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Localization using a Mobile Beacon in Wireless Sensor Networks

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Abstract: Localization is a crucial issue and acts as a fundamental element in wireless sensor networks. The location accuracy of sensor node increases with the number of beacon points which can provide reference information for localization. However, the more beacons are used, the higher implementation cost is. In the study, a distributed algorithm called RSS-assisted range-free is proposed to locate sensor nodes using mobile beacons. The proposed algorithm only uses three beacon points to estimate the position of the sensor node. In the proposed scheme, two beacon points are used to obtain candidate positions of the sensor node and the third beacon point is used to determine which one of the candidates would be the actual position of the sensor node. To improve the location accuracy, the study estimates sensor position from possible candidate regions by using geometric conjecture and Received Signal Strength (RSS) constraints. The simulation results have shown that the proposed algorithm is feasible and significantly improves on location accuracy.

Key words: Wireless sensor networks, localization, mobile beacon, range-free, received signal strength

INTRODUCTION

Wireless Sensor Networks (WSNs) typically consist of a large number intelligent sensor nodes with sensing, processing and wireless communicating capabilities. WSNs are deployed to implement complicated tasks in the specified sensing field, such as monitoring certain physical phenomena or detecting and tracking certain targets. In WSNs, the position of the event is a very important part of the monitoring information. In most cases, the monitoring data without positional information cannot be used and even have no significance (Hightower and Borriello, 2001; Harter *et al*., 2002). For example, in the environmental monitoring applications, we need to know the position of the collection information corresponding to specific regions; for emergency event, we need to know the position of the forest fire, the movement region of enemy vehicles on the battlefield, the specific position of the natural gas pipeline leak. For these problems, the sensor node must know its own position coordinate which is the basis of taking further measures and make decisions.

The best way to obtain the position of sensor node is artificial deployment or equipped with a Global Positioning System (GPS) for each sensor node (Sichitiu and Ramadurai, 2004). However, it's not conducive to large-scale applications, in which all sensor nodes are artificial deployment or equipped with GPS. In WSNs, a small number of sensor nodes called beacon nodes which know their position coordinates are deployed to locate unknown sensor nodes. The unknown sensor nodes use the network connectivity relation or distance and angle information from beacon nodes to implement localization. This process of locating can be done using various techniques or algorithms (Li *et al*., 2010).

The sensor node localization mechanism can be classified as range-based and range-free localization. In range-based schemes, sensor nodes estimate their positions based on measured distance or angle estimations from beacon nodes. The measurement methods can be classified as the following categories (Patwari *et al*., 2005): Received Signal Strength Indicator (RSSI) (Patwari *et al*., 2003) Angle-of-arrival (AOA) (Niculescu and Nath, 2004), the Time-of-arrival (TOA) (McCrady *et al*., 2000) and Time-difference-of-arrival (TDOA) (Priyantha *et al*., 2000). The location accuracy of sensor node has a great improvement by using different range-based measurement techniques. Under different environmental factors, there would be a big measurement error with RSSI-based localization method. AOA, TDOA and TOA localization methods provide a reasonably high degree of accuracy, but the methods require each sensor node to be equipped with additional hardware. Range-free approaches (Bulusu *et al*., 2000; He *et al*., 2003; Chan and Soong, 2011; Wu *et al*., 2011) do not require accurate distance measurements, whereas, locating the unknown node based on beacon proximity, network connectivity

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information or localization events detection. Range-free schemes usually provide coarse location accuracy, but it can avoid the requirement for specific hardware support and reduce the cost of the sensor nodes. Hence, it can be more widely used in practical applications.

It's obvious that the location accuracy of sensor node increases with the number of beacon nodes which can provide reference information for localization. After localization complete in the networks, the beacon nodes transform themselves into normal nodes. Therefore, too many beacon nodes are deployed in the sensor networks which would cause great waste and increase the cost of the networks. To decrease the number of beacon nodes, many literatures (Chen *et al*., 2010; Zhang *et al*., 2010; Chang *et al*., 2012; Ssu *et al*., 2005; Ou, 2011; Xiao *et al*., 2008; Kim *et al*., 2011) have proposed a new localization idea by using mobile beacon-assisted. Mobile beacon equipped with GPS which moves around in the sensing field and broadcasts its current position periodically. And there would be many virtual beacons in the sensing field. The virtual beacon can replace the traditional static beacon, it can greatly reduce the cost of deployment and maintenance which caused by the static beacon. Hence, localization schemes using mobile beacons have the similar effect with using many static beacons in terms of improving location accuracy.

