Postprint of Improved DV-Hop Algorithm Based on Hop Count Correction and LM Optimization

Authors: high-definition source, Xu Zengchun, Hu Ping

Date: 2018-05-20T00:00:00+00:00

Abstract

To address the problem of hop count and hop distance estimation errors in DV-Hop localization algorithm under sensor network topology environments with non-uniform node distribution, an improved algorithm named ILDV-Hop is proposed. First, based on the difference between estimated distances and actual distances among beacon nodes, a network-wide effective hop distance is proposed. Second, a correction term is added during the multi-hop calculation process between beacon nodes and unknown nodes, while the Received Signal Strength Indicator (RSSI) value is utilized to optimize the single-hop distance. Finally, the Levenberg-Marquardt algorithm is employed to estimate the optimal positions of unknown nodes. Simulation results demonstrate that, compared with the traditional DV-Hop algorithm and the DV-Hop algorithm based on quasi-Newton iteration, the localization error of the ILDV-Hop algorithm is reduced by approximately 23% and 10%, respectively, with a significant improvement in localization accuracy.

Full Text

Preamble

Improved DV-Hop Algorithm Based on Hop Correction and LM Optimization

Gao Qingyuan, Xu Zengchun, Hu Ping
(School of Computer Science & Technology, Nanjing Tech University, Nanjing 211816, China)

Abstract: In sensor network topology environments with uneven node distribution, the DV-Hop localization algorithm often produces large errors in hop count and hop distance estimation. To address this problem, this paper proposes an improved algorithm named ILDV-Hop. First, based on the difference between estimated and actual distances among beacon nodes, we propose an effective hop size for the entire network. Second, we add correction values during multi-hop calculations between beacon nodes and unknown nodes, while simultaneously using Received Signal Strength Indicator (RSSI) values to optimize single-hop distances. Finally, the Levenberg–Marquardt algorithm is employed to estimate the optimal positions of unknown nodes. Simulation results demonstrate that compared with the traditional DV-Hop algorithm and the DV-Hop algorithm based on Quasi-Newton iteration, the ILDV-Hop algorithm reduces localization errors by approximately 23% and 10% respectively, achieving significant improvement in localization accuracy.

Keywords: DV-Hop algorithm; effective hop size; hop count; Levenberg–Marquardt algorithm

0 Introduction

Wireless sensor networks typically consist of numerous 微型 sensor nodes that generally possess computing, communication, and storage capabilities. The primary task of sensor nodes is to collect and aggregate remote sensing data in sensor network environments for further processing at sink nodes that serve as base stations. Without sensor location information contained in message reports generated by nodes, sensor networks cannot function properly, making localization a significant challenge in sensor network research. Many localization schemes assume that only a small portion of beacon nodes can obtain location information through manual deployment or by carrying GPS modules. However, this approach is unsuitable for sensor networks due to the high power consumption and expensive equipment associated with GPS systems.

Wireless sensor network localization algorithms can be broadly classified into two categories: range-based and range-free algorithms. The most commonly used range-based methods include Time of Arrival (TOA), Angle of Arrival (AOA), and Received Signal Strength Indicator (RSSI) localization. While these methods improve localization accuracy, they also increase hardware and manpower costs. Common range-free algorithms include the Centroid algorithm, DV-Hop algorithm, APIT algorithm, and Amorphous algorithm. These algorithms offer advantages such as low cost without requiring external equipment. Among them, the DV-Hop algorithm is one of the most widely applied localization algorithms, utilizing the average hop size of the nearest beacon node to unknown nodes for self-localization, featuring simplicity and low cost. However, its localization accuracy degrades significantly as hop counts between nodes accumulate, which represents the algorithm’ s main drawback.

To address the insufficient localization accuracy of the DV-Hop algorithm, scholars have proposed various improvement methods. Kumar et al. proposed a weighted least squares-based DV-Hop improvement algorithm that modifies the calculation method in the third stage of DV-Hop localization by subtracting first and then squaring, with error correction terms demonstrating higher accuracy.

