Impact of Irregular Radio and Faulty Nodes on Localization in Industrial WSNs

Xiaoman Ran[1,2], Lei Shu[2,3](✉), Mithun Mukherjee[2], Yuntao Wu[1], Yuanfang Chen[2], and Zhihong Sun[1,2]

[1] School of Computer Science and Technology, Wuhan Institute of Technology, Wuhan 430205, Hubei, China
xiaoman.Ran@outlook.com, ytwu@sina.com, zhihong.sun2016@outlook.com
[2] Guangdong Provincial Key Lab of Petrochemical Equipment Fault Diagnosis, Guangdong University of Petrochemical Technology, Maoming 525000, China
{lei.shu,m.mukherjee,yuanfang_chen}@ieee.org
[3] School of Engineering, University of Lincoln, Lincoln, UK

Abstract. Location information of nodes is one of the basis for many applications in Wireless Sensor Networks (WSNs). In this paper, based on the implementation of the original DV-Hop localization algorithm and two variations: DV-Hop with Correction (CDV-Hop) and Improved DV-Hop (IDV-Hop), we investigate the impact of Irregular Radio and Faulty Nodes on the performance of localization. This study designs a new system model by considering Irregular Radio and random Faulty Nodes. With this new model, extensive experiments are used to conduct the investigation. From the simulation results, it is observed that both Irregular Radio and Faulty Nodes adversely affect the localization accuracy. By this investigation, the obtained conclusion can be used to direct localization algorithm design under a more realistic scenario and providing better parameter configuration for a given WSN.

Keywords: Industrial wireless sensor networks · Localization
Irregular radio · Faulty nodes

1 Introduction

Location information of sensor nodes add significant value to many applications, including military surveillance, environmental monitoring and indoor tracking [1–3]. To estimate the location of sensor nodes, a few global positioning system-equipped sensor nodes are deployed with known geographic location. These nodes are called as anchor nodes that are used to estimate the location of unknown nodes. Existing localization algorithms are broadly categorized into *range-free* [4] and *range-based* architectures [5]. An absolute point-to-point distance or angle estimation between neighbor nodes are required in range-based localization. Most of these range-based algorithms exploit received signal strength indicator (RSSI) [6], time of arrival (ToA) [7], time difference on arrival (TDoA) [8], and angle of arrival (AoA) [9]. These schemes provide

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higher localization accuracy, however, additional hardware for distance measurement results in high cost for large-scale IWSNs. Since range-free techniques do not use signal strength, they are more robust to noise and fading. There are several range-free localization algorithms, such as Centroid [10], distance vector-hop (DV-Hop) [11], Amorphous [12] and approximate point-in triangulation test (APIT) [4]. DV-Hop is a distributed algorithm, and is easy to implement. However, the localization accuracy of DV-Hop needs to be improved. So in this paper, we focuses on the performance of DV-Hop and two variations of DV-Hop: DV-Hop with correction (CDV-Hop) [13] and improved DV-Hop (IDV-Hop) [14]. Meanwhile, none of previous schemes have considered the situation where nodes are radio irregular and random failure. The generic DV-based localization methods are not high-precision in this situation, because the connectivity of networks will be greatly affected due to nodes' radio irregular and random failure. As we can see from the Fig. 2, the communication between any pair of nodes will be affected dramatically. Therefore, the impact of irregular radio and faulty nodes on the performance of localization needs to be studied.

The rest of this paper is organized as follows: Sect. 2 briefly presents the related work on localization algorithms with irregular radio and random faulty nodes. Section 3 presents our system model. In Sect. 4, DV-Hop family-based localization algorithms are discussed. The simulation results are presented in Sect. 5. Finally, conclusions are drawn in Sect. 6.

2 Related Work

2.1 Range-Based Localization Schemes

Several range-based techniques have been proposed for WSNs, such as received signal strength indicator (RSSI) [6], time of arrival (ToA) [7], time difference on arrival (TDoA) [8], and angle of arrival (AoA) [9]. With hardware limitations and inherent energy constraints of sensor nodes, TOA-based localization methods are costly. The TDOA estimates the distance between two communicating nodes using peripheral equipment. AHLos [15] is a TDOA-based work, and it employs the TDOA technology in infrastructure-free sensor network. Like TOA, the TDOA has same problem, and further, it relies on extensive hardware which makes it less suitable for networks with low-power sensor nodes. As an augment of TDOA and TOA technologies, the AOA is proposed and it allows nodes to estimate and map relative angles between two nodes. Moreover, the AOA also requires extra hardware and this is too expensive to be used in large scale sensor networks. The RSSI technology (e.g., RADAR [16]) is used in hardware-constrained systems widely and its basic idea is to translate signal strength into distance estimation. When the environment is controllable (e.g., laboratory environment), and only when distance can be determined using signal strength, propagation patterns, and fading models, RSSI-based methods can work well.

