The Insights of Localization through Mobile Anchor Nodes in Wireless Sensor Networks with Irregular Radio

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Abstract

Recently there has been an increasing interest in exploring the radio irregularity research problem in Wireless Sensor Networks (WSNs). Measurements on real test-beds provide insights and fundamental information for a radio irregularity model. In our previous work “LMAT”, we solved the path planning problem of the mobile anchor node without taking into account the radio irregularity model. This paper further studies how the localization performance is affected by radio irregularity. There is high probability that unknown nodes cannot receive sufficient location messages under the radio irregularity model. Therefore, we dynamically adjust the anchor node’s radio range to guarantee that all the unknown nodes can receive sufficient localization information. In order to improve localization accuracy, we propose a new 2-hop localization scheme. Furthermore, we point out the relationship between degree of irregularity (DOI) and communication distance, and the impact of radio irregularity on message receiving probability. Finally, simulations show that, compared with 1-hop localization scheme, the 2-hop localization scheme with the radio irregularity model reduces the average localization error by about 20.51%.

Keywords: WSNs, localization, mobile anchor node, degree of irregularity

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1. Introduction

1.1 Background and Motivation

In WSNs, many applications require sensor nodes to obtain their locations. For example, a deployed WSN for monitoring fire event should ideally pinpoint the location of fire with good accuracy to enable firefighters to correctly respond. In addition, many geographic routings and data dissemination schemes, e.g., [1][2][3], rely on sensor nodes' locations. Thus, each sensor node is required to report not only sensing data but also current position.

Developing effective localization schemes has become a pressing issue in WSNs, e.g., [4][5][6][7][8][9][10][11]. In these studies, they do not consider any specific trajectory for the mobile anchor node. Furthermore, they usually use only idealistic radio propagation models in simulations to investigate and evaluate localization algorithms. In the idealistic radio propagation models, all sensor nodes have fixed spherical radio range [12]. However, the realistic radio range is irregular. Therefore, sensor nodes cannot receive sufficient location messages from the mobile anchor node.

Radio irregularity is a phenomenon in WSNs that makes its radio range non-spherical in nature. It results in irregularity in radio range and variations in packet loss in different directions. Pawlikovski et al. [13] identify the simple idealistic radio models popularly adopted by most researchers and simulators. Experiments show that the majority of recently published results of simulation studies do not satisfy the basic criteria of credibility. Since the idealistic radio irregularity models yield experiment results radically different from reality.

In this paper, we consider two major facts: 1) mobile anchor node; 2) radio irregularity, and aim at quantifying the influences of mobile trajectory and radio irregularity on localization accuracy from various perspectives. There is only one mobile anchor node with a Global Positioning System (GPS) in WSN. The mobile anchor node periodically sends message packets with the position information to unknown nodes. Unknown nodes are localized based on the position of the mobile anchor node. Through simulation, it is found that the radio irregularity model greatly degrades the performance of the localization algorithms.

1.2 Contributions

In [11], we reveal the relationship between the trajectory of mobile anchor node and the localization error. We also introduce a Localization algorithm with a Mobile Anchor based on Triangulation in WSNs (LMAT). The performance analysis and simulation results show that, when the trajectory of mobile anchor node form equilateral triangle, the localization accuracy is the highest [14]. But we do not take into account the radio irregularity model. Based on LMAT, in order to research the impact of radio irregularity on localization accuracy, we need to focus on some fundamental issues such as the relationship between DOI and communication distance, and the impact of radio irregularity on message receiving probability.

In summary, the contributions of this paper are listed as follows:

- We study the relationship between DOI and communication distance. Under radio irregularity, some unknown nodes cannot receive messages from anchor nodes; even they are in the idealistic radio ranges of the anchor nodes.

- In order to improve localization accuracy, the anchor node's radio range is dynamically adjusted to guarantee that all the unknown nodes can receive sufficient localization information.
- We study the impact of radio irregularity on message receiving probability. If the message receiving probability is too small, unknown nodes cannot receive sufficient localization information to localize themselves.
- Under radio irregularity, combine 2-hop localization algorithm with LMAT to improve localization accuracy. Furthermore, we evaluate the performance of the 2-hop localization algorithm based on simulation results.

1.3 Paper Organization

The rest of the paper is organized as follows. Section 2 introduces related work. Section 3 studies the relationship between DOI and communication distance. Section 4 researches the modified radio range and studies the impact of radio irregularity on message receiving probability. Section 5 investigates the 2-hop localization scheme on LMAT, and studies the message receiving probability in the 2-hop localization scheme. Section 6 presents the simulation parameters. Section 7 presents the evaluation results. Finally, Section 8 concludes the paper.

