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An Improved DV-Hop Localization Algorithm Based on Selected Anchors

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Abstract: Wireless Sensor Network (WSN) based applications has been extraordinarily helpful in monitoring interested area. Only information of surrounding environment with meaningful geometric information is useful. How to design the localization algorithm that can effectively extract unknown node position has been a challenge in WSN. Among all localization technologies, the Distance Vector-Hop (DV-Hop) algorithm has been most popular because it simply utilizes the hop counts as connectivity measurements. This paper proposes an improved DV-Hop based algorithm, a centroid DV-hop localization with selected anchors and inverse distance weighting schemes (SIC-DV-Hop). We adopt an inverse distance weighting method for average distance amelioration to improve accuracy. Also in this paper, we propose an inclusive checking rule to select proper anchors to avoid the inconsistency existing in centroid localization schemes. Finally, an improved multilateration centroid method is presented for the localization. Simulations are conducted on two different network topologies and experiments results show that compared with existing DV-Hop based algorithms, our algorithm can significantly improve the performance meanwhile cost less network resource.

Keywords: DV-Hop, selective mechanism, centroid estimation.

1 Introduction

The ever-growing number of networked devices has boosted the applications of Wireless Sensor Networks (WSN) in various fields, such as environment monitoring, medical care, industry control and smart home [Adam, Anisi and Ali (2020)]. As the physical position of sensor nodes plays an important role in WSN based applications, the localization technology has been one of the primary services. Usually, only a few portion of network nodes called anchor nodes have determined locations. The unknown node, which has no information of its position, estimates the location is by interacting with anchors. The accuracy is important for localization algorithms as it directly affects the performance of the entire network [Zheng, Zhang and Zhao (2010)]. Localization schemes can be classified as range-based [Jeong, Jeong, Namjeong et al. (2010); Yang, Ma and Lu (2018); Marko, Rui and Paulo (2016)] or range-free [Nagpal (2003); Doherty, Pister and Ghaoui (2002); Janarthanan and Kumar (2019)] schemes. The range-based schemes obtain distance measurements to from received signal strength (RSS) [Chen, Chen and Wei (2015)], time

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of arrival (TOA) [Seongah, Kyung, Lee et al. (2014)] or signal angle of arrival (AOA) [Yu, Guo and Hedley (2009)]. Range-based technologies demands specific hardware to achieve higher accuracy. Range-free methods are easier to implement because these technologies do not require extra device that consume more network resource. Nevertheless, the deficiency is an obvious low accuracy. Representative range-free algorithms include Centroid [Prashar and Jyoti (2019)], Approximate Point in Triangle Test (APIT) [Liu, Feng, Zhang et al. (2016)], Amorphous [Zhao, Wen and Li (2015)] and the Distance Vector-Hop (DV-Hop) [Xiang and Tan (2013)], etc.

The DV-Hop algorithm is designed based on distance vector routing protocol by Niculescu and Nath [Niculescu and Nath (2003)]. The technique utilizes multi-Hop communication to broadcast information through the network. The principle is to estimate unknown path length to neighbouring anchors through hop-counts and an adjusted average distance. The process of the algorithm can be summarized in three phases: Firstly, anchors flood the network with location messages using the distance vector routing protocol. Meanwhile each source node calculates the hop-count from anchors when the message is being broadcasted. Secondly, DV-Hop calculates the average hop distance with distance measurements and minimum hop-count. Finally, localize source nodes by multilateration. Compared with other algorithms, the computational complexity of DV-Hop is much lower. However, the overestimated hop-counts in the shortest path will cause large errors.

DV-hop based algorithm aiming on improved accuracy have been proposed in recent literature. In Ji et al. [Ji and Liu (2008)], authors formulated the localization as a minimum mean-squared error optimization problem. With the communication range constraint, the accuracy has been improved. However the inconsistent problem existing in multilateration remains unsolved. In Lin et al. [Lin, Chen and Liu (2009)], authors used Taylor series expansion with weighing technique to correct the error in multilateration. However, the computational complexity is much higher. Recently, bio-inspired computing featured fast convergence has been adopted in the DV-Hop localization [Li, Xiong and Liang (2013)] but these techniques usually requires support from offline computational facilities. Zhou et al. proposed a RSSI-based DV-Hop weighting algorithm in Zhou et al. [Zhou, Qian and Zeng (2011)]. The principle is to calculate average hop distance with weighted values according to the received signal power strength. Although the algorithm improves the average distance measurement, it is not suitable for anisotropic networks where detoured paths often occur. Wang et al. adopted in Wang et al. [Wang, Gao, Wei et al. (2019)] a mobile agent for gathering information along a predefined path. The paper presented a network partition technique and cluster head selection algorithm with weighing method for energy efficient routing protocol design.