2.2 Range-Free Localization Schemes

The range-free approaches do not require any distance or orientation information between nodes for localization. Network connectivity is enough for localization of unknown nodes. Although estimation accuracy is lower than range-based algorithms, the simple and cost-effective features in range-free algorithms draws significant attention in localization algorithms. Several algorithms like approximate point-in triangle test (APIT) [4], centroid [10], Amorphous [12], and distance vector-hop (DV-Hop) [11] algorithms are proposed to improve the estimation accuracy in range-free algorithms. In APIT, an unknown node is identified by the possible triangles that enclose its location, thereafter, obtaining the center of gravity of overlapping area of triangles. The localization accuracy of APIT [4] and Centroid [10] depends largely on anchor node density and transmission radius of the sensor nodes. Amorphous [12] employs more complex ways of calculating the minimum hop-counts between the sensor nodes and estimating the average hop-distance, however, requires an estimation of the average sensor node density of the WSNs.

Niculescu and Nath proposed a distributed algorithm, called DV-Hop localization [11], which is a hop-by-hop localization algorithm. In this algorithm, at first, each node counts the minimum hop number to the anchor node and then computes the distance between the anchor node and itself by multiplying minimum hop number and average hop-distance. The node finally estimates its position using either triangulation algorithm or maximum likelihood estimators (MLE) [17]. The DV-based localization algorithms are easy to implement, however, the location accuracy is one of the major challenges. To improve the estimation accuracy, Kumar and Lobiyal [18] proposed an algorithms that refines the hop-count of anchor nodes. In addition this scheme significantly reduces time and energy consumption in localization. Chen et al. [14] proposed an improved scheme to estimate hop-distance according to the number of the neighbors that belong to the same *block*. An weighted node distance was introduced to estimate the node's location.

A differential error correction scheme was proposed in [19] to improve the estimation accuracy in traditional DV-based algorithms. This scheme reduced the cumulative distance error and node location error accumulated over the multiple hops. However, high computation and communication overhead are main drawback of this scheme. Another DV-based algorithm was suggested in [20] with a correction in location estimation. Further, the estimation accuracy was improved in [14] where the anchor node broadcasts the corrected hop-distance that is the average of all anchor nodes hop-distances to the network as correction. This scheme uses 2-dimensional Hyperbolic localization algorithm instead of using the traditional triangulation to calculate the final position of a node. Gui et al. [21] discussed Checkout DV-hop algorithm that estimates the mobile node position by utilizing the nearest anchor. To improve localization accuracy, Selective 3-Anchor DV-hop algorithm was proposed to choose the best 3 anchors.

2.3 Irregular Radio and Faulty Nodes

Irregular Radio. In order to approach the real environment, we consider the irregular radio of node. In [4], He et al., for the first time, proposed an irregular radio range model: DOI model which assumes the upper bound and lower bound on the radio propagation range and three communication scenarios: (i) symmetric communication, two nodes in the communication range with each other; (ii) unidirectional & asymmetric communication, one node within another node's communication range and the another node is not in the communication range of the one node and (iii) no communication, two nodes are without the communication range of each other. However, the DOI model does not take the interacting of nodes into account. And then the paper [22] extends the DOI model considering the radio interference among sensor nodes and the new model is called as radio irregularity model (RIM) which is based on experimental results that are made with a pair of MICA2 nodes, and the RIM is used to analyze the impact of radio irregularity on MAC and routing protocols. As shown in the Fig. 1, when the DOI is zero, there is no range variation, and the communication range is a perfect circle, when we increase the value of DOI, the communication range becomes more and more irregular.