2. Related Work

Lots of localization schemes with mobile anchor node have been proposed, e.g., [5][6][7][8][9][10][11][12][13][15][16]. In those schemes, unknown nodes are localized based on the position of the mobile anchor node. In [8][16], the mobile anchor node moves randomly. In [5][6][7][8][9][10][11][12][13][15], the researchers mainly study the path planning of mobile anchor node.

In [5], the researchers proposed the circular and the S-shaped path planning methods. What the two methods have in common is that no matter how the nodes are distributed, the mobile anchor node moves according to the planned path to locate unknown nodes. When the unknown node is closer to the planning path of mobile anchor node, the localization accuracy is higher. In contrast, when the unknown node far away from the planning path, the localization accuracy is low or even the unknown node cannot receive any message from the mobile anchor node.

Ou [8] proposed a novel flying anchor localization algorithm. In the algorithm, the anchor node is equipped with a GPS receiver and broadcasts its location information as it flies through the sensing area. After receiving the location information from the flying anchor nodes, each unknown node in the sensing area estimates its own location by basic geometry principles. If the unknown node receives more than four anchor nodes’ information, the four anchor nodes form two groups of intersecting circles with two lines, which are separately perpendicular to the communal diameters of the two intersected circle. The intersection point of the two lines is the estimated location of unknown node. The algorithm makes a certain contribution to calculate coordinates of unknown nodes, but it does not involve the path planning of mobile anchor node.

In [11], a novel movement trajectory of mobile anchor node is proposed. The mobile anchor node traverses the entire network area along the boundaries of the equilateral triangles. The trajectory guarantees all the unknown nodes receive message packets and obtain estimated positions. Compared to random movement of anchor nodes, the trajectory significantly reduces the average localization error.

In short, previously, researchers have proposed many algorithms to solve the path planning problem, but these algorithms do not consider the impact of radio irregularity.

The radio irregularity has been known for a long time. However, researches on the impact of radio irregularity on localization is still in infancy. Most researchers mainly focus on these studies: 1) providing more evidence to further quantify the radio irregularity [17][18], 2) clarifying and demonstrating the weakness of using the ideal circular model in existing protocols and algorithms [19], and 3) developing other algorithms that are less dependent on the radio shape [20].

He [21] provided an irregular radio model: Degree Of Irregularity (DOI). The model assumes the upper and lower bounds on the radio propagation range. When a neighbor node is beyond the upper bound, it is out of the communication range; and when it is within the lower bound, the node is guaranteed to be within communication range. If the distance between the two neighbor nodes is between these two boundaries, the communication is dependent on the actual radio range in that direction. In simulation, the particular radio range in each direction is calculated based on a random number and a pre-assigned irregularity factor. While this paper is a good start for the research on irregular radio, the DOI model does not take the environment parameters into account. Also, the model usually results in undetermined and abrupt changes of range values in all directions.

Zhou [22] extended the DOI model by considering the radio interferences among devices. The new model is called Radio Irregularity Model (RIM). RIM is based on experimental results made with a pair of MICA2 motes. The authors run a set of simulation experiments to investigate radio irregularity's impact on localization and topology control, finding that the increasing radio irregularity leads to larger localization error. The communication connectivity becomes harder to maintain when the radio becomes more irregular. However, Zhou in [22] does not research the problem of mobile path planning.

Therefore, in this paper, we both take into account the mobile anchor node's path planning and the radio irregularity. We further study the relationship between DOI and communication distance, and the impact of radio irregularity on message receiving probability. Based on LMAT, we propose a 2-hop localization scheme, in which unknown nodes can receive four triangulation anchor nodes' packages to localize themselves.

3. The Relationship Between DOI And Communication Distance

Radio irregularity is caused by the presence of physical obstacles in indoor environments, multi-path fading, irregularity of radiation pattern of transmitters and other environmental factors. One of the proposed irregularity models suggests a stochastic pattern for radio irregularity of transmitters and receivers [22]. The model which called RIM defines the communication range varies as the DOI changes, as shown in **Fig. 1**.