In this paper, we propose an improved localization algorithm named SIC-DV-Hop. The algorithm considers reduction of average distance error, selection of anchors and solving inconsistency issue in centroid methods to enhance accuracy. The main contributions of this paper are as follows:

- We consider that different anchor nodes have different effects on the unknown node and we adopt an inverse distance weighting method to reduce errors.
- An inclusive checking rule is presented to select proper anchors that can better support the localization and solve the inconsistency in centroid localizations.

- We propose an adjusted centroid scheme for the unknown node location estimation. With the selected anchor nodes, this algorithm effectively gives the solution for inconsistent situations.

The rest of this paper is organized as follows: Section 2 introduces the background and related works. In Section 3, we present the motivations of the proposed SIC-DV-Hop localization algorithm based on anchor selective mechanism. Section 4 illustrates the simulation results through Matlab and evaluates the theoretical performance of the new algorithm in two different network topologies. Simulations are conducted in comparison with the conventional DV-hop and two other improved methods. In the end, Section 5 gives a conclusion.

2 Background and related work

2.1 Summary of original dv-hop algorithm

The goal of conventional DV-hop localization algorithm is fulfilled in three phases.

Firstly, two information is broadcasted through the network: coordinates of the anchor nodes and estimations of the shortest path hop-counts from the source node to anchors. The basic connectivity information is therefore collected. In this phase, each node is required to maintain a table that contains a list of its neighbors and hop-counts with them.

Secondly, according to Eq. (1), an average distance per hop is calculated by each anchor node using the known distances and hop-counts between pair-wise anchors. After this phase is accomplished, hop-counts can be now used as equivalent measurement as distances.

$$\boldsymbol{C}_i = \frac{\sum_{i \neq j} \left\| \boldsymbol{p}_i - \boldsymbol{p}_j \right\|_2}{\sum_{i \neq j} \boldsymbol{h}_{ij}} \tag{1}$$

where $\boldsymbol{p}_i = [\boldsymbol{x}_i, \boldsymbol{y}_i]^T$, p_i and p_j are the known coordinates for anchor i and j respectively and h_{ij} is the minimum hop counts of the shortest path between those two anchors. Then, given the average hop distance from Eq. (2), the unknown node M estimates the shortest path distance d_{Mi} from anchor i .

$$d_{Mi} = C_M \times hop_{Mi} \tag{2}$$

where hop_{Mi} denotes the hop count between the unknown node M and anchor i along the shortest path.

Finally, with enough distances estimations from anchors, the unknown location can be estimated through the multilateration method.

After the node M acquires the estimated distance from each anchor node, a process of multilateral measurement is performed as follows:

$$\begin{cases}(x_1-x_0)^2+(y_1-y_0)^2=d_{M1}{}^2\\(x_2-x_0)^2+(y_2-y_0)^2=d_{M2}{}^2\\\dots\\(x_N-x_0)^2+(y_N-y_0)^2=d_{MN}{}^2\end{cases}\tag{3}$$

Where Eq. (3) is equal to Eq. 4:

$$\begin{cases}x_1{}^2-x_N{}^2-2(x_1-x_N)x_0+y_1{}^2-y_N{}^2-2(y_1-y_N)y_0=d_{M1}{}^2-d_{MN}{}^2\\x_2{}^2-x_N{}^2-2(x_2-x_N)x_0+y_2{}^2-y_N{}^2-2(y_2-y_N)y_0=d_{M2}{}^2-d_{MN}{}^2\\\dots\\x_{N-1}{}^2-x_N{}^2-2(x_{N-1}-x_N)x_0+y_{N-1}{}^2-y_N{}^2-2(y_{N-1}-y_N)y_0=d_{M(N-1)}{}^2-d_{MN}{}^2\end{cases}\tag{4}$$