However, this improvement neglects the influence of different beacon nodes on unknown nodes in earlier stages, resulting in limited optimization effects. Wen et al. proposed an RSSI-based improvement algorithm that discretizes single-hop counts using RSSI values between nodes and corrects inter-node hop counts by using distance as weights to reduce localization errors. The drawback of this method is the substantial increase in hardware power consumption and cost. Qiao et al. proposed the improved CNDV-Hop algorithm, which first sets a hop count threshold, optimizes beacon nodes in the sensor network while correcting the average hop size, and finally uses the Quasi-Newton method to estimate unknown node coordinates through iteration. Yu et al. employed an improved particle swarm algorithm for unknown node coordinate self-localization, but the high complexity of the improved particle swarm algorithm increases computational overhead.

While the aforementioned research has reduced localization errors to some extent, each approach has its drawbacks. Building upon the traditional DV-Hop localization algorithm, this paper proposes the ILDV-Hop algorithm from the root causes of errors. First, we redefine the network-wide average hop size and correct hop counts between beacon nodes and unknown nodes by adding weighting coefficients. Simultaneously, we discretize single-hop distances between nodes, and finally employ the LM optimization algorithm for unknown node self-localization through iteration.

2 DV-Hop Algorithm Error Analysis

As a typical range-free distributed algorithm, DV-Hop localization consists of three stages:

a) Each beacon node broadcasts messages using a distance vector exchange protocol. The broadcast packet contains the beacon node’ s ID, coordinates, and a hop count initialized to 0. This allows the network to record minimum hop counts between any two beacon nodes.

b) After obtaining coordinates and hop count information from other beacon nodes, each beacon node calculates the average per-hop distance to other beacon nodes, denoted as $HopSize_i$. The calculation formula is:

$$HopSize_i = \frac{\sum_{j\neq i}\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}}{\sum_{j\neq i} hop_{ij}}$$

where M is the number of beacon nodes, hop_{ij} is the hop count between beacon nodes i and j, and (x_i, y_i), (x_j, y_j) represent the coordinates of beacon nodes i and j respectively.

Once $HopSize_i$ is calculated, beacon nodes broadcast this value throughout the network. Unknown nodes receive average hop sizes from all beacon nodes and select the nearest beacon node' s average hop size as their calculation standard. The distance between unknown node s and each beacon node i is calculated as:

$$d_{si} = HopSize_{si} \times hop_{si}$$

c) Unknown nodes perform self-localization using beacon node coordinates and distance information through maximum likelihood estimation. Assuming M beacon nodes are used to estimate the position of unknown node s, the following system of equations can be derived from the estimated inter-node distances:

$$\begin{cases} (x_s - x_1)^2 + (y_s - y_1)^2 = d_{s1}^2 \\ (x_s - x_2)^2 + (y_s - y_2)^2 = d_{s2}^2 \\ \vdots \\ (x_s - x_M)^2 + (y_s - y_M)^2 = d_{sM}^2 \end{cases}$$

Analysis of the DV-Hop localization process reveals that the algorithm localizes unknown nodes through network connectivity and distance vector protocols, with errors arising from several aspects. First, since nodes are randomly distributed in sensor networks, uneven network topology causes errors when calculating average hop size using zigzag paths between beacon nodes, with errors increasing as hop counts grow. Second, the original algorithm uses only the nearest beacon node' s average hop size for unknown nodes, providing limited reference value. Moreover, when unknown nodes have 1-hop connections to multiple beacon nodes at varying distances, all are treated as 1-hop, often deviating from reality. Finally, in unknown node self-localization calculation, a nonlinear equation system is forcibly converted into a linear least squares problem, ignoring the impact of linearization and inevitably causing significant iteration errors.

ILDV-Hop Localization Algorithm

Building upon the traditional DV-Hop localization algorithm, this chapter proposes the ILDV-Hop improvement algorithm, primarily addressing errors in stages a) and b).