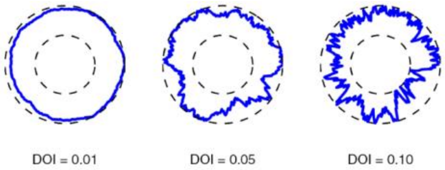


Fig. 1. RIM with three different DOI

The RIM Model reflects two main properties of radio irregularity, namely anisotropy and continuous variation, The RIM Model adjusts the value of path loss models based on DOI values, which is represented as follows:

$$P_r = P_s - P_{DOI} + P_f \tag{1}$$

Here P_r is the received signal strength, P_s is the sending signal power of the sender, P_f is the fading exponent, and P_{DOI} describes the signal's energy loss as it travels to the receiver. $P_{DOI} = \eta_1 \times K_i$, η_1 is path loss parameter and K_i is a coefficient to represent the difference in path loss in different directions. Specifically, K_i is the i^{th} degree coefficient, which is calculated as follows:

$$K_i = \begin{cases} 1, & i = 0 \\ K_{i-1} \pm Rand \times DOI, & i = 1, 2, \ldots, 359 \end{cases} \tag{2}$$

The literature [23] represents radio propagation in natural environments. In fact, both theoretical and practical measurement based propagation models indicate that average received signal power decreases logarithmically with distance. [23] represents the following radio propagation path loss model:

$$PL(d) = PL(d_0) + 10\eta_2 \lg \frac{d}{d_0} - X_\sigma \tag{3}$$

where d is the communication distance between the sender and receiver. $PL(d)$ is the power loss corresponding to d, and $PL(d_0)$ is the power loss corresponding to d_0, which is a reference distance. $PL(d_0)$ can be determined in the process of system calibration. η_2 is the path loss exponent standing for the rate at which the path loss increases with regard to distance. The lognormal shadowing effect is expressed as a gaussian random variable X_σ of zero mean and standard deviation σ. That is $X_\sigma \sim N(0, \sigma^2)$. Thus, we have

$$P_r(d) = P_s(d) - PL(d) = P_s(d) - PL(d_0) - 10\eta_2 \lg \frac{d}{d_0} + X_\sigma \tag{4}$$

In [24], it is known that $PL(d_0)$ is related with the working band and environment factors. $PL(d_0)$ does not have the concrete formula and usually is obtained by the experience value. Based on literature [25], we can get $\eta_2 \in [1, 7], \sigma \in [2, 14]$. But for CCl100 radio frequency module, when the center frequency is 439.15 MHz, the data transfer rate is 500kbps and the receiving sensitivity is -88dBm. According to the actual measurements, the typical value of η_2 is 3 (indoor, outdoor) and that of σ is 5 (outdoor) or 7 (indoor).

Based on $X_\sigma \sim N(0, \sigma^2)$ and the generic 3σ principle from gaussian distribution, we derive

$$P_r(d) - P_s(d) + PL(d_0) + 10\eta_2 \lg \frac{d}{d_0} \sim N(0, \sigma^2) \tag{5}$$

Hence, we can get:

$$P_{r\_\min} = P_s(d) - PL(d_0) - 10\eta_2 \lg\frac{d}{d_0} - 3\sigma \tag{6}$$

$$P_{r\_\max} = P_s(d) - PL(d_0) - 10\eta_2 \lg\frac{d}{d_0} + 3\sigma \tag{7}$$

where $P_{r\_\min}$ and $P_{r\_\max}$ are the minimum and maximum received signal strength respectively. According to Eq. (6) and Eq. (7), we can derive P_r as following:

$$P_r \propto -10\eta_2 \lg\frac{d}{d_0} \tag{8}$$

Since η_2 and d_0 are constants, we have

$$DOI \propto -d \tag{9}$$

As defined, d is the average distance between the sender and receiver, which is called the average communication distance. Therefore, the average communication distance is directly impacted by DOI. d decreases as the value of DOI increasing, as shown in **Fig. 1**. The circular area is the real communication range, while the area with an irregular shape is the realistic radio range.

4. The Impact Of Radio Irregularity On Message Receiving Probability

4.1 The Modified Radio Range

Radio irregularity greatly influences localization performance. Take one range-free localization scheme, e.g., DV-HOP [26], for example. In DV-HOP, the anchor nodes flood their locations throughout the whole network. Any unknown node receiving the package records its hop-count to the corresponding anchor nodes. Then using the recorded hop-counts, the average distance per hop and the anchor nodes' locations, each unknown node can figure out its own location. However, the radio range is irregular, and the communication ranges do not have an invariant value in different propagation directions. The estimated distance of each hop is impacted by DOI. Therefore, it is misleading to calculate the distance between an unknown and an anchor node based on the hop-count and the average distance per hop.