In the study, a distributed method is proposed to locate sensor nodes using moving beacons that sensor nodes compute their positions based on RSS-assisted range-free approach. First, instead of directly mapping RSSI values into physical distances, the RSSI values between the sensor node and the beacon points are used to estimate the position relationships between the beacon points and the communication circle of the sensor node. Then, two candidate positions of the sensor node can be obtained by utilizing the geometric relationship of the circle intersection. Finally, the third beacon point is used to decide which candidates would be the actual position of the sensor node. In the whole process of the proposed algorithm, there are only three selected beacon points used to estimate the position. Thus, the calculation is simple and the communication data is very small.

Extensive researches have already been done on localization in WSNs in the last decade. However, most localization methods are static, since both the sensor network and the beacons are static. Many static localization algorithms are not suitable for the mobile localization system. In the mobile beacon localization scheme, sensor nodes compute their positions based on the beacon messages received from location-aware mobile beacon points as they move through the sensing field. These schemes can be categorized as either range-based or range-free. The major studios in mobile beacon localization are summarized in the sections below.

Sichitiu and Ramadurai (2004) proposed a range-based localization mechanism using a single mobile beacon aware of its position. Sensor nodes received beacon messages can estimate their positions by using an RSSI technique. The location accuracy can be improved when the sensor node receives more beacon messages. Three different types of static paths are proposed for the mobile beacon (Koutsonikolas *et al*., 2007). The proposed range-based localization scheme uses the RSSI for ranging. A three-dimensional space-based location algorithm is proposed by Fu *et al*. (2011). The proposed Single Mobile Anchor Location scheme uses single flying anchor which equipped a GPS to calculate the positions of location-unaware sensor nodes through the localization measurement flying model in the three-dimensional coordinate system.

Ssu *et al*. (2005) proposed a range-free localization scheme using the geometry conjecture to calculate the position of the node. The mobile beacon was equipped with GPS which moved around in the sensing field and broadcast its current position periodically. The position of sensor node was estimated as the intersection point of two perpendicular bisectors of the chords obtained by three reference beacon points. However, the location accuracy has a close relationship with the beacon interval and the minimum chord length. To resolve the problem, (Xiao *et al*., 2008) proposed a localization algorithm which utilized the Arrival and Departure Overlap (ADO) area to represent the position of the sensor node within a possible sensing area in accordance with geometric constraints. The author analyzed the upper bound of error of the position estimation, it implied that to obtain an accurate localization of sensor nodes, the moving beacon should shorten its message broadcasting interval. A range-free localization scheme for WSNs using mobile beacon equipped with four directional antennas was presented by Ou (2011). The mobile beacon broadcasted the information of its coordinates via four fixed directional antennas while it moved through the sensing field. The sensor nodes detected the beacon messages and utilized a simple mathematical processing scheme to compute their own positions. However, the mobile beacons were required to be fitted with an antenna system which comprised four directional antennas. Liao *et al*. (2011) proposed a range-free localization scheme using a mobile beacon node, in which two beacon points were used to estimate two candidates for the location of sensor node. Also, the third beacon point was selected to determine the final location within the two candidates. The selected beacon points may not be exact on the communication circle of the sensor node, thereby it caused a large location error. To solve the adjacent erroneous beacon points, Lee and Kim (2010) proposed an improved localization scheme. The location of a sensor node was estimated as the intersection point of two circles which center was the beacon points and the radius was a refined value. Whereas, the proposed scheme also requires a short beacon interval, to enhance the accuracy of the localization.

The proposed method differs significantly from those previous mobile beacon localization works. This study combines the geometry conjecture scheme with RSS technique to improve precision in the localization process.

