collect results from neighboring devices and choose the correct coordinate;
11   Go to Step 4;
12 **else if** *The number of elements in Set* $S_{r,i} = 1$ **then**
13   Send query request to neighboring devices for assistance;
14   Collect results from neighboring devices and reduce the possible range of coordinates;
15   Go to Line 17;
16 **Step 4:** Provide positioning services to the other smart devices in anchor-like manner;
17 **return** Positioning results ;

In Step 1, smart device j requesting localization service sends a UWB signal to detect neighboring UWB anchors and smart devices with known physical locations. After receiving feedback from neighboring devices, it forms a set $S_{r,i}$ of reference devices that can be used for positioning.

In Step 2, for each device in $S_{r,i}$, smart device j obtains their coordinates and measures the distances collaboratively using UWB. An example of collaborative distance measurement is shown in Fig. 1. After receiving the coordinates of reference devices, smart device j starts the positioning process in Step 3.

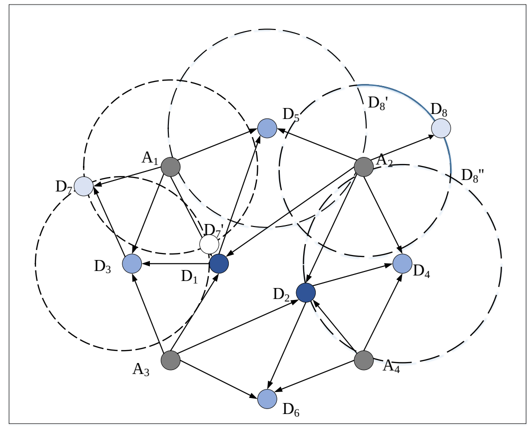

Fig. 3. Example network of crowdsourcing-based localization.

In Step 3, smart device j determines the physical location with the informations obtained from reference devices in $S_{r,i}$. Here, three cases are considered according to the number of reference devices which have been detected. In Cases 1 and 2, accurate physical positions can be obtained. As a result, these smart devices can offer positioning services to the other devices in an anchor-like manner afterwards. In Case 3, it is impossible to get the accurate coordinate for smart device j. Thus, it cannot provide positioning services to avoid unnecessary positioning errors.

- Case 1, in which no less than three reference devices are detected. Smart device j is capable of calculating the physical location locally.
- Case 2, in which two reference devices are detected. Smart device j gets two answers from the local computation, but can determine the actual position by sending a query request to neighboring devices.
- Case 3, only one reference device is detected. Smart device j only obtains an arc with the neighboring device as the origin to indicate possible locations through local computation.

For Case 1, the least square method introduced in [12] is used for calculate the position of smart device j. The coordinates of reference devices around it are $(x_1, y_1), (x_2, y_2), ..., (x_k, y_k) \in S_{r,i}$ and the corresponding UWB measuring distance are $\{d_1, d_2...d_k\}$, k is the number of reference devices of smart device j. The coordinates of smart device j can be set as (x, y), and the Eq. (2) can be obtained.

$$\begin{cases} (x_1 - x)^2 + (y_1 - y)^2 = {d_1}^2 \\ (x_2 - x)^2 + (y_2 - y)^2 = {d_2}^2 \\ ... \\ (x_k - x)^2 + (y_k - y)^2 = {d_k}^2 \end{cases} \quad (2)$$

After adding up all the rows in Eq. (2) and averaging, we can get Eq. (3).

$$x^2+y^2-2x\frac{\sum_{i=1}^{k}x_i}{k}-2y\frac{\sum_{i=1}^{k}y_i}{k}=\frac{\sum_{i=1}^{k}(d_i^2-x_i^2-y_i^2)}{k} \tag{3}$$

After expanding Eq. (2), subtract Eq. (3) from each row and eliminate x^2+y^2, we can get its matrix expression as Eq. (4).

$$X\beta=Y \tag{4}$$

X is the coefficient matrix, Y is the augmented matrix, each part is shown in Eq. (5).

$$\beta=\begin{bmatrix} x \\ y \end{bmatrix}$$
$$X=\begin{bmatrix} \frac{\sum_{i=1}^{k}x_i}{k}-x_1, \frac{\sum_{i=1}^{k}y_i}{k}-y_1 \\ \frac{\sum_{i=1}^{k}x_i}{k}-x_2, \frac{\sum_{i=1}^{k}y_i}{k}-y_2 \\ \cdots \\ \frac{\sum_{i=1}^{k}x_i}{k}-x_k, \frac{\sum_{i=1}^{k}y_i}{k}-y_k \end{bmatrix} \tag{5}$$
$$Y=\begin{bmatrix} [d_1^2-x_1^2-y_1^2-\frac{\sum_{i=1}^{k}(d_i^2-x_i^2-y_i^2)}{k}]/2 \\ [d_2^2-x_2^2-y_2^2-\frac{\sum_{i=1}^{k}(d_i^2-x_i^2-y_i^2)}{k}]/2 \\ \cdots \\ [d_k^2-x_k^2-y_k^2-\frac{\sum_{i=1}^{k}(d_i^2-x_i^2-y_i^2)}{k}]/2 \end{bmatrix}$$