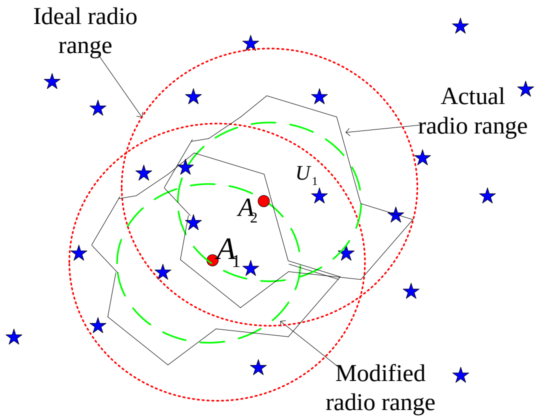


Fig. 2. The impact of radio irregularity on localization

For the idealistic circular radio propagation, localization method generates regular radio range for all nodes. However, under realistic operating environment, the radio ranges among communicating nodes are irregular. As shown in **Fig. 2**, the unknown node U_1 cannot receive message of the anchor node A_1 in irregular radio model. Consequently, the estimated distance between the unknown and anchor node contains much larger errors, and thus localization performance is greatly affected.

In order to obtain reliable distance estimation, it is critical to select a regular radio range for the communicating nodes. Accordingly, it is essential to adjust the anchor node' radio range to guarantee that unknown nodes within the range can receive enough data packets. In this paper, when the realistic radio range is R, the modified radio range is defined as $R \times (1 - DOI)$, and the distance between two neighbor anchor nodes is $R \times (1 - DOI)$. In the process of localization, the modified radio range is used instead of the realistic one. The idea is to constrain unknown nodes within an optimal range, thus all the unknown nodes are within the modified radio range and can receive at least three messages from anchor nodes. Then, we compute the estimated locations of the unknown nodes using the equilateral triangle.

4.2 The Message Receiving Probability Under Radio Irregularity

The irregular radio model is considered to reflect the real sensor networks. We introduce a DOI to denote the irregularity of radio pattern in [21]. In such a radio environment, in order to guarantee reliable communication between $[R \times (1 - DOI), R]$, three scenarios are possible: symmetric communication, unilateral communication and no communication. The study in [22] gave detailed analysis of irregular radio propagation and its impact on localization.

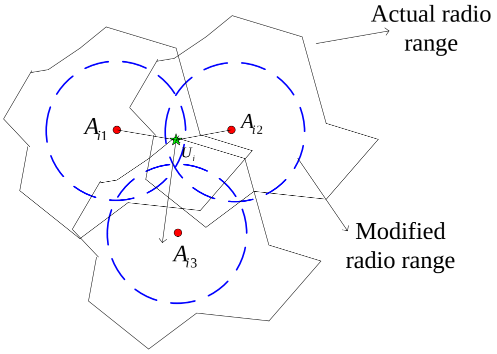


Fig. 3. 1-hop localization under radio irregularity

As shown in **Fig. 3**, we assume A_i is an anchor node that bi-directionally communications with an unknown node U_i. For any anchor node A_i, if U_i and A_i cannot communicate with each other, the unknown node cannot be localized. We use the distance between A_i and U_i to determine whether U_i falls into the radio range of A_i.

If the Euclid distance $d(U_i, A_i) < R \times (1 - DOI)$, the receiving probability $p_i = 1$. If $d(U_i, A_i) > R$, $p_i = 0$. For any nodes with distance $R \times (1 - DOI) \le d(U_i, A_i) \le R$, $p_i \sim U(0,1)$ is randomly distributed within [0, 1]. The receiving probability $p_i = 1$ means that the unknown node can be reliable to communicate with anchor nodes. Otherwise, their communication is uncertain.

Elfes [27] proposed that the coverage probability is $e^{-\lambda\alpha^{\beta}}$, when $R-\delta < d(U_i, A_i) < R+\delta$. δ is the measurement error deviation. $\alpha = d(U_i, A_i) - (R-\delta)$. λ and β are parameters that measure detection probability when an unknown node located within the anchor node's radio range. The one-hop neighbor anchor nodes set is denoted as S $(\forall A_i \in S)$. The lower and upper bound of the radio irregularity are denoted as $R\times(1-DOI)$ and R respectively. Based on the coverage probability model, we define the following receiving probability to represent the effectiveness of communication:

$$\begin{cases} 0, & \exists A_i \in S, d(U_i, A_i) > R \\ 1, & \forall A_i \in S, d(U_i, A_i) < R\times(1-DOI) \\ e^{-\lambda\alpha^{\beta}}, & \forall A_i \in S, R\times(1-DOI) \le d(U_i, A_i) \le R \end{cases} \tag{10}$$

The anchor nodes can be divided into two categories. For the first category, the distance between an unknown node and anchor nodes is within the lower and upper bounds. For second category, the distance between an unknown node and anchor nodes is beyond the lower and upper bounds. Then we can calculate the message receiving probability of three anchor nodes according to Eq. (11). It is clear that if there is an unknown node whose distance to the anchor node is greater than the upper bound of the radio irregularity, then this unknown node cannot receive the message packet.