PROPOSED LOCALIZATION SCHEME

System environment: In Fig. 1, M static sensor nodes and N mobile beacons are distributed randomly in the sensing field. The static sensor nodes don't know their position coordinates, commonly called sensor node. The mobile beacons have location-aware abilities by using a GPS or other positioning devices. Assume that the mobile beacons are able to move by themselves or other carriers, such as the robot and broadcast beacon messages during the localization process. The sensor nodes and the mobile beacons have the same transmission range. And the sensor nodes can receive messages from the mobile beacon points to locate themselves.

Proposed algorithm: In the RSS-assisted range-free localization scheme, it can locate a sensor node after obtaining only three beacon points. Among the three beacon points, two beacon points are used to obtain two candidate positions of the sensor node and the third beacon point is used to determine which one of the two candidates should be the actual position of the sensor node. Thus, the proposed localization scheme includes three steps:

Step 1: Select two beacon points from the received beacon to realize preliminary locating

Step 2: Estimate two candidates' positions of the sensor node using geometric conjecture and RSS constraints

Step 3: Select the third beacon point to calculate the final location of the sensor node

Beacon points selection: This step is similar to Ssu *et al.* (2005) scheme, where a mobile beacon is assumed to have a straight movement. The mobile beacon moves around

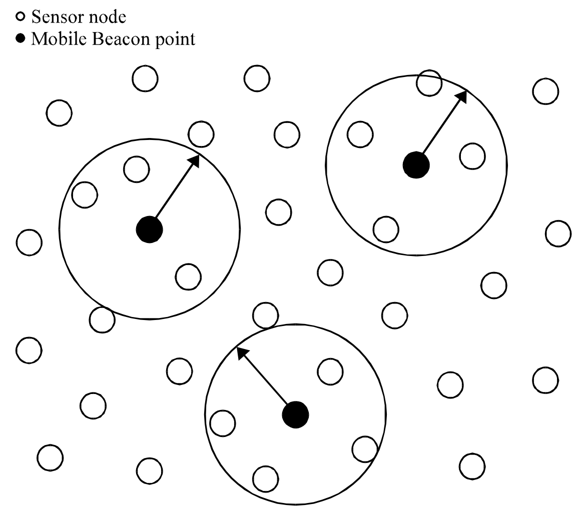

Fig. 1: Schematic of the system environment

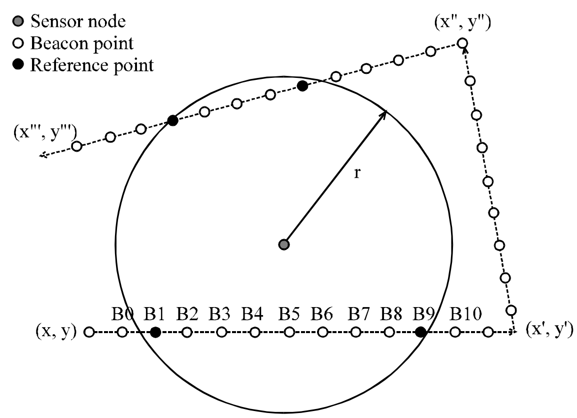

Fig. 2: Beacon point selection, r: Communication radius of sensor node, Bx: Beacon points of mobile Beacon

the sensing field at a constant speed and broadcasts beacon message periodically. The beacon message includes its own position information, beacon ID and the current timestamp. The sensor node maintains a visitor list that stores the beacon message received from the mobile beacon. The first and last beacons of the visitor list are selected as the first beacon point and the second beacon point. The mobile beacon follows the Random Waypoint (RWP) model (Broch *et al.*, 1998) that the mobile beacon moves in a series of straight paths to random destinations, as illustrated in Fig. 2.

When the mobile beacon moves from (x, y) to (x, y), the sensor node receives the first beacon from the mobile beacon, i.e., B1 in Fig. 2. Therefore, B1 is selected as the first beacon point. After receiving the first beacon point,

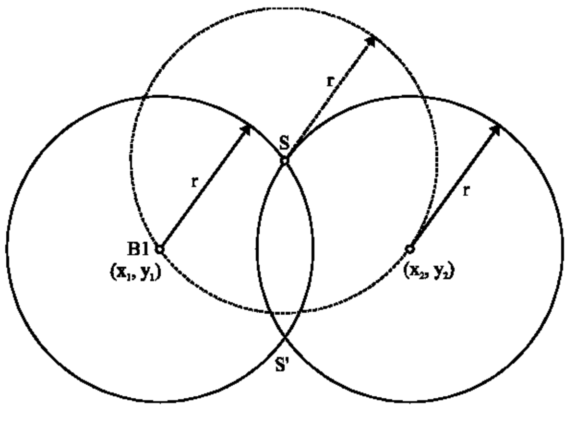

Fig. 3: Intersection of two circles, r: Communication radius of sensor node, S: Candidate positions of sensor node, B1 and B2: Selected beacon points