The result to calculate coordinate(s) is summarized by Eq. (6).

$$\beta'=(X^TX)^{-1}\cdot X^TY \tag{6}$$

For Case 2, since the coordinate cannot be obtained through local computation, smart device j can calculate its possible position coordinates in the following way: based on Eq. (2), it uses geometric mathematical formulas to solve the intersection of two circles with two neighbors as the centers and their respective distances as the radius. And it will get two possible estimated coordinates. Then, smart device j sends a query request to reference devices in $S_{r,i}$ for assistance. After receiving the query request, the reference devices broadcast the query from smart device j to their one-hop neighbors. Based on their local informations, such as their physical locations and the communication range, these devices compute and exclude the incorrect coordinate(s) and send feedback to reference devices. After going through the above query request process, smart device j can determine its actual position.

For Case 3, smart device j only obtains the location of its neighboring device. Since smart device j has only one neighboring device, it cannot be within the communication range of its two-hop neighbors. Based on this observation, a query request is sent to the neighboring device to obtain the locations of its two-hop neighbors. After collecting all the results from neighboring device, smart device j can infer the arc of its position as shown by the D_8 in Fig. 3.

IV. Simulation Analysis

This section conducts simulation experiments to offer an demonstration and estimate the performance of the crowdsourcing-based localization scheme for UWB-enabled smart devices.

A. Experimental Settings

In this study, simulation analysis of the proposed scheme are conducted with MATLAB. Considering the characteristics of UWB technology, the communication distance of UWB transceivers are set to $80m$ and the error of distance measure is randomly generated in the range of 0 to $15cm$.

In an area of $400 \times 400m$, 100 devices are deployed with the physical locations randomly generated. In this scenario, 10 UWB anchors with known locations (indicated by pentagrams) are deployed, while the others are smart devices (indicated by circles) requiring positioning service. The device deployment and network connections are illustrated in Fig. 4.

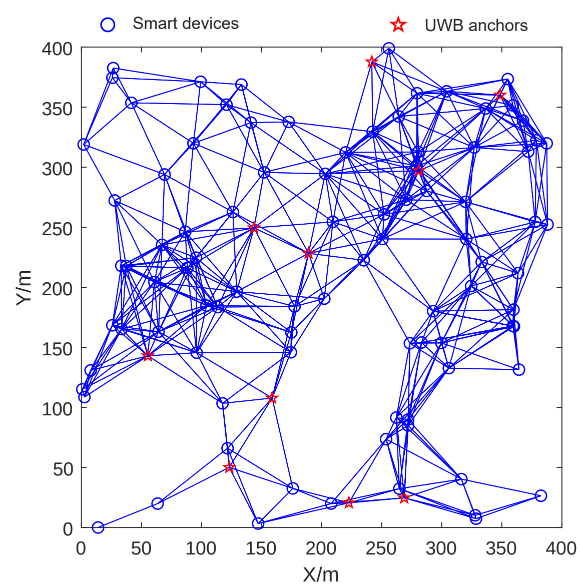

Fig. 4. Example of device deployment and network connections.

B. Simulation Results

Fig. 5 shows the positioning results without crowdsourcing. Circles indicate physical locations of smart devices and stars indicate the estimated locations of successful located devices. As indicated by blue circles, a smart device only obtains its location successfully when it has direct connection with sufficient number of UWB anchors. Despite of the high accuracy, the successful positioning rate is low. Most devices fail to obtain the locations successfully, as indicated by black circles. Without crowdsourcing, it requires to increase the number of UWB anchors significantly to provide satisfactory positioning services.

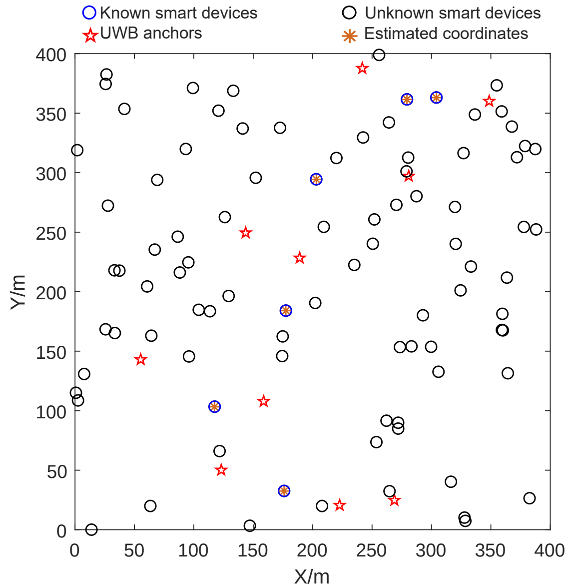

Fig. 5. Localization of smart devices without crowdsourcing.