In the matrix formation of $AX=b$, Eq. (4) is transformed as follows in Eqs. (5)-(7):

$$A=2\begin{bmatrix}(x_1-x_N) & (y_1-y_N)\\(x_2-x_N) & (y_2-y_N)\\\dots\\(x_{N-1}-x_N) & (y_{N-1}-y_N)\end{bmatrix}\tag{5}$$

$$b=\begin{bmatrix}x_1{}^2-x_N{}^2+y_1{}^2-y_N{}^2+d_{MN}{}^2-d_{M1}{}^2\\x_2{}^2-x_N{}^2+y_2{}^2-y_N{}^2+d_{MN}{}^2-d_{M2}{}^2\\\dots\\x_{N-1}{}^2-x_N{}^2+y_{N-1}{}^2-y_N{}^2+d_{MN}{}^2-d_{M(N-1)}{}^2\end{bmatrix}\tag{6}$$

$$X=\begin{bmatrix}x_0\\y_0\end{bmatrix}\tag{7}$$

Where the localization is formed into the least-squares problems shown in Eq. (8):

$$X=(A^TA)^{-1}A^Tb\tag{8}$$

Errors are mostly introduced in the second phase where overestimated hop-counts may occur. And most improvements in recent literature put efforts on average distance ratification.

2.2 Related work

Error of the DV-Hop algorithm are mainly introduced in the average hop distance calculation and multilateration, many efforts have been put in these aspects.

One improvement is to use a threshold value of distance or hop count to optimize the calculation. Wang et al. adopted a threshold value in Wang et al. [Wang, Gao, Yin et al. (2018)] to protect the dying nodes from energy drain. Xiang et al. presented in the literature

[Xiang, Wang and Yang (2016)] an algorithm to select a reasonable maximum hop count by hop size comparison. They use the single-hop average error function and the sub-error estimation function to adjust the average hop distance of the source node under different scenarios. This algorithm can effectively reduce error caused by using all the anchors. However, the process acquires a large amount of online and offline calculation and the solution is very sensitive to the network topology. Cheng et al. [Cheng and Guang (2017)] adopt a weighting method from a global perspective and calculates weighted average hop distance to improve accuracy. The method does not perform well in the anisotropic network either. Liu et al. [Liu, Yu and Tan (2012)] proposed a weighting method based on the measurement error. The paper considers the influence of each group of measurement errors on the positioning results. Friis transmission model is used to derive the weighting matrix that reflects the influence of each group of measurement errors on the localization results. Despite the effort, the performance is not constantly stable.

Multilateration usually causes errors in the last phase of DV-hop. Cui et al. [Cui, Xu, Li et al. (2018)] considered a differential evolution (DE) algorithm to rectify the accuracy. The DE algorithm uses stochastic search and is conducted in three stages: mutation, crossover and selection. The goal is to select appropriate candidate individual to replace its parents and eventually accomplish the genetic evolution. The random search algorithm transforms the localization into an optimization problem, which demands highly complex operation. Gui et al. [Gui, Val, Wei et al. (2015)] proposed a scheme that picks best candidate from different anchor combinations to perform multilateration. Many studies adopt centroid based techniques to improve the localization. Janarthanan et al. [Janarthanan and Kumar (2019)] used principles of hexagon and the centroid of partitioned regions as a position estimation. Tomic et al. [Tomic and Mezei (2016)] uses a centroid of intersections as the inconsistency compensation. However, with no selection of anchors the estimation may be skewed from the true location.

3 SIC-DV-Hop algorithm

3.1 Inverse Distance Weighting (IDW) method

As summarized in Subsection 2.1, the DV-hop based algorithm should firstly improve accuracy of the average hop distance. According to the previous introduction of the DV-Hop algorithm, the traditional algorithm requires the hop count from every anchor for average hop distance calculation. However, different influence of each anchor is neglected. In this subsection we consider the effect of each anchor node on the average hop distance calculation of the source node and adopt the inverse distance weighting (IDW) correction method to obtain more accurate average hop distance.

The process of IDW is conducted by giving different weights to anchors based on the distances. The idea is obvious that the anchor nearby should be assigned a heavier weight and anchor further away with less influence will be given a lighter weight. The inverse distance weighted correction method uses an inverse distance power value for the adjustments and we consider the number of 2. The specific steps of the inverse distance weighting algorithm are as follows:

Firstly, follow the conventional DV-Hop algorithm and calculate the average hop distance

C_i using Eqs. (1) and (2).