Faulty Nodes. The sensor nodes in the IWSNs have simple structure and limited energy, so they may go to fault due to environment interference and energy depletion, in this situation, it will brings about a direct impact on the accuracy, integrity and timeliness of the network monitoring, sometimes even lead to the collapse of the network. The research of faulty nodes has attracted people's attention and can be roughly divided into two aspects: (1) to prevent the failure of node in the beginning of network deployment, such as the use of multiple node coverage and multiple connectivity to improve network survivability, or to designing the topology control algorithm to reduce the energy loss in the data transmission [23]; (2) to detect and repair the faulty nodes, to judge the faulty node type in the process of network operation [24].

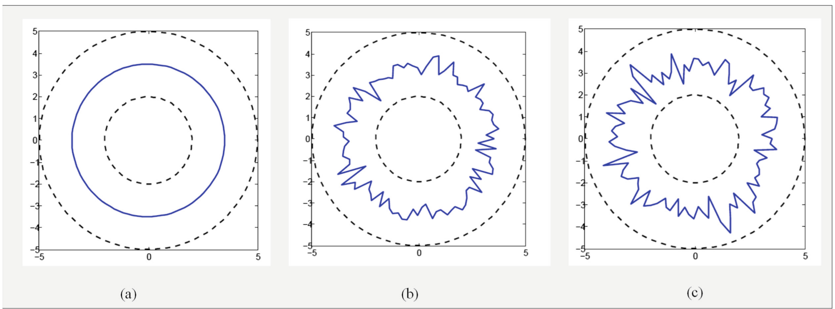

Fig. 1. Degree of irregularity: (a) DOI = 0, (b) DOI = 0.003, (c) DOI = 0.01

3 System Model

3.1 Network Model

We consider a multihop WSN with uniformly and randomly deployed sensor nodes in a large-scale 2-dimensional sensing field. Let $G = (S, L)$ be a network graph, where S and $L = \{l(1,2), l(1,3), \ldots, l(N,N)\}$ are the set of sensor nodes with total N number of sensor nodes and the set of edges between sensor nodes, respectively. The deployed sensor nodes consist of anchor nodes $S_{\text{anchor}} = \{s_{a,1}, s_{a,2}, \ldots, s_{a,N_{\text{anchor}}}\}$ and unknown nodes $S_{\text{unknown}} = \{s_{u,1}, s_{u,2}, \ldots, s_{u,N_{\text{unknown}}}\}$, where N_{anchor} and N_{unknown} are the number of anchor nodes and unknown nodes, respectively and $N = N_{\text{anchor}} + N_{\text{unknown}}$. In this research work, bi-directional communication between neighbors is considered. It is supposed that the industrial sensor nodes can harvest energy from environment by using additional device, e.g., solar power panel. In addition, the situation with a strong wind and the wind direction has not been taken into account in this paper.