$$p_i = \begin{cases} 0, & \exists A_i \in S, d(U_i, A_i) > R \\ 1, & \forall A_i \in S, d(U_i, A_i) < R\times(1-DOI) \\ 1-(1-e^{-\lambda\alpha_{Ai1}^{\beta}})(1-e^{-\lambda\alpha_{Ai2}^{\beta}})(1-e^{-\lambda\alpha_{Ai3}^{\beta}}), & \\ \{\forall A_{i1} \in S, R\times(1-DOI) \le d(U_i, A_{i1}) \le R\} & \\ \cup\{\forall A_{i2} \in S, R\times(1-DOI) \le d(U_i, A_{i2}) \le R\} & \\ \cup\{\forall A_{i3} \in S, R\times(1-DOI) \le d(U_i, A_{i3}) \le R\} & \\ 1-(1-e^{-\lambda\alpha_{Ai2}^{\beta}})(1-e^{-\lambda\alpha_{Ai3}^{\beta}}), & \\ \{\forall A_{i1} \in S, d(U_i, A_{i1}) < R\times(1-DOI)\} & \\ \cup\{\forall A_{i2} \in S, R\times(1-DOI) \le d(U_i, A_{i2}) \le R\} & \\ \cup\{\forall A_{i3} \in S, R\times(1-DOI) \le d(U_i, A_{i3}) \le R\} & \end{cases} \tag{11}$$

5. 2-hop localization

5.1 The Proposed 2-Hop Localization Scheme

In LMAT, the localization error is reduced by having the mobile anchor node travel along an optimal refined trajectory. The optimal equilateral triangle trajectory is shown in Fig.4. In that case, unknown nodes can receive more beacons. However, the mobile anchor node traverses the network only once; some unknown nodes cannot be localized. That is, when the mobile anchor node travels along a very coarse trajectory, a certain number of unknown nodes cannot receive any beacons, because they are far away from the trajectory. Therefore, in order to make sure that all the unknown nodes can be localized, the 2-hop localization algorithm is adopted.

The idea of 2-hop localization scheme was proposed by Dimitrios *et al.* in [28]. In the 2-hop localization, unknown nodes that receive beacons directly from the mobile anchor node firstly estimate their locations, and then broadcast beacons with their own position information. In this way, unknown nodes that are far away from the mobile anchor node can localize themselves by using beacons emitted by other unknown nodes. However, the 2-hop localization algorithm does not remove the accumulative localization error. Since the estimated positions of the unknown nodes, which provide their position information for neighbor nodes, already contain some localization errors.

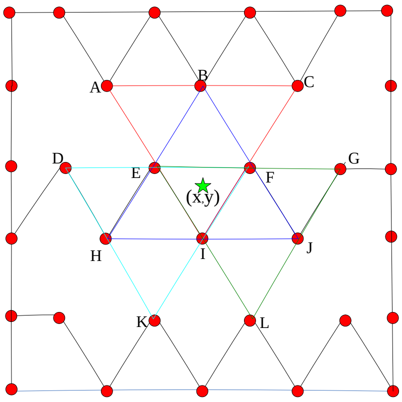


Fig. 4. 2-hop localization

In order to avoid the impact of the accumulative localization error, we propose a new 2-hop localization scheme based on LMAT localization scheme. In our new 2-hop localization scheme, the mobile anchor node's radio range is increased from R to $2R$. Therefore, the unknown nodes can use the 2-hop beacons to localize themselves. As shown in **Fig. 4**, around the unknown node (x, y), the anchor node's position for sending localization information can form four triangulation ($\Delta ACI, \Delta BHJ, \Delta DFK, \Delta EGL$). Based on each triangulation, the unknown node can calculate an estimate position (x_i, y_i) by trilateration method, where $i = 1, 2, 3, 4$. Then the estimated coordinates (x, y) of unknown node is $(\frac{x_1 + x_2 + x_3 + x_4}{4}, \frac{y_1 + y_2 + y_3 + y_4}{4})$.

Obviously, compared with the 1-hop localization scheme, e.g., LMAT, our 2-hop localization scheme can localize more unknown nodes. Furthermore, compared with the conventional 2-hop localization scheme [28], which uses position information of localized neighbor nodes to localize the unknown nodes that cannot receive beacons from anchor nodes, our 2-hop localization scheme uses beacons directly from the mobile anchor node to localize all unknown nodes. Therefore, our 2-hop localization scheme has no accumulative error. Without the influence of accumulative error, the unknown nodes' localization accuracy will be improved.