Then, the weight value W_i of the average hop distance of anchor node i is calculated according to the Eq. (9).

$$W_i = \frac{d_{Mi}^{-2}}{\sum_{j}^{N} d_{Mj}^{-2}} \tag{9}$$

Finally, with weight value W_i, the average hop distance C_M of the source node M is estimated using Eq. (10).

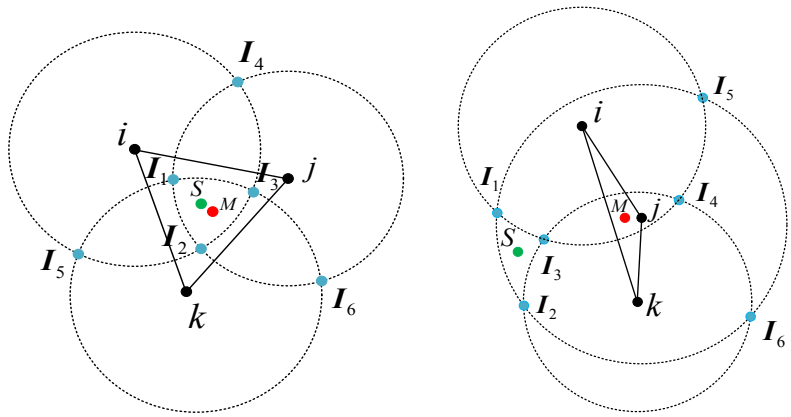
$$C_M = \sum_{i=1}^{N} C_i \times W_i \tag{10}$$

3.2 Selected anchors scheme

3.2.1 Motivations

The conventional algorithms usually employ every anchor in the localization process of DV-Hop. Recent research has found the notable influence on the localization accuracy [Cao and Wang (2019)]. Most of the selective scheme are based on selecting the optimum set of anchor nodes combination. However this takes precious network resource in the calculation of all the possible candidates, especially in situations such as military or emergency response [Albaidhani, Morell and Vicario (2019)]. In order to better support our new algorithm in the final phase of DV-hop, it is necessary to have an analysis of the centroid localization in the design of suitable anchor set selection scheme.

Because errors in distance measurement is inevitable, multilateration often encounter an inconsistent situation where centroid based localization algorithms give poor performance. This can be illustrated in Fig. 1. We assume a network in a 2D-plane and three anchor nodes i, j, k, and the node M in red is a centroid estimation and S in green denotes the true location. Fig. 1 shows a consistent situation of centroid localization methods when M lies inside Δijk (Fig. 1(a)) and M is close to the true location S. Meanwhile when M lies outside Δijk (Fig. 1(b)), we observe that M is skewed away from S and centroid methods will yield biased estimation. Therefore, a selective mechanism should be designed to choose the suitable anchor sets involved in localization.



(a) Consistent situation (b) Inconsistent situation

Figure 1: Localization with centroid methods

3.2.2 Inclusive anchor nodes selection algorithm

As described in Subsection 3.2, the centroid methods can approximate the true source location only when the node lies inside the triangle formed by reference anchors. To check this condition, we consider an anchor selection process before a centroid estimation method is performed. In this subsection, we propose the inclusive checking rule for anchor selection algorithm which is to be conducted in phase 2 of DV-Hop.

As Fig. 2 shows, node M resides within the boundaries of the triangle formed by three anchors as vertices. This is a desirable condition and our goal is to construct a checking rule to make sure M does not fall outside the boundaries. Otherwise, we should consider other anchor candidates. The inclusive checking rule is proposed as follows. Assume that node M is surrounded by the initially selected anchor nodes i, j, and k, as shown in Fig. 4, the connectivity between M and three anchors form angles α, β and γ.

By the law of cosines:

$$\cos\alpha = \frac{d_{Mi}^{\ 2} + d_{Mj}^{\ 2} - d_{ij}^{\ 2}}{2 \times d_{Mi} \times d_{Mj}} \tag{11}$$

$$\cos\beta = \frac{d_{Mk}^{\ 2} + d_{Mj}^{\ 2} - d_{kj}^{\ 2}}{2 \times d_{Mk} \times d_{Mj}} \tag{12}$$

$$\cos\gamma = \frac{d_{Mi}^{\ 2} + d_{Mk}^{\ 2} - d_{ki}^{\ 2}}{2 \times d_{Mi} \times d_{Mk}} \tag{13}$$

where distances d_{Mj}, d_{Mk}, d_{Mi} is obtained by the previous inverse weighted distance estimation.