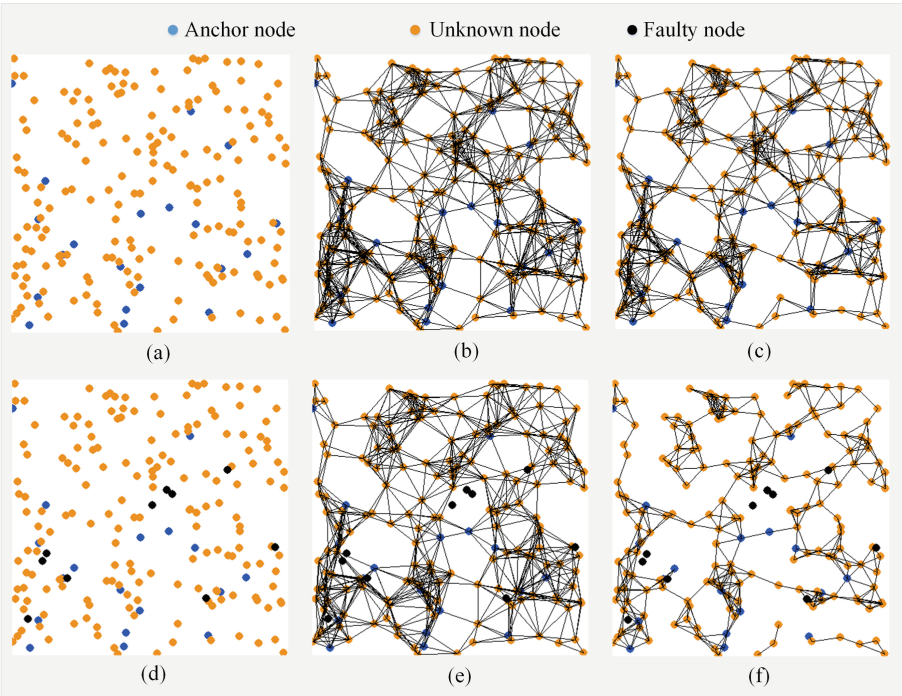

Fig. 2. An illustration of connectivity in an area of 600×600 m^2 with total 200 number of sensor nodes. (a) Ideal network, (b) Connectivity in ideal network, (c) Connectivity with irregular radio (DOI = 0.3), (d) Network with 5% faulty nodes, (e) Connectivity with 5% faulty nodes, and (f) Connectivity with irregular radio (DOI = 0.3) and 5% faulty nodes.

3.2 Irregular Radio and Faulty Nodes Model

Irregular Radio. In real environment, node's transmit power varies in different directions due to non-isotropic nature of electromagnetic transmission, path-loss, noise, and temperature. Thus, irregular radio results in link asymmetry, thereafter, affects the performance of localization in IWSNs. As shown in Fig. 2(b) and (c), it is easy to see that the connectivity of the network is reduced when the irregular radio is taken into consideration.

Faulty Nodes. In this paper, we have considered the case that the sensor nodes cannot work properly due to various natural (e.g., earthquakes and fires) or their own (e.g., energy depletion and hardware failure) reasons. Considering the robustness of our localization algorithm, we need to ensure that the accuracy of localization cannot be affected by random faulty nodes. Besides, we have investigated the combined influence of both random faulty nodes with irregular radio on the localization algorithms. Faulty nodes will affect the connectivity of the network. As shown in the Fig. 2(b) and (e), when the network is ideal, all sensor nodes within the transmission region R can communicate with each other freely, but in the Fig. 2(d), when we take the faulty nodes into consideration, the connectivity of network will be greatly influenced.

3.3 Localization Error Model

A localization error is calculated as the deviation between node's actual coordinate (x_i, y_i) and estimated coordinate $(x_i{'}, y_i{'})$ and is expressed as $\sum_{i=1}^{N_{\text{unknown}}} \frac{\Delta d_i}{R \times N_{\text{unknown}}}$, where $\Delta d_i = \sqrt{(x_i - x_i{'})^2 + (y_i - y_i{'})^2}$.

4 DV-Hop Family-Based Localization Algorithms

4.1 DV-Hop Localization Algorithm

Traditional DV-Hop algorithm [11] has the following steps:

1. *Step 1: A Distance-vector Exchange:* By broadcasting the location information over the network, all anchor nodes get the distance and hops to the other anchor nodes. In addition, all unknown nodes obtain the hop-counts to the nearest anchor node.
2. *Step 2: Calculate Average Hop-distance:* To convert hop count into physical distance, the average hop-distance for any anchor node $S_{a,i}$ with coordinates (x_i, y_i) is estimated by

$$\text{HopDistance}_i = \frac{\sum \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}}{\sum h_{ij}} (i \neq j), \tag{1}$$

   where h_{ij} is the number of hops between the anchor node $S_{a,i}$ and $S_{a,j}$. Then, the estimated average hop-distance is broadcasted over the network.

3. *Step 3: Estimation of Unknown Node's Location:* Each unknown node calculates its location (x, y) using the equation-set as:

$$\begin{cases} \sqrt{(x - x_1)^2 + (y - y_1)^2} = d_1 \\ \sqrt{(x - x_2)^2 + (y - y_2)^2} = d_2 \\ \quad \cdots \\ \sqrt{(x - x_n)^2 + (y - y_n)^2} = d_n \end{cases}, \tag{2}$$

where $d_i = K_i \times \mathrm{HopDistance}_i$ is the distance between the anchor nodes and the unknown nodes with hop-count K_i. Finally, traditional Triangulation algorithm is applied to obtain the location of unknown nodes.

4.2 CDV-Hop Localization Algorithm

The d_i in *Step 3* of traditional DV-Hop algorithm is improved with a correction factor c_i in DV-Hop with correction (CDV-Hop) [13] localization algorithm and is expressed as $d_i = K_i \times \mathrm{HopDistance}_i + c_i$, where $c_i = \dfrac{K_i \times (R - \mathrm{HopDistance}_i)}{R}$.