Fig. 6 shows the positioning results of smart devices surrounded by sufficient number of reference devices. Overall, with the successful located smart devices acting in anchor-like manner, the successful positioning rate is significantly improved and the accuracy is satisfactory. However, there are still some smart devices failing to get their locations, as indicated by black circles.

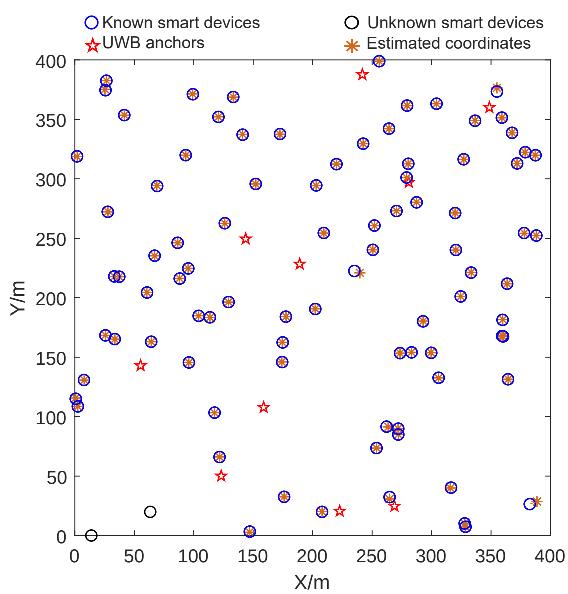

Fig. 6. Localization of smart devices with sufficient references during crowdsourcing.

The Fig. 7 shows the positioning results after sending query request to neighboring reference devices for assistance. It can be found that even if these smart devices have not enough neighboring reference devices for localization, their locations can still be deduced by sending query request. In addition, some of them still achieve quite good positioning accuracy when two neighboring reference devices exists. For the smart device with only one neighbor, although we can not get the accurate location, an arc on which the device locates on can be obtained as shown in the lower left corner of Fig. 7.

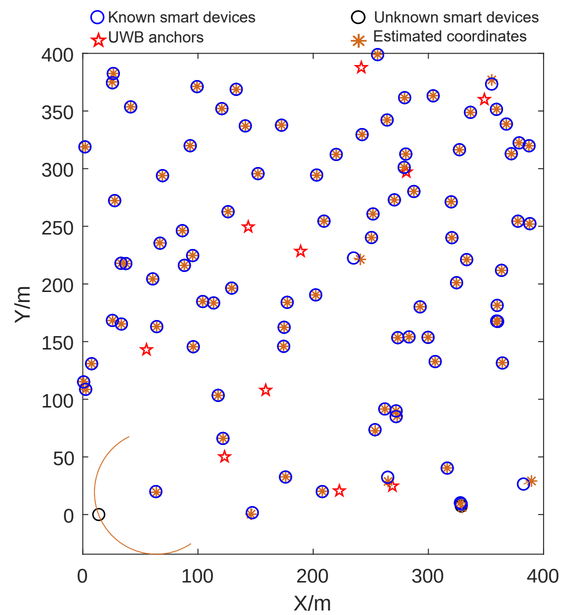

Fig. 7. Localization of smart devices after query request.

Table II gives the number of smart devices that are successfully and unsuccessfully localized in different cases. With crowdsourcing and query request, the number of successfully located smart devices are increase significantly. Table III summarizes the positioning accuracy with root mean square error (RMSE) [13], indicating the performance of the proposed crowdsourcing-based localization scheme. For smart devices with only one neighbor, it is only possible to obtain the arc, they are clarified as unlocalized device in Table III.

TABLE II
POSITIONING COVERAGE

	Without crowdsourcing	With sufficient references	After query request
Localized device no.	6	88	89
Unlocalized device no.	84	2	1

TABLE III
ROOT MEAN SQUARE ERROR OF THE POSITIONING.

	Without crowdsourcing	With sufficient references	After query request
RMSE/m	0.1245	1.1652	1.2833

V. CONCLUSIONS

It is highly expected that UWB-enabled smart devices will be popular in the near future. With the consideration of this trend, a crowdsourcing-based localization scheme is introduced for UWB-enabled smart devices. In crowdsourcing manner, only a small number of UWB anchors are required to provide positioning services and the other smart devices collaborate to calculate their physical locations. The simulation results have demonstrated that the proposed crowdsourcing-based scheme improves the successful positioning rate and achieves high accuracy. For the future, with the consideration of practical constraints in real-world applications, it is necessary to focus on the impact of device mobility, obstacles, network density, etc.

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