3.1 Beacon Node Hop Count Correction

The main disadvantage of the DV-Hop algorithm is that localization accuracy is affected by hop counts between unknown nodes and beacon nodes, with errors increasing when hop counts rise or network topology becomes uneven. This section redefines the average per-hop distance between beacon nodes through the following steps:

Each beacon node first estimates distances to other beacon nodes using obtained hop counts and hop sizes:

$$est\_dist_{ij} = HopSize_i \times hop_{ij}$$

where hop_{ij} is the hop count between beacon nodes i and j. Then, beacon nodes calculate actual distances through:

$$true\_dist_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$$

Next, each beacon node computes distance errors between estimated and actual distances:

$$error_{ij} = true\_dist_{ij} - est\_dist_{ij}$$

We propose the concept of effective hop size calculated from error estimates, denoted as $effHopSize_i$:

$$effHopSize_i = \frac{1}{M-1} \sum_{j \neq i} \left(\frac{HopSize_i}{1 + \frac{error_{ij}}{M \cdot hop_{ij}}} \right)$$

Finally, each beacon node broadcasts this effective hop size throughout the network during the flooding process.

3.2 Unknown Node and Beacon Node Hop Correction

3.2.1 Single-Hop Classification Processing When unknown nodes and beacon nodes are 1 hop apart, the estimated distance often contains significant errors. As shown in [Figure 1: see original paper], assuming unknown node s has communication radius R and contains two nodes A and B within its communication range, node s considers both nodes to be 1 hop away during distance calculation, leading to imprecise estimates. Clearly, node A is closer to s in the figure, and the distance calculated using the network-wide average hop size will be much greater than the actual distance. Therefore, this section proposes a single-hop correction method based on RSSI values.

RSSI is a technology that estimates inter-node distances through continuously attenuating signal strength during propagation, commonly using the Shadowing model in wireless sensor networks:

$$P_r(d) = P_r(d_0) - 10n \log\left(\frac{d}{d_0}\right) + X_\sigma$$

where d is the estimated distance between two nodes, d_0 is the reference distance, and n is the path loss exponent that varies with environmental factors. Clearly, the farther apart nodes are, the smaller the received signal strength.

In the ILDV-Hop improvement algorithm, unknown nodes compare the wireless signal strength $P_r(d_{ij})$ received from beacon nodes with the signal strength $P_r(d_0)$ at reference distance. (This method only compares signal strength values without considering signal propagation range.) If $P_r(d_{ij}) < P_r(d_0)$, the hop count between unknown node and beacon node is recorded as 0.5 hops; otherwise, it is recorded as 1 hop. This method classifies 1-hop nodes hierarchically, making some hop counts between unknown nodes and beacon nodes non-integer, effectively improving hop count credibility through this discretization process.

3.2.2 Multi-Hop Weighted Processing For cases where hop counts between unknown nodes and beacon nodes exceed 1, to control communication power consumption, we no longer use RSSI estimation but instead introduce correction values to optimize hop counts. The weight calculation method is:

$$weight_{ij} = k \cdot \frac{hop_{ij}}{effHopSize_i}$$

where hop_{ij} is the hop count between unknown node i and beacon node j, $effHopSize_i$ is the effective hop size calculated in the previous stage, and k is an adjustment coefficient. The corrected distance between unknown node and beacon node is:

$$corr\_dist_{ij} = effHopSize_i \times hop_{ij} + k \cdot effHopSize_i$$

When hop_{ij} values are larger, the calculated inter-node distance errors increase, indicating that the correction value k needs to be set larger. Based on experimental simulation data, the localization error of the improved algorithm has a close relationship with k size. For example, under conditions where node communication radius is 25m, total node number is 100, and beacon nodes account for 20% of total nodes, the relationship between parameter k and localization error is shown in [Figure 2: see original paper]. The figure reveals that when k approaches 1.2, node localization error reaches its minimum. In practical localization, k values can be selected specifically according to different application scenarios.

3.3 Unknown Node Localization

In the classical DV-Hop localization algorithm, unknown nodes use trilateration or maximum likelihood estimation for self-localization after receiving hop distances from beacon nodes. This process forcibly converts a nonlinear equation system into a linear least squares problem, causing computational errors. To control errors, nonlinear methods must be used to solve nonlinear problems. Therefore, the ILDV-Hop algorithm introduces optimization concepts, using the Levenberg-Marquardt (LM) optimization algorithm to address nonlinear problems in unknown node localization.

The LM optimization algorithm is a gradient-based method for solving extremum problems, applicable to nonlinear least squares problems. It combines characteristics of gradient descent and Gauss-Newton methods, using directional search to find optimal solutions. In the ILDV-Hop algorithm, the unknown node coordinate determination process is as follows: First, obtain the initial iteration coordinates of unknown nodes from all beacon node coordinates. Then, gradually iterate the unknown node coordinates using the improved LM algorithm initial values, finally obtaining the optimal coordinate solution that meets requirements. In each iteration, a new vector direction for the nonlinear least squares problem is selected through mathematical derivation similar to the gradient method.