5.2 The Message Receiving Probability In 2-Hop Localization Scheme

In Eq. (11), we only consider one-hop anchor nodes. But in our localization algorithm, we use the observations from both one-hop and two-hop anchor nodes. The two-hop neighbor anchor nodes set is denoted as T, then the results of receiving probability in Eq. (11) is partially changed. The receiving probability is zero, if there is an anchor node in T whose distance to the unknown node is greater than the double radio range, that is:

$$\forall B_i \in T, d(U_i, B_i) > 2R \tag{12}$$

The receiving probability will be equal to 1 if the following condition satisfies:

$$\forall B_i \in T, d(U_i, B_i) < 2R \times (1 - DOI) \tag{13}$$

For a more constrained condition:

$$\begin{aligned}
&\{\{\forall A_{i1} \in S, R \times (1-DOI) \le d(U_i, A_{i1}) \le R\} \\
&\cup \{\forall A_{i2} \in S, R \times (1-DOI) \le d(U_i, A_{i2}) \le R\} \\
&\cup \{\forall A_{i3} \in S, R \times (1-DOI) \le d(U_i, A_{i3}) \le R\} \wedge \\
&\{\exists B_{i1} \in T, 2R \times (1-DOI) \le d(U_i, B_{i1}) \le 2R\} \\
&\cup \{\forall B_{i2} \in T, 2R \times (1-DOI) \le d(U_i, B_{i2}) \le 2R\} \\
&\cup \{\forall B_{i3} \in T, 2R \times (1-DOI) \le d(U_i, B_{i3}) \le 2R\}
\end{aligned} \tag{14}$$

The receiving probability will be a value less than 1 which we define as:

$$\begin{aligned}
p_i = {} & [1-(1-e^{-\lambda \alpha_{Ai1}^{\beta}})(1-e^{-\lambda \alpha_{Ai2}^{\beta}})(1-e^{-\lambda \alpha_{Ai3}^{\beta}})] \\
& \times [1-(1-e^{-\lambda \alpha_{Bi1}^{\beta}})(1-e^{-\lambda \alpha_{Bi2}^{\beta}})(1-e^{-\lambda \alpha_{Bi3}^{\beta}})]
\end{aligned} \tag{15}$$

6. Simulation Parameters

This section describes the simulation parameters used in our evaluation. We use the NetTopo WSNs simulator [29] to check the impact of radio irregularity on localization algorithm.

Radio Model: Some previous work in localization assumes that a perfect circular radio model exists. As stated before, empirical studies [21] have shown that this assumption is invalid for WSNs. To ensure that our evaluation is as practical as possible, we use a more realistic radio model in our evaluation, which is denoted by DOI. It is defined as the maximum radio range variation per unit degree change in the direction of radio propagation. When the DOI is set to zero, there is no range variation, resulting in an idealistic circular radio model.

Placement Model: In our simulations, there is one mobile anchor node for LMAT. Unknown nodes are distributed in a rectangular terrain in accordance with the predefined density. Two common placement strategies are investigated, namely random and uniform (Grid, Ring) placement. Random placement distributes all the unknown nodes randomly throughout the WSN. Uniform placement distributes all the unknown nodes uniformly throughout the WSN. In the scenarios, unknown nodes are static and a mobile anchor moves around them. The speed of the mobile anchor is a constant and equal to 2 m/s. The number of sensor nodes is 50.The network size is $400 \times 400m^2$.

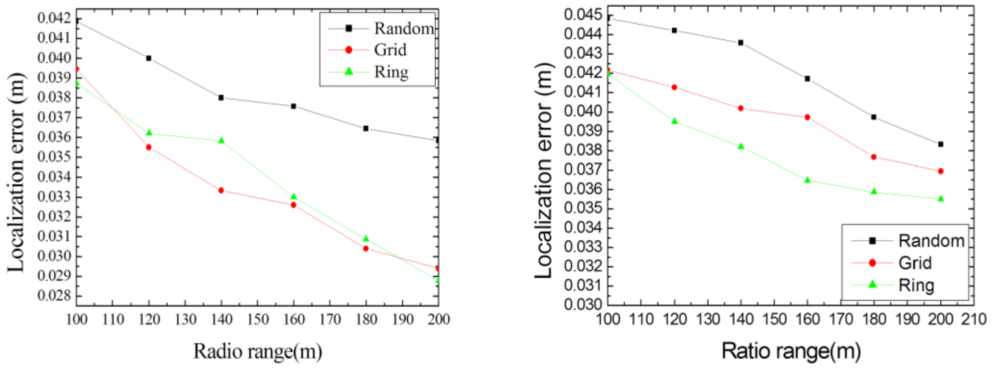
Simulation Parameters: To quantify the performance of the proposed algorithm, we use localization error to denote localization accuracy, which is defined as the average distance deviation between an unknown nodes real position and calculated position divided by the communication radius. We performed two different sets of simulations. In the first set experiment, we study several parameters' impact on the localization error. The parameters are: 1) the anchor nodes' radio range R, 2) DOI and 3) Trajectory Resolution (TR), which is the distance between the neighbor position where the anchor node sending message. In the second experiment, we evaluate the localization accuracy of LMAT and the 2-hop localization scheme.