It is obvious that in the ΔMik $\alpha+\beta+\gamma=360^{\circ}$. Without loss of generality, we assume that γ is the largest angle and α is the smallest, then γ should satisfy $0^{\circ}<\gamma<180^{\circ}$. Otherwise, as shown in Fig. 3, M falls outside of the triangle and this conflicts the inclusive rule. Therefore, the following Eq. (14) is proposed to check the position of M. If M lies outside the triangle, abandon anchor i, choose the next anchor candidate and re-check the inclusive rule.

$$r=\begin{cases}0^{\circ}<r<180^{\circ}, The\ node\ M\ lies\ inside\ \Delta ijk \\ 180^{\circ}<r<360^{\circ}, The\ node\ M\ lies\ outside\ \Delta ijk\end{cases} \tag{14}$$

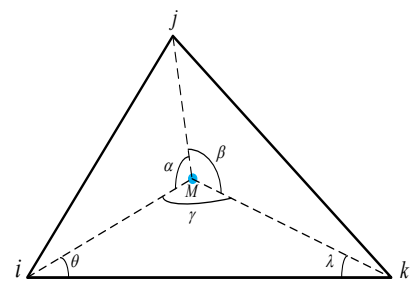


Figure 2: Node M lies inside the triangle

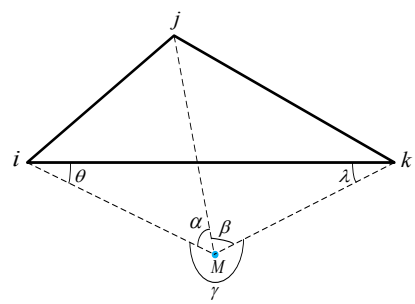


Figure 3: Node M lies outside the triangle

3.4 Multilateration centroid location estimation method

In the previous subsection we proposed the inclusive checking rule for anchor selection which effectively support the centroid localization. Since anchors satisfy inclusive rule can still be found in the consistent situations, as shown in Fig. 1, there exist an appropriate centroid estimation. In this subsection we present a multilateration centroid method that features light computational complexity and we will describe it in details as follows:

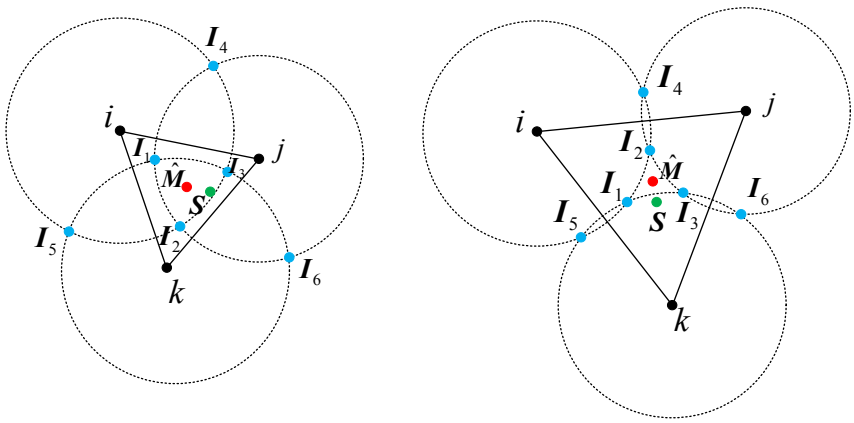
Firstly, use the distance measurement obtained with IDW and the anchors selected by using inclusive checking rule to perform multilateration.

Secondly, obtain the intersections in blue formed after multilateration as shown in Fig. 3(a). The coordinates of intersections can be determined according to Eq. (3).

After obtaining the coordinates of intersections, the position of the unknown node can be estimated according to the following Eq. (15), the coordinates of the intersections $\boldsymbol{I}_l = (\boldsymbol{x}_l, \boldsymbol{y}_l) \in \{\boldsymbol{D}_i \cap \boldsymbol{D}_j \cap \boldsymbol{D}_k | \boldsymbol{l} = 1,2,3..., \boldsymbol{N}_c\}$ and the centroid estimations are:

$$\begin{cases} \hat{\boldsymbol{x}} = \dfrac{\sum_l \boldsymbol{x}_l}{\boldsymbol{N}_c} \\ \hat{\boldsymbol{y}} = \dfrac{\sum_l \boldsymbol{y}_l}{\boldsymbol{N}_c} \end{cases} \tag{15}$$

where $\boldsymbol{N}_c = |\boldsymbol{D}_i \cap \boldsymbol{D}_j \cap \boldsymbol{D}_k|$. As shown in Fig. 4, the new centroid method can provide an accurate estimation at M in red, which is very close to the true location at S in green.