Let s represent an unknown node with coordinates (x_s, y_s), and a_j represent beacon nodes with coordinates (x_j, y_j). Using d_{sj} to denote the distance between unknown node and beacon nodes, the residual vector is:

$$f_s(d_s) = \begin{bmatrix} \sqrt{(x_s - x_1)^2 + (y_s - y_1)^2} - d_{s1} \\ \sqrt{(x_s - x_2)^2 + (y_s - y_2)^2} - d_{s2} \\ \vdots \\ \sqrt{(x_s - x_M)^2 + (y_s - y_M)^2} - d_{sM} \end{bmatrix}$$

Thus, the entire unknown node self-localization solution process is transformed into the following nonlinear least squares problem:

$$\min_s \frac{1}{2} \|f_s(d_s)\|^2$$

Let the initial estimate in the LM improved algorithm be s_0, the damping coefficient value be μ, and the Jacobian matrix in the k-th iteration increment normal equation be $J(s_k)$. The calculation formulas for s_0, μ, and $J(s_k)$ are given by equations (14)-(16).

Here, the initial iteration point value is selected as the arithmetic mean of all beacon node coordinates. The uniqueness of LM optimization lies in its addition of a damping coefficient. For the damping coefficient μ in the ILDV-Hop algorithm: when μ is small and approaches 0, the LM algorithm becomes the Gauss-Newton method; conversely, when μ approaches 1, the LM algorithm approximates gradient descent. Typically, a relatively small μ value is set initially. When the objective function value increases instead, μ is increased to use gradient descent for rapid searching, then decreased to use Gauss-Newton method for searching.

The specific steps for the LM algorithm in ILDV-Hop unknown node self-localization are:

a) Calculate the unknown node iteration initial point s_0, set target error ε (adjusted according to localization accuracy requirements), set iteration count $k = 0$, step size factor $v = 10$, and select initial damping coefficient μ_0. The initial μ value should be small, corresponding to formula (14) where $\rho = 0.1$ is used for calculation, i.e., $\mu_0 = 0.1$.

b) In the k-th iteration, calculate the Jacobian matrix $J(s_k)$ of $f_s(d_s)$, then construct the increment normal equation $(J(s_k)^T J(s_k) + \mu_k I)\delta_k = -J(s_k)^T f_s(d_s)$ (where I is the identity matrix).

c) First solve for step size δ_k, then perform the following loop judgment steps:

  (a) Check condition: if $\|f_s(d_s + \delta_k)\|^2 < \|f_s(d_s)\|^2$, stop the entire iteration process and output the result as the optimal coordinate value of the unknown node; if not satisfied, let $s_{k+1} = s_k + \delta_k$ and proceed to step 2.

  (b) If $\|f_s(d_s + \delta_k)\|^2 > \|f_s(d_s)\|^2$, then $\mu_{k+1} = \mu_k \cdot v$ and reiterate from step 1 until iteration termination conditions are met.

In this step, ε is set to satisfy iteration termination conditions, and the target error ε in ILDV-Hop algorithm experiments is set to 0.5. Each iteration process requires finding an appropriate damping factor μ_k to minimize the objective function value.

4 Experimental Analysis and Simulation

This section analyzes and compares the performance of the ILDV-Hop algorithm with other localization algorithms. By setting different scenarios, we examine the impact of various parameters on localization error.

4.1 Simulation Parameter Settings

To verify algorithm performance, this section uses Matlab2014b software for simulation comparisons. In simulation experiments, all nodes are randomly deployed in a 100m × 100m simulation area without interfering obstacles (such as holes). All beacon nodes are randomly distributed in this area. The total number of nodes is set in the range of 50-300, node communication radius is set in the range of 20-40m, and the number of beacon nodes is set in the range of 10-40. The following three groups of simulations will be conducted in scenarios with different parameters to analyze the localization error of the ILDV-Hop algorithm and compare it with the traditional DV-Hop algorithm and the CNDV-Hop improvement algorithm from literature [10], making the localization performance differences more apparent.