4.3 IDV-Hop Localization Algorithm

The estimation in localization is improved in [14], which is called improved DV-Hop (IDV-Hop) algorithm. This localization differs from *Step 2* and *Step 3* of traditional DV-Hop [11] as follows:

Step 2 of IDV-Hop. After obtaining the HopDistance using (2), each anchor node broadcasts its HopDistance value in a message to network. Each unknown node stores the HopDistance received from different anchor nodes. This process ends when unknown does not receive any HopDistance messages after a certain period of time. At the end of this process, each unknown node stores the HopDistance received from the anchor nodes in S_{anchor}.

Step 3 of IDV-Hop. Each unknown nodes calculate the average $\mathrm{HopDistance}_{\mathrm{avg}}$ by the formula:

$$\mathrm{HopDistance}_{\mathrm{avg}} = \frac{\sum_{i=1}^{n} \mathrm{HopDistance}_i}{n}, \tag{3}$$

where n is the number of anchor nodes it can hear. Each unknown nodes calculate the distance to the anchor nodes based on its $\mathrm{HopDistance}_{\mathrm{avg}}$ and hops to the anchor nodes using $d_i = K_i \times \mathrm{HopDistance}_{\mathrm{avg}}$. Finally, 2-D Hyperbolic location algorithm [14] is used instead of triangulation algorithm as in the traditional DV-Hop algorithm to estimate the coordinates of unknown nodes.

5 Simulation Results

In this section, we evaluate the impact of (a) irregular radio, (b) faulty nodes, and (c) irregular radio with faulty nodes on the performance of DV-Hop family-based localization algorithms in IWSNs. We also compare the performance of various DV-Hop family-based algorithms with irregular radio and faulty nodes.

Table 1. Simulation parameters

Parameters	Values
Network size	$600 \times 600\,\text{m}^2$
Default anchor node density	10%
Default transmission radius (R)	60 m
Total number of sensor nodes	300 to 1000 (with a step 100)
DOI	0 to 0.8 (with a step 0.1)
Faulty node percentage	0% to 18% (with a step 6%)

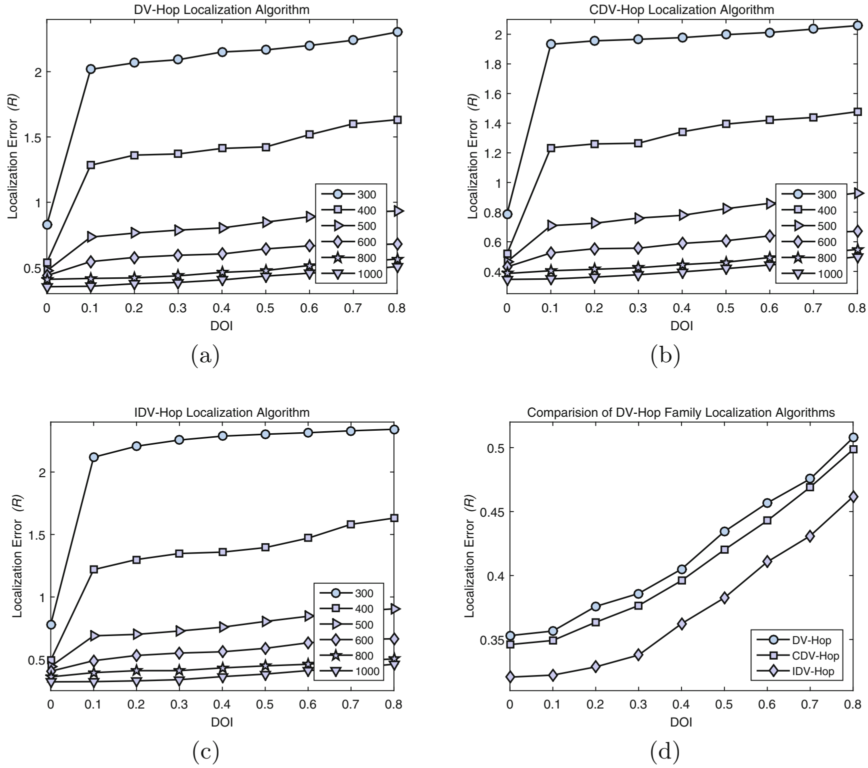

Fig. 3. Performance of localization error in various deployed total sensor nodes with different DOI values of irregular radio in (a) traditional DV-Hop, (b) CDV-Hop, and (c) IDV-Hop localization algorithms. (d) Performance comparison of different DV-Hop family-based localization algorithms with total 1000 nodes.