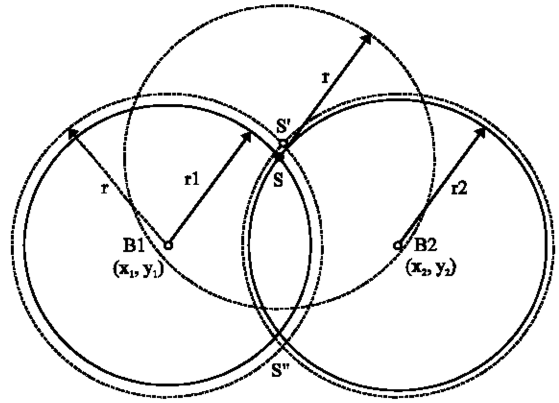

Fig. 4: Sensor node location estimation, r: Communication radius of sensor node, S and S': Two candidate positions of sensor node, B1 and B2: Selected beacon points

the sensor node maintains a visitor list that stores the beacon message received from the mobile beacon. The sensor node will receive no further beacons during a predefined time after receiving the last beacon point and the beacon is selected as the second beacon point. In Fig. 2, it shows that beacon points B1 and B9 are the points that first enters into and last leaves the communication circle of the sensor node, respectively.

Node position estimation: The proposed localization algorithm is based on geometrical conjecture between beacon points and the sensor node. In Fig. 3, the beacon points B1(x_1, y_1) and B2(x_2, y_2) are located on the communication circle of the sensor node with radius r. Therefore, the position of sensor node S(x, y) is one of the intersection points of the two circles centered at B1 and B2 with radius r. And the coordinates of the intersection points of the two circles can be calculated by:

$$\begin{cases}(x-x_1)^2+(y-y_1)^2=r^2\\(x-x_2)^2+(y-y_2)^2=r^2\end{cases}\qquad(1)$$

The two selected beacon points are the beacons that first enters into and last leaves the communication circle of the sensor node, respectively. The selected beacon points are considered as approximate endpoints on the communication circle. If the beacon points are exactly on the communication circle of the sensor node, the location of sensor node can be estimated from Eq. 1, just like (Liao *et al*., 2011) scheme. However, the beacon points are always not exactly on the communication circle, i.e., B1 and B9, in Fig. 2. That's because the beacon message broadcasting of mobile beacon is not continuous. The mobile beacon broadcasts a beacon message after a moving distance d, for this reason the sensor node receives a beacon message at every beacon distance d.

As shown in Fig. 4, B1 and B2 are not exactly on the communication circle of the sensor node, there is a large deviation between the actual position S and the estimated position S' using the scheme (Liao *et al*., 2011). The maximum location error will increase as the beacon distance increasing. In the study, an adaptive node localization algorithm is proposed. In this scheme, the radii of the two selected beacon points are adaptively adjusted, according to the location relationships between the selected beacon points and the communication circle. The idea of the localization scheme is that if the centers and radius r of two circles are known, then it is possible to obtain their two intersection points. The intersection points of two circles can be calculated by simple calculation. The geometric equations of the two circles are given as follows:

$$\begin{cases}(x-x_1)^2+(y-y_1)^2=r_1^2\\(x-x_2)^2+(y-y_2)^2=r_2^2\end{cases}\qquad(2)$$

In Eq. 2, the key is how to obtain the appropriate radius r_1 and radius r_2, according to the location relationships between the beacon points and the communication circle.