(a) Overestimated distance situation (b) Underestimated distance situation

Figure 4: Localization using inclusive rule and new centroid scheme

3.5 The Complete SIC-DV-Hop algorithm

The following Fig. 5 shows specific flow chart of the SIC-DV-Hop localization algorithm proposed in this paper. We follow the DV-Hop 3-phase framework and implement inverse distance weighted average hop distance rectification in phase 1. Our proposed inclusive checking rule for anchor selection is conducted in phase 2 and multilateration centroid method is performed in the final phase 3.

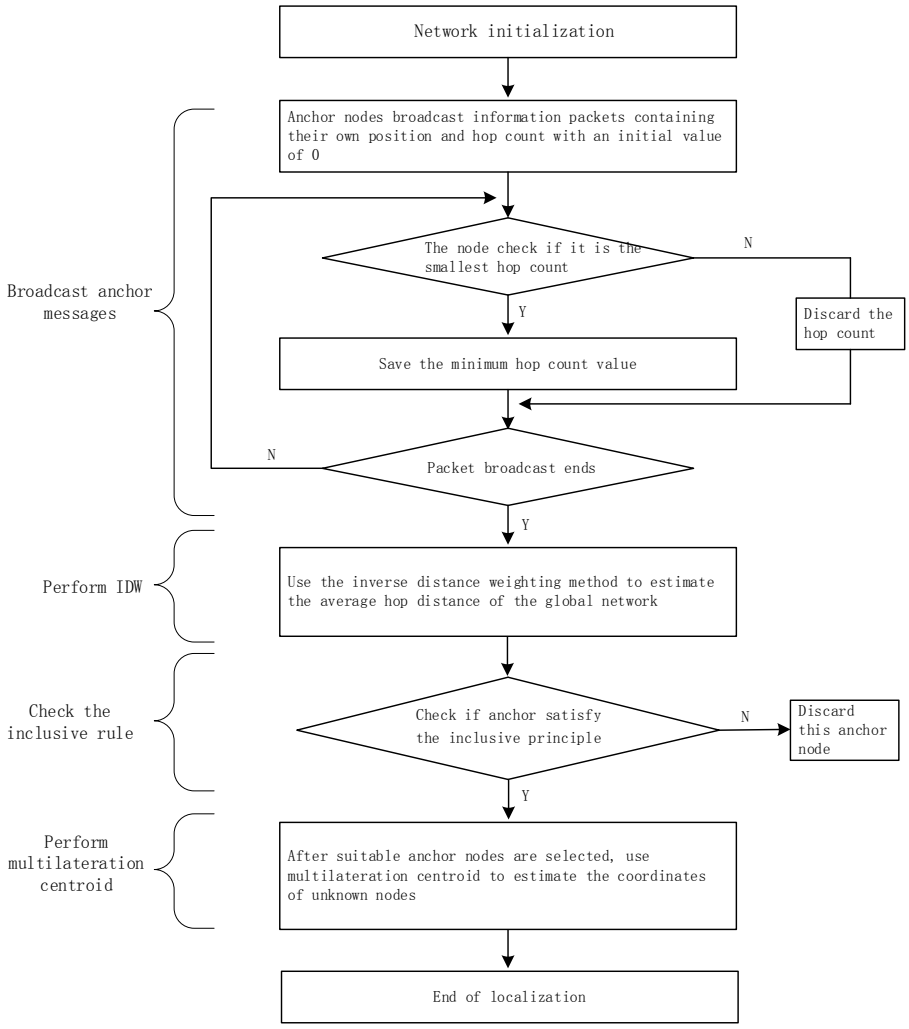


Figure 5: Work flow of the proposed SIC-DV-Hop localization algorithm

4 Simulation analysis

4.1 Experimental environment set-up and evaluation criteria

In this section, we give the simulated results of the new SIC-DV-Hop positioning algorithm proposed in this paper. Experiments are conducted in Matlab. We consider different network deployment scenarios, including the uniform network and one anisotropic form of the C-shaped network shown in Fig. 6. In Tab. 1, the parameters used in simulations and the performance of the new algorithm is analyzed in comparison with the conventional DV-Hop, TMCD-DV-Hop and IDV-Hop.