7. Simulation Results

7.1 Localization error and R

We set $TR = 50m$, $DOI = 0.2$ and $DOI = 0.6$ in **Fig. 5(a)** and **Fig. 5(b)** respectively. **Fig. 5** shows that the localization error decreases as the radio range increases. Since for unknown nodes, the number of received messages increases as the radio range increases. For example, in **Fig. 5(a)**, when $R = 100m$ and the placement is random, the localization error is 0.04187m. But when R increases to 160m, the localization error decreases to 0.03758m.

Furthermore, the localization error is different under different placements. For example, the localization error of random placement is greater than uniform placement. Since some unknown nodes in random placement are on the border of the deployment area and three beacon positions on the border of the deployment area do not form equilateral triangle, thus the localization error of unknown node is higher. Compare **Fig. 5(a)** with **Fig. 5(b)**, and it shows that the localization error increases as DOI increases.

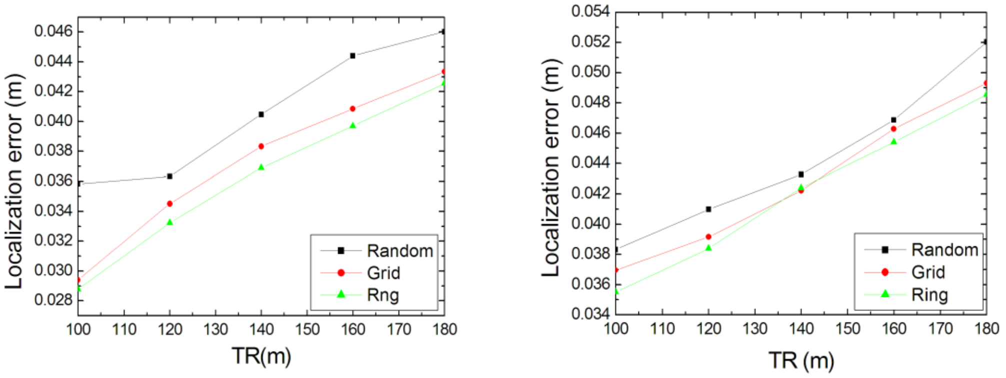


(a) DOI=0.2 (b) DOI=0.6

Fig. 5. Localization error vs. R

7.2 Localization Error And TR

We set $R = 200m$, $DOI = 0.2$ and $DOI = 0.6$ in **Fig. 6(a)** and **Fig. 6(b)** respectively. **Fig. 6** shows the impact of TR on the localization accuracy. We can see that localization error increases as the TR increases. Since the radio range is fixed, the received message of unknown nodes will decreases as the TR increases. For example, in **Fig. 6(a)**, when $TR = 100m$ and the placement is random, the localization error is 0.038m. But when TR increases to 180m, the localization error increases to 0.046m. Compare **Fig. 6(a)** with **Fig. 6(b)**, and it shows that the localization error increases as DOI increases.