Based on the above analysis, a method that combines geometry conjecture and Received Signal Strength (RSS) is presented in the study to locate the sensor nodes. However, there will be a large model error when RSS values are directly mapped into physical distances. It's difficult to establish a kind of self-adaptive radio signal propagation models, mainly for the uncertain influences, such as interference, reflections, signal fading and non-uniform spreading. Although RSS is irregular in practice, it is usually a fact that the RSS between two nodes monotonically decreases as the nodes move further away from each other. Therefore, instead of directly mapping RSS values into physical distances, the study contrasts the RSS of sensor node between the selected beacon points and reference point exactly on the communication circle to estimate the position relationship between the beacon points and the communication circle of the sensor node. And then, based on the RSS constraint, the functions of radius r_1 and r_2 can be established to estimate the position of the sensor node.

During the prepare phase of networks, the sensor node repeats the measurement of the corresponding RSS values, when the distances between mobile beacon points and sensor node are r and r-d, respectively, as the reference values of RSS. And the reference RSS values are recorded as D_r and D_{r-d}, respectively. By the back and forth moving of the mobile beacon to look for the communication radii r and r-d, the reference RSS values can be measured. Then, when the mobile beacon moves in the network, the sensor node selects two beacons B1 and B2 which enters and leaves its communication circle among the received beacon as the beacon points. And the sensor node measures the RSS values when the mobile beacon at B1 and B2, recorded as D_1 and D_2. Finally, the sensor node compares the received RSS D_1 and D_2 with the reference RSS r_1 and r_2. Therefore, r_1 and r_2 can be calculated by:

$$\begin{cases} r_1 = r - \dfrac{D_r - D_1}{D_r - D_{r-d}} \bullet d + \xi \\ r_2 = r - \dfrac{D_r - D_2}{D_r - D_{r-d}} \bullet d + \xi \end{cases} \quad (3)$$

where, r_1 and r_2 are the radii of two circles centered at the two selected beacon points, respectively. D_1 and D_2 are the RSS values between the sensor node and two selected beacon points. D_r and D_{r-d} represent the RSS of the sensor node when the beacon points are on the communication circle with radius r and on the communication circle with radius r-d, respectively. ξ is a compensation value.

According to the RSS values between the sensor node and the two beacon points, the positional relationships of the two beacon points and the communication circle of the node can be estimated. Thus, the circle radii of the two beacon points can be adjusted adaptively. It can reduce the estimated position error that caused by the beacon points which are not exactly on the communication circle of the sensor node. As shown in Fig. 4, the possible candidate positions of the sensor node S are the intersection points of the two circles centered at beacon points at B_1 and B_2 with radius r_1 and r_2, respectively.

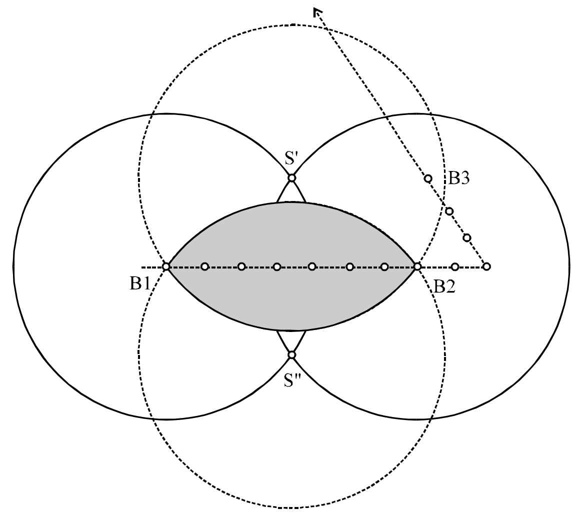

Fig. 5: Determine the location of the sensor node, r: Communication radius of sensor node, S' and S'': Two candidate positions of sensor node, B1 and B2: Selected beacon points

The node localization: The intersection points of two circles centered at B_1 and B_2 are S' and S" which are the possible candidate positions of the sensor node, as shown in Fig. 5. However, only two beacon points can't confirm which candidate positions is the actual position of the sensor node. Thus, the third beacon point B_i is chosen from the beacon visitor list to decide which one of the two candidates would be the actual position of the sensor node. If there is any beacon point B_i in the visitor list, the distance between B_i and S' is less than r, but B_i and B_2 is greater than r, then we can conclude that the position of the sensor node is S. That' because the third beacon point should lie inside the communication range of the sensor node, the distance between the beacon point and the exact position of the node S should be less than r. Therefore, when $\|B_i\text{-}S'\|>r, \|B_i\text{-}S''\|<r$ or $\|B_i\text{-}S'\|<r, \|B_i\text{-}S''\|>r$, the exact position of the node can be determined.

