Enhanced Range-Free Localization in Wireless Sensor Networks Using a New Weighted Hop-Size Estimation Technique

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***Abstract*—Wireless sensor networks (WSNs) have recently enabled many new applications often dubbed "smart" as a result of it. And researchers are currently giving much attention to localization in WSNs for the increasing number its use cases in real life. Two main localization categories prevail in the literature: range-based and range-free. The latter exploit the networks connectivity information in order to approximate the nodes locations, while the former accomplishes that by measuring actual distances. One of the widely investigated range-free WSN localization techniques is the DV-Hop. In this paper, we will develop and analyze the performance of a new enhanced version of this reference technique using a novel weighted hop-size expression. The simulation results indicate an improvement of the performance in terms of accuracy.**

***Index Terms*—Localization; range-free; wireless sensor networks; hop-size; estimation.**

I. Introduction

WSNs are one of the most popular research domains that researchers from different disciplines have been working on for the last several years. A WSN can be defined as a large set of low-cost tiny sensor devices scattered in an area where usually human intervention is impossible in order to monitor a physical parameters such as temperature, pressure, humidity, etc. These devices have a very limited computational capability, are powered by small batteries or an energy harvesting component, and communicate over wireless links [1][2].

WSNs gather sensor data and forward it to a central station (sink). We should note that communicating and processing data without knowing where it came from can render it meaningless in several cases. It is therefore crucial to know the locations of wireless sensor nodes location, for instance in application such as pipeline monitoring in arid areas, animal tracking, forest fire detection, etc. [3].

Over the last few years, researchers have been working on a wide range of localization algorithms [4]. In most cases, a small set of nodes known as anchor nodes and equipped with a built-in localization capability such as a GPS module [5][6] will serve as references for the estimation of the other node locations.

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As explained above the location can be estimated with a range-based [7][8] or a range-free [9] algorithm. In the first one, dedicated hardware is needed to determine indicators such as the time of arrival (ToA) [10], the angle of arrival (AoA) [11], or the received signal strength (RSS) [12]. The results are very accurate and promising in this case. But they are obtained at the expense of a higher cost. On the other hand, with the range-free technique, no additional hardware is necessary and a node would implicitly take into consideration the distance from the anchor nodes only.

In an overall view, range-free localization algorithms are more convenient for WSNs. As a result, several range-free localization techniques have been proposed, such as the centroid algorithm [14], the APIT algorithm [15], etc, and DV-Hop [13], the most popular among all.

In this paper, we will develop and analyze an the performance of a new enhanced version of the DV-Hop reference technique using a novel weighted hop-size estimation method.

The remainder of this paper is organized as follows: In section II, we give an insight into the prior art on the DV-Hop technique and all its improved variants. We propose our new DV-Hop-based scheme in section III. In section IV, we assess and confirm by simulations the significant accuracy gains it achieves over the current state of the art. Finally, we conclude in section V.

II. Prior Art on DV-Hop

A. DV-Hop Algorithm

Similar to a basic routing scheme based on distance vector, Niculescu and Nath in [13] developed a range-free distance vector hop (DV-hop) localization algorithm. DV-hop does not require any additional circuitry since it only uses multi-hop distance estimation. We can divide it in three main steps:

1) The minimum number of hops separating each unknown node from the anchor node is counted. The anchor node floods a packet in the whole network where it indicates its coordinates and a hop count attribute initially set to one. A receiving node would then cache only the coordinates and the hop-count

of the anchor node having the minimum hop count value. Then, each node that receives the packet would increment the hop count by one. Eventually, all the unknown nodes will have the minimum hop-count cached in their memory.

2) An anchor node would then estimate the average hop-size based on the values received from the other anchors using formula (1) and broadcasts it. The next step is to compute the hop-size $\bar{h}_i$ at each anchor node i as the ratio of the actual physical distance to the anchor over the hop-count value and the remaining number of anchors:

$$\bar{h}_i^s = \frac{\sum_{j \neq i} \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}}{\bar{h}_{ij}^c \times (N_a - 1)} , \quad (1)$$

and where $(x_i, y_i), (x_j, y_j)$ are the coordinates the anchor nodes i, j, the hop-count value $\bar{h}_{i,j}^c$ is the minimum number of hops between the latter, and N_a is the total number of anchors.
Each anchor estimates its hop-size and floods it to the whole network. Unknown nodes receive the hop-size information and save the first one while broadcasting this value to their neighbors. At the end of this step, an unknown node u with coordinates (x_u, y_u) estimates its distance to each anchor node j as follows:

$$\hat{d}_{uj} = \bar{h}_j^s \times \bar{h}_{uj}^c \ . \quad (2)$$

3) In the case where a node with unknown coordinates (x_u, y_u) receives more than two distance estimates from the anchor nodes, we use the maximum likelihood estimation method in order to determine its locations:

$$\begin{bmatrix} (x_1 - x_u)^2 + (y_1 - y_u)^2 \\ (x_2 - x_u)^2 + (y_2 - y_u)^2 \\ \vdots \\ (x_n - x_u)^2 + (y_n - y_u)^2 \end{bmatrix} = \begin{bmatrix} \hat{d}_{u1}^2 \\ \hat{d}_{u2}^2 \\ \vdots \\ \hat{d}_{un}^2 \end{bmatrix} . \quad (3)$$

Eq.(3) can be transformed into matrix form as:

$$AX_u = B \ , \quad (4)$$

where

$$A = 2 \times \begin{bmatrix} x_n - x_1 & y_n - y_1 \\ x_n - x_2 & y_n - y_2 \\ \vdots & \vdots \\ x_n - x_{n-1} & y_n - y_{n-1} \end{bmatrix} , \quad (5)$$

$$B = \begin{bmatrix} \hat{d}_{u1}^2 - \hat{d}_{un}^2 - x_1^2 + x_n^2 - y_1^2 + y_n^2 \\ \hat{d}_{u2}^2 - \hat{d}_{un}^2 - x_2^2 + x_n^2 - y_2^2 + y_n^2 \\ \vdots \\ \hat{d}_{u(n-1)}^2 - \hat{d}_{un}^2 - x_{n-1}^2 + x_n^2 - y_{n-1}^2 + y_n^2 \end{bmatrix} , \quad (6)$$

$$X_u = \begin{bmatrix} x_u \\ y_u \end{bmatrix} . \quad (7)$$

According to the least square (LS) method, the solution to eq. (4) is given by

$$\hat{X}_u = (A^T A)^{-1} A^T B \ . \quad (8)$$

B. A Survey of DV-Hop improvements

After the algorithm was proposed by Niculescu and Nath back in 2001, it has been witnessing a lot of improvements made by many researchers. It is still very popular due to its simplicity, cost effectiveness, and robustness. Therefore, researchers keep working on improving the accuracy using several approaches (e.g. by modifying the hop-size, special deployment of anchors, etc.).

Chen et al. [16] proposed a method to ameliorate the localization accuracy of DV-Hop by modifying the hop-size using averages. They have also adopted the 2D hyperbolic localization scheme instead of traditional trilateration.

An improved version named weighted DV-Hop was developed in