Table 1: Simulation parameters in Matlab

Simulation Parameter	Value
Borders	$(100\times100)m^2$
Total nodes	100
Node density	$10/10^2 m^2$
Anchors	10%-40%
Transmission range R	$15m$-$39m$
Hop-count threshold	7-16

The evaluation criterion in this paper is the localization error rate (LER):

$$LER = \frac{\sum_{d=1}^{N_s}\sqrt{(x_d-\overline{x_d})^2+(y_d-\overline{y_d})^2}}{N_s\times R} \tag{16}$$

where LER defines the discrepancy between the estimations and the actual locations of source throughout the whole network.

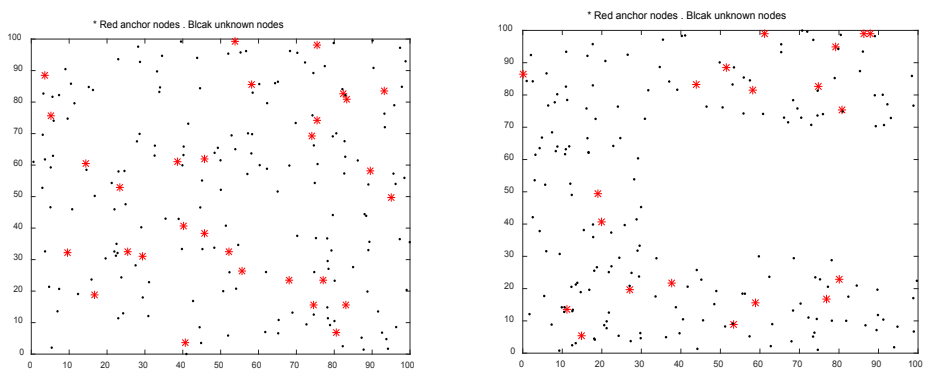


Figure 6: Different network scenarios

4.2 Simulated results

4.2.1 Effect of ratio of anchor on LER

To evaluate the new algorithm, a total number of 100 nodes are deployed the anchor ratio over the whole network nodes gradually changes from 10% to 40%.

Figs. 7 and 8 illustrate the impact on LER by varying the ratio of anchors. Results show that all of the LER decreases because of increased anchors participating in calculation and the error decreases in average hop distance calculations. However, there still shows and obvious advantage of the new SIC-DV-Hop. Especially in the C-Shaped networks, LER of the shows that new algorithm can effectively reduce error because of the rectified average hop distance.

As the ratio of anchor nodes increases, the proposed SIC-DV-Hop gives the best performance which demands less ratio of anchors and the cost of network resource is the lowest.