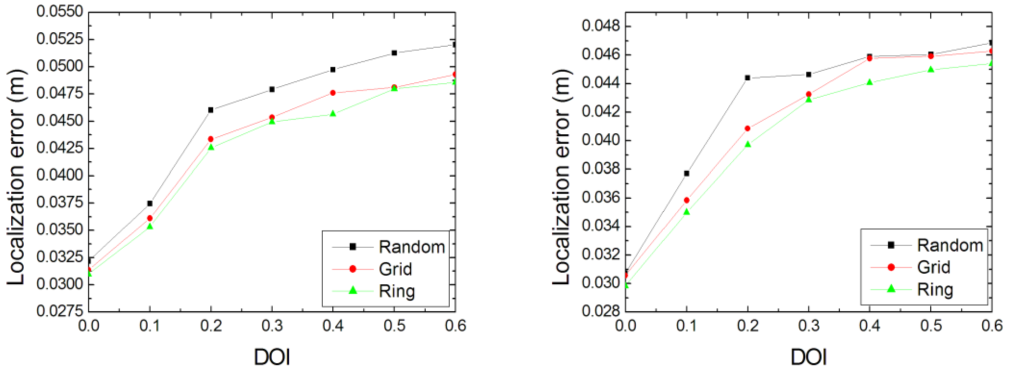


(a) DOI=0.2 (b) DOI=0.6

Fig. 6. Localization error vs. TR

7.3 Localization Error And DOI

We set $TR = 50m$, $R = 100m$ and $R = 200m$ in **Fig. 7(a)** and **Fig. 7(b)** respectively. **Fig. 7** shows that the localization error increases as DOI increases. The anchor node's radio range is not isotropic and does not have an invariant value in different propagation directions. Larger DOI values lead to less localization messages and more inaccurate calculated distance. For example, in **Fig. 7(a)**, when DOI is 0 and the placement is random, the localization error is 0.0325m. When DOI increases to 0.8, the localization error increases to 0.0523m. Compare **Fig. 7(a)** with **Fig. 7(b)**, and it shows that the localization error decreases as R increases.



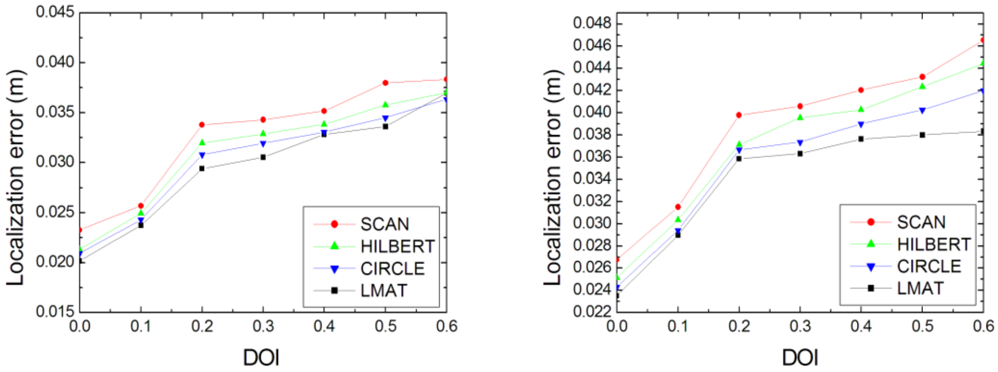
(a) $R = 100m$ (b) $R = 200m$

Fig. 7. Localization error vs. DOI

7.4 Localization Error Of LMAT

We compare the performance of LMAT with that of other three schemes: CIRCLE [5], SCAN [6] and HILBERT [6] algorithm. As shown in **Fig. 8**, it is obvious that the performance of the

LMAT algorithm is better than those of other algorithms, since LMAT has the least localization error. In **Fig. 8(a),** the unknown nodes are uniformly deployed, and in **Fig. 8(b),** the unknown nodes are randomly deployed.



(a) Uniformly deployed (b) Randomly deployed

Fig. 8. Comparison of localization error vs. DOI

7.5 Localization Error Of The 2-Hop Localization Scheme

When the unknown nodes randomly deployed, **Fig. 9** shows the average localization error with different DOI for the 1-hop and the 2-hop localization schemes. In the 2-hop localization scheme, many unknown nodes can receive beacons from the mobile anchor node. Thus, the average localization error of the 2-hop localization scheme is smaller than that of the 1-hop localization scheme about 20.51%.

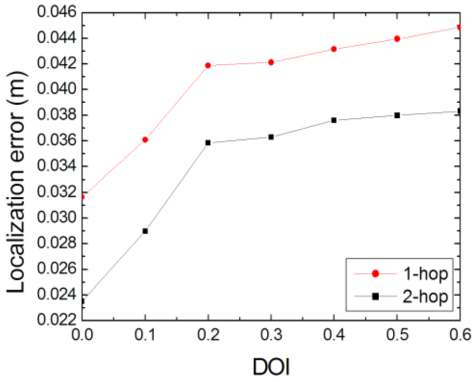


Fig. 9. Comparison of localization error vs. DOI

8. Conclusion

In order to evaluate the impact of radio irregularity on localization accuracy, this paper studied fundamental issues such as the relationship between DOI and communication distance, the impact of radio irregularity on message receiving probability. We also ran a number of simulations and found that the increasing DOI and TR lead to larger localization error, while increasing R leads to smaller localization error. Furthermore, we proposed the modified radio range and the 2-hop localization scheme to reduce localization error. Compared with 1-hop localization scheme, our 2-hop localization scheme has better localization performance. Simulations show that the proposed algorithm is able to substantially improve localization accuracy.

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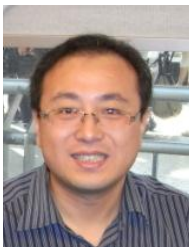

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