Other network model or simulation parameter settings are as follows:

a) All nodes are stationary (no mobile anchor nodes).

b) Wireless transmission is in normal mode.

c) Sensor nodes are homogeneous: nodes have identical communication and storage capabilities.

d) Communication channels are bidirectional. Nodes can receive and forward messages from other nodes.

To obtain optimal results, experiments are conducted 100 times under the same network environment, with final results being the average localization error of 100 simulations. The Normalized Average Localization Error (NALE) for unknown nodes is expressed by equation (17):

$$NALE = \frac{1}{K \cdot N \cdot R} \sum_{i=1}^{K} \sum_{j=1}^{N} dist_{est-true}(i, j)$$

where N is the number of unknown nodes, K is the number of simulations (set to 100), $dist_{est-true}(i, j)$ is the Euclidean distance between the true position and estimated position of sensor node j, and R represents the communication radius of sensor nodes.

4.2 Localization Effect and Error Analysis

Figure 4: see original paper(b) respectively simulate the true and estimated positions of unknown nodes for the DV-Hop algorithm and ILDV-Hop algorithm when the number of beacon nodes is 20 and node communication radius is 25m. At this time, beacon nodes account for 20% of total nodes, and the number of unknown nodes is 50. In the figures, “ ”represents unknown nodes’ true positions, “*” represents unknown nodes’ estimated positions, and “ ” represents beacon nodes distributed in the network. From the ILDV-Hop algorithm localization effect diagram, the connecting lines between unknown nodes’ true positions and estimated positions are shorter, indicating better localization performance.

[Figure 5: see original paper] shows the comparison of algorithm localization errors under different total node numbers. From the figure, as the total number of nodes continuously increases, inter-node connectivity also increases. Since hop count and hop distance information become more accurate, localization errors of all three algorithms decrease. Under the same total node number conditions, the ILDV-Hop algorithm’ s localization error is reduced by approximately 24.5% and 10.2% on average compared with the DV-Hop algorithm and CNDV-Hop algorithm respectively. When the total node number exceeds 200, the ILDV-Hop algorithm’ s localization effect becomes less significant, with error variation amplitude decreasing accordingly. Due to network structure changes caused by increasing node numbers, combined with algorithm limitations and simulation experiment randomness, the localization error curves of the three algorithms exhibit slight fluctuations during node number increases, but overall show a continuously decreasing and stabilizing trend.

Scenario 2: The total node number is constantly set to 200, node communication radius is set to 25m, and beacon node number varies in the range of 10-40.

[Figure 6: see original paper] shows the comparison of algorithm localization errors under different beacon node numbers. From the figure, when beacon node number is small (10), the ILDV-Hop algorithm' s localization error shows little difference from the CNDV-Hop algorithm, with advantages not yet apparent. As beacon node number increases, the ILDV-Hop algorithm' s localization error decreases sharply, with localization performance being optimized. When beacon node number gradually increases, unknown nodes obtain more reference information, and localization errors of all three algorithms generally show a decreasing trend. Under the same beacon node number conditions, the ILDV-Hop algorithm always achieves optimal localization performance, with errors reduced by approximately 22.5% and 11.7% on average compared with the DV-Hop algorithm and CNDV-Hop algorithm respectively. Meanwhile, the DV-Hop algorithm' s error curve exhibits certain fluctuations due to numerous interference factors in its localization process.

Scenario 3: The total node number is constantly set to 200, the proportion of beacon nodes is constantly set to 20%, and node communication radius uniformly increases from 20m to 40m.

[Figure 7: see original paper] shows the comparison of algorithm localization errors under different communication radii. From the figure, as node communication radius continuously increases, inter-node connectivity is affected, and errors of all three algorithms decrease slightly and tend to stabilize. Under the same communication radius conditions, the ILDV-Hop algorithm always has the smallest localization error, reduced by approximately 23.6% and 8.8% on average compared with the DV-Hop algorithm and CNDV-Hop algorithm respectively. When node communication radius exceeds 30m, localization effects of all three algorithms become less significant, with error reduction amplitude decreasing accordingly, and the ILDV-Hop algorithm' s localization accuracy is least affected by node communication radius.