Simulation Setup: We conducted extensive simulations using WSN simulator NetTopo[1]. We average the localization error over 100 different network topologies. The simulation parameters are summarized in Table 1.

5.1 Impact of Irregular Radio

Figure 3 illustrates the impact of irregular radio on the performance of traditional DV-Hop, CDV-Hop, and IDV-Hop localization algorithms. From Fig. 3(a)–(c), we observe that the localization error increases with the increase of DOI for all three localization algorithms. The impact of irregular radio is more when the number of deployed sensor node is less than total 500 nodes. There is no significant change in estimation error beyond total 500 nodes for all localization

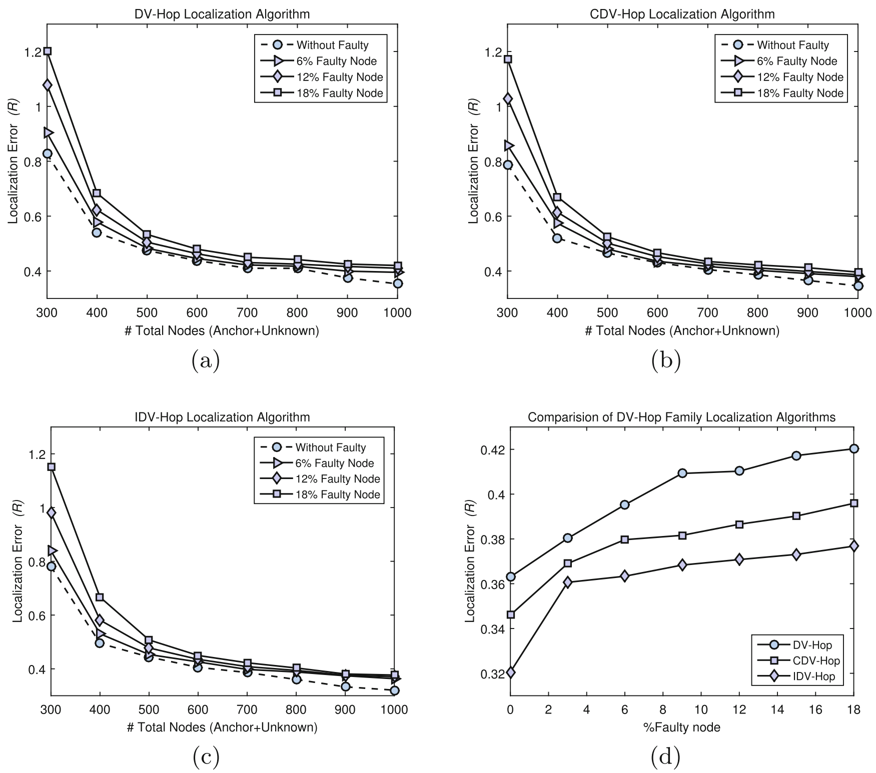

Fig. 4. Performance of localization error in various deployed total sensor nodes with various percentages of faulty nodes in (a) DV-Hop, (b) CDV-Hop, and (c) IDV-Hop localization algorithms. (d) Performance comparison of different DV-Hop family-based localization algorithms with total 1000 nodes.

[1] NetTopo (online at http://sourceforge.net/projects/nettopo/) is an open source software for simulating and visualizing WSNs.