The selected principle of the third beacon point satisfies that the beacon point must be outside of the shadow region, in Fig. 5. If the beacon point lies in the shadow region, the distance between the candidate positions S' and S" must be less than r and then the node position cannot be determined. Thus, the third beacon point inside the shadow region should not be selected to estimate the node position. For example, in Fig. 5, the sensor node S already has two possible candidate positions S' and S". When the node S receives beacon packet B_3, it calculates the distances $\|B_3\text{-}S'\|<r, \|B_3\text{-}S''\|>r$.

Hence, the position of node S is S'. If there is none beacon point in the visitor list that be outside of the shadow region, then the sensor node S cannot determine its actual position. In this case, the sensor node keeps the two possible locations S' and S", until another beacon point that is able to determine the position of the sensor node is received.

In a few cases, the solution of the Eq. 2 may be one, it means that there is only one candidate's position, namely the candidate is the exact position of the sensor node. Then there's no need selecting the third beacon point to confirm the node position.

SIMULATION RESULTS

Here, the simulation results of the proposed localization algorithm using a mobile beacon and compares the simulation results with other localization schemes is shown.

Simulation settings: The study analyzes the performance of the proposed algorithm using MATLAB simulator and compares the performances with (Liao *et al*., 2011; Ssu *et al*., 2005; Lee *et al*., 2009). The network model for simulation consists of uniformly and randomly deployed 200 nodes in a square area over 100×100 m^2. Assume that the static nodes and mobile beacon nodes have the same transmission range and set the range to 10 m. The mobile beacon is assumed to move straight at a velocity of 1 m sec^{-1} and broadcast a beacon message per second, thus the beacon distance is 1 m.

In the real-world environment, based on the experiment conducted by Zhou *et al*. (2006), the path losses should be non-isotropic, it means that the path losses vary in directions. Therefore, to verify the reality of the proposed algorithm, this study uses an irregular radio model with the Degree of Irregularity (DOI) which is defined as the maximum radio range variation per unit degree change in the direction of radio propagation. According to these observations, the model for RSS calculation can be represented as follows (Zhou *et al*., 2006):

$$\text{RSS} = \text{Sending power-DOI Adjusted path loss+Fadding} \quad (4)$$

Where:

$$\text{DOI Adjusted Path Loss} = \text{Path Loss} \times \text{Ki} \quad (5)$$

$$K_i = \begin{cases} 1, & i = 0 \\ K_{i-1} \pm \text{Rand} \times \text{DOI}, & 0 < i < 360 \wedge i \in N \end{cases} \quad (6)$$

where, $|K_0 - K_{359}| \leq \text{DOI}$.

Considering the effect factors on location accuracy, the study makes simulations with the parameters as shown in Table 1.

Simulation results

Impact of transmission range: The average localization error (Fig. 6) as the transmission range increased incrementally from 10-30 m^2. In the simulation, the velocity of the mobile beacon was 3 m sec^{-1} and the beacon broadcast a beacon message per second. In Fig. 6, it showed that the average localization error of sensor node increased with the transmission range. And the result showed that the average localization error of the proposed approach is less than Liao's and Lee's approaches.

Impact of moving velocity: The moving velocity of the mobile beacon (namely the beacon interval) has a great effect on the location accuracy. The beacon interval is defined as the distance between the two continuous broadcast messages of the mobile beacon. In Fig. 7, different velocities of the mobile beacon were taken into consideration in the proposed approach and other approaches. The result showed that the average localization error increased with the velocity of the mobile beacon, especially in Ssu's and Liao's approaches. That's because the candidate beacon points may no longer be exactly on the communication circle of the sensor node while the velocity of the mobile beacon increases. By contrast, the proposed scheme utilizes the RSS-assisted

Table 1: Simulation parameters

Parameters	Value
No. of sensor nodes	200
Size of the sensing region	100×100 m
Transmission range	10-30 m
Speed of the mobile beacon	1-5 m sec^{-1}
Degree of irregularity	0-0.4