5 Conclusion

This paper proposes the ILDV-Hop algorithm to address issues in the traditional DV-Hop localization algorithm, including hop count dependency, linear position estimation, and hop size uniformity. The improved algorithm makes the following enhancements compared with traditional localization algorithms: First, it introduces an effective hop size for the entire network while correcting hop counts between beacon nodes and unknown nodes through weighted coefficients. Simultaneously, it discretizes single-hop distances between nodes using RSSI values, and finally employs the LM optimization algorithm instead of maximum likelihood method to solve nonlinear least squares problems in unknown node self-localization. Simulation results demonstrate that compared with the traditional DV-Hop localization algorithm, the ILDV-Hop algorithm significantly improves algorithm accuracy with only slight increases in hardware power consumption and computational overhead. Future research will focus on further reducing algorithm complexity while improving localization accuracy in anisotropic sensor networks with holes.

References

[1] Zeng Yuanyuan. Wireless Sensor Network Technology and Application [M]. Beijing: Tsinghua University Press, 2014: 16-28.

[2] Qian Zhihong, Wang Yijun. Survey on Wireless Sensor Networks for Internet of Things [J]. Journal of Electronics & Information Technology, 2013, 35(1): 215-227.

[3] Pan Zhuojin, Liu Wenchun, Luo Zhen, et al. Improvement of DV-Hop Localization Algorithm for Wireless Sensor Networks [J]. Computer Engineering and Design, 2016, 37(7): 1701-1704.

[4] Oguejiofor O S, Aniedu A N, Ejiofor H C, et al. Trilateration based localization algorithm for wireless sensor network [J]. International Journal of Science and Modern Engineering, 2013, 1(10): 356-368.

[5] Naeimi S, Chow C O, Ishii H. Directional multi-hop clustering routing protocol for wireless sensor networks [J]. International Journal of Ad Hoc & Ubiquitous Computing, 2013, 14(2): 123-134.

[6] Yang Xiang, Liu Meifeng, Deng Dengteng. An improved DV-Hop algorithm based on RSSI for WSN [C]// Proc of IEEE International Conference on Signal Processing, Communications and Computing. 2015: 1-5.

[7] Niculescu D, Nath B. DV based positioning in Ad hoc networks [J]. Telecommunication Systems, 2003, 22(1): 267-280.

[8] Kumar S, Lobiyal D K. An advanced DV-hop localization algorithm for wireless sensor networks [J]. Wireless Personal Communications, 2013, 71(2): 1365-1385.

[9] Wen Jiangtao, Fan Xuemin, Wu Xijun. Improved DV-Hop algorithm based on RSSI hop correction [J]. Chinese Journal of Sensors and Actuators, 2014, 27(1): 113-117.

[10] Qiao Xin, Chang Fei, Ding Enjie, et al. Quasi-Newton iterative localization algorithm for WSN based on hop distance correction [J]. Chinese Journal of Sensors and Actuators, 2014, 27(6): 797-801.

[11] Yu Quan, Sun Shunyuan, Xu Baoguo, et al. Node localization in wireless sensor networks based on improved particle swarm optimization [J]. Journal of Computer Applications, 2015, 35(6): 1519-1522.

[12] Pan Zhuojin, Liu Wenchun, Luo Zhen, et al. Improvement of DV-Hop Localization Algorithm for Wireless Sensor Networks [J]. Computer Engineering and Design, 2016, 37(7): 1701-1704.

[13] Kaur A, Kumar P, Gupta G P. A novel DV-Hop algorithm based on Gauss-Newton method [C]// Proc of the 4th International Conference on Parallel, Distributed and Grid Computing. 2016: 625-629.

[14] Zhang Dengyin, Cui Guodong. A Union Node Localization Algorithm Based

on RSSI and DV-Hop for WSNs [C]// Proc of International Conference on Instrumentation. 2013: 1094-1098.
[15] Dennis J E J, Schnabel R B. Numerical methods for unconstrained optimization and nonlinear equations [M]. Beijing: Science Press, 2009: 162-180.
[16] Zhu Qiang, Li Shaokang, Xu Zhen. Research on LM algorithm for solving large residual nonlinear least squares problems [J]. China Measurement & Test, 2016, 42(3): 12-16.

Note: Figure translations are in progress. See original paper for figures.