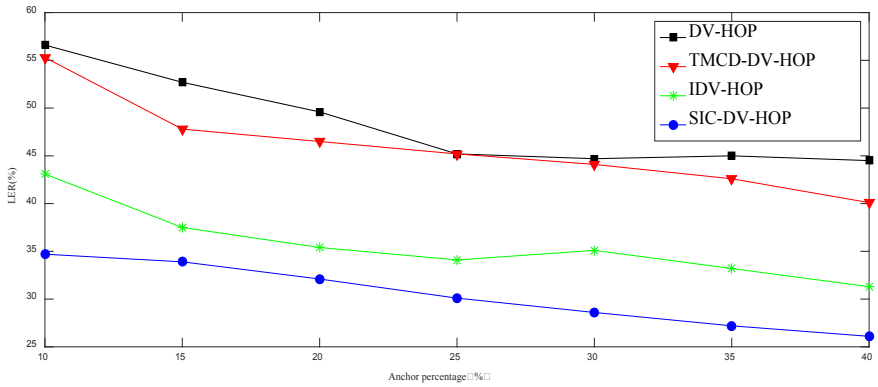


Figure 7: Impact on LER by changing anchor ratios on uniform networks

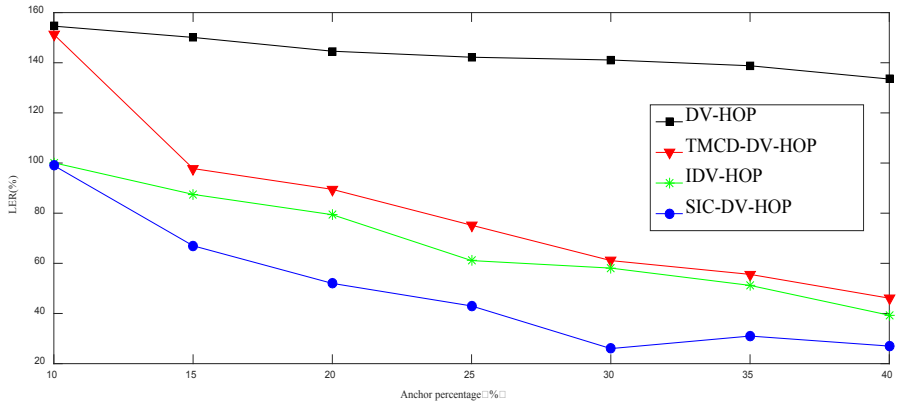


Figure 8: Impact on LER by changing anchor ratios on C-shaped networks

4.2.2 Transmission range impact on LER

The effect of communication range is demonstrated in Figs. 9 and 10. For the simulation, experiments are conducted by changing the value of transmission ranges. For all simulations, the density remains the same and anchor ratio is 20%. The experimental results show a downward trend of LER with the increase of transmission range for all four algorithms and the proposed SIC-DV-Hop always gives the best performance. In the uniform network, when the communication range R of the anchor node is 21 m, the LER of the SIC-DV-Hop is reduced by 11.8%, and when $R = 33m$, LER of proposed algorithm is less than the conventional DV-Hop algorithm by 8.2%. In the C-shaped network, the LER of the conventional DV-Hop always remains high. For the other three improved algorithms, the measurement error is significantly lowered with the increase of the transmission range. As the range increases, less nodes are isolated and more direct connections can be established. This will be beneficial to the reduction of the errors. In particular, the proposed SIC-DV-Hop algorithm has significantly improved accuracy compared with the other three algorithms.

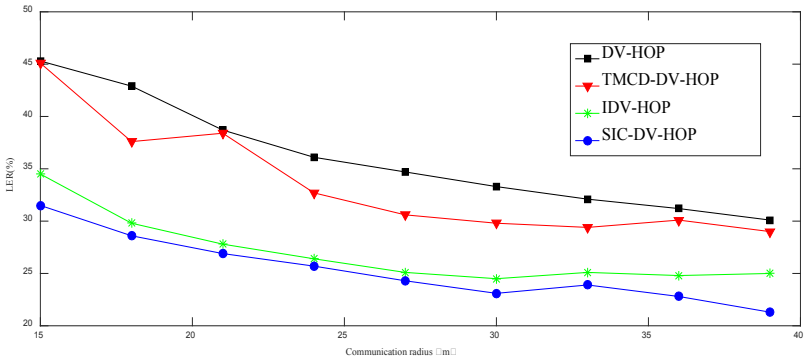


Figure 9: Impact on LER by changing transmission radius on uniform networks

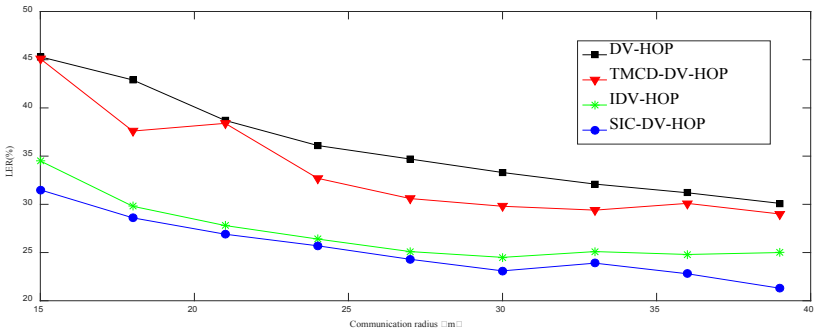


Figure 10: Impact on LER by changing transmission range on C-shaped networks

5 Conclusions

In this paper, we propose a new SIC-DV-Hop localization algorithm. We adopt an inverse weighting method to improve the accuracy of calculation in average distance per hop in the first phase of conventional DV-Hop. Also, an inclusive checking rule is presented for selecting anchor nodes that can avoid inconsistency in centroid localization. Finally, a new centroid algorithm is presented, which can effectively reduce resource consumption in computation. Simulations show an obvious advantage in performance of the new algorithm in two different networks.

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