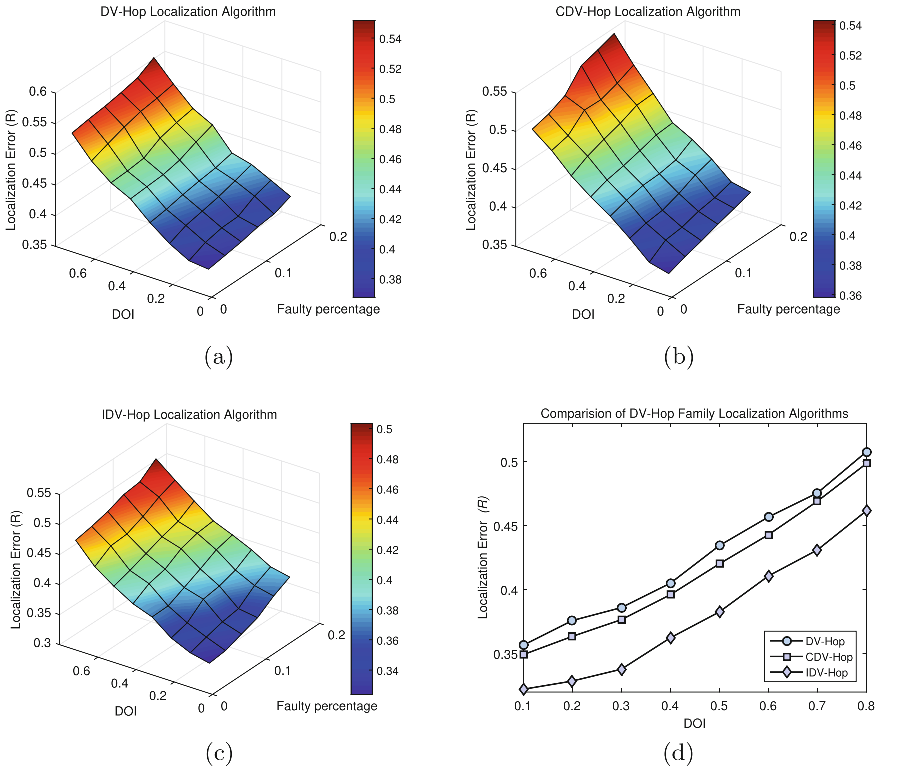

Fig. 5. Performance of localization error in various deployed total sensor nodes with various percentages of faulty nodes and DOI values in (a) DV-Hop, (b) CDV-Hop, and (c) IDV-Hop localization algorithms. (d) Performance comparison of different DV-Hop family-based localization algorithms with total 1000 nodes and 6% of faulty nodes.

algorithms due to sufficient number of anchor nodes. As expected, from Fig. 3(d), it is observed that IDV-Hop localization algorithm performs significantly better than both traditional DV-Hop and CDV-Hop localization algorithms in presence of radio irregularity with total 1000 sensor nodes.

5.2 Impact of Faulty Nodes

From Fig. 4, it is observed that increasing the faulty node percentage in DV-Hop family-based localization algorithms results in higher localization error compared to without faulty node for all of the three localization algorithms. However, the change in localization error becomes less after total 500 node deployment for the three localization algorithms. Therefore, we find the optimum deployment number as about 500 nodes without increasing the deployment cost. Furthermore, it is observed from Fig. 4(d) that CDV-Hop localization algorithm obtains lower localization error compared to traditional DV-Hop localization algorithm.

Further improvement in unknown node's location estimation is observed in IDV-Hop localization algorithm compared to CDV-Hop localization algorithm with various faulty node percentages.

5.3 Impact of Irregular Radio with Faulty Nodes

Finally, Fig. 5 shows the performance of localization error in DV-Hop family-based localization algorithms with both irregular radio and faulty nodes. The combined influence of irregular radio and faulty nodes results in link failure among unknown nodes as well as anchor nodes. As these DV-based localization algorithms strongly depend on hop-by-hop transmission, the estimate error dramatically increases with increasing values of faulty node percentage and DOI in all these DV-based algorithms. From Fig. 5(d), it is shown that IDV-Hop performs better than CDV-Hop and traditional DV-Hop localization algorithms in presence of both irregular radio and faulty nodes.

6 Conclusion

In this paper, we investigated the impact of both irregular radio and faulty nodes on DV-Hop and its two improved variations, which are called CDV-Hop and IDV-Hop localization algorithms. It has been observed that when the number of sensor nodes is less than 500, the irregular radio and faulty nodes have an adverse influence on all of three localization algorithms. However, the change in localization error is less when the deployed node is above 500. Therefore, the optimum number of sensor is found without any further deployment cost. The CDV-Hop localization algorithm provides better estimation compared to traditional DV-Hop localization algorithm in presence of irregular radio, faulty node, and combined impact of irregular radio with faulty node. Furthermore, the performance of IDV-Hop outperforms CDV-Hop localization algorithm with these realistic situations with irregular radio and faulty nodes. This study will be a useful reference to further design a new improved algorithm without losing the localization accuracy for a given deployed sensor networks under more realistic environment.

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