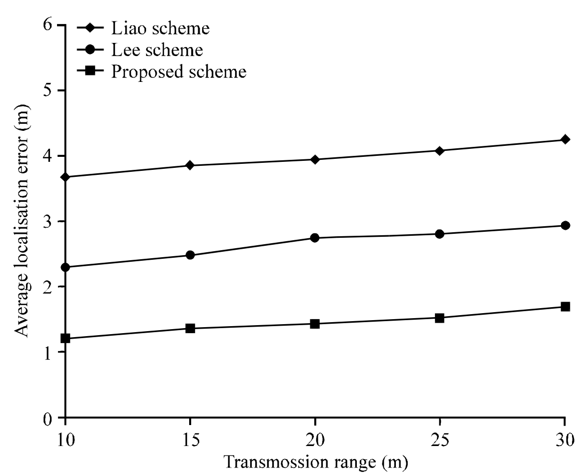

Fig. 6: Average localization error vs. transmission range

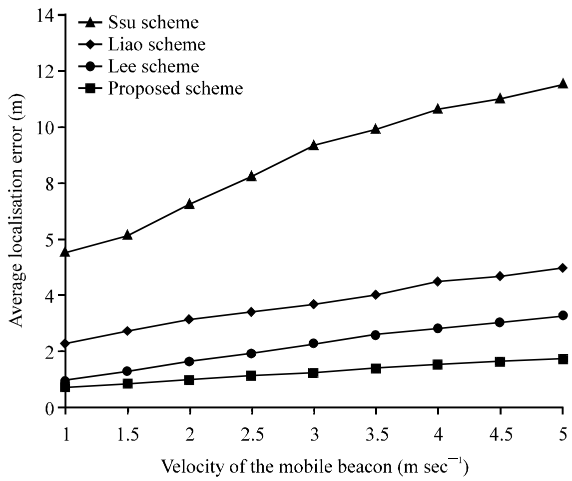

Fig. 7: Average localization error vs. Beacon interval

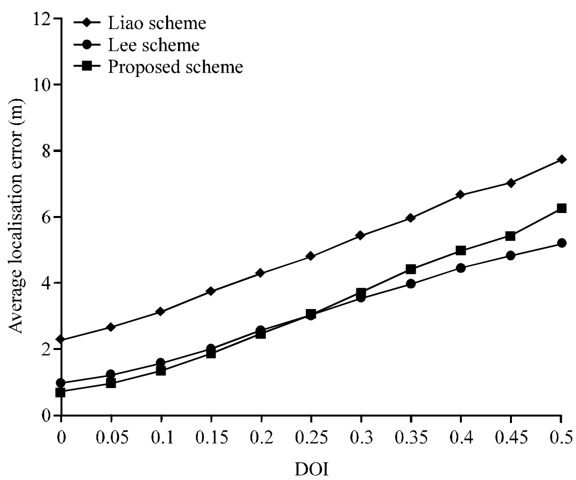

Fig. 8: Average localization error vs. degree of irregularity (DOI)

technology to estimate the position relationship between the beacon points and the communication circle of the sensor node and reduce the effect on the location accuracy. So, the proposed algorithm has a higher location accuracy than the other three schemes as the increase of the beacon interval.

Impact of DOI: Figure 8 showed the average location error when DOI was varied from 0 to 0.5. Compared with other mobile beacon-assisted range-free localization algorithms, the proposed algorithm had a little location error when DOI was less than 0.25. But the localization error increased while DOI was higher than 0.25. According to the result, It's concluded that the schemes are vulnerable to radio irregularities, for the communication range of the sensor node will not be a regular circle with increasing of DOI.

CONCLUSION

In the study, a distributed localization algorithm using a mobile beacon is proposed. The proposed algorithm only uses three beacon points, where two beacon points are used to obtain two candidate positions of the sensor node and the third beacon point is used to determine which one of the two candidates should be the actual position of the sensor node. In addition, to improve the location accuracy, the study adopts a practical RSS model to contrast the RSS values between the beacon points and the sensor node and estimate the position relationships between the beacon points and the communication circle of the sensor node. Simulation results show that the proposed algorithm significantly improves on location accuracy and outperforms other schemes that mentioned in the paper in terms of the localization accuracy under different transmission range, beacon interval and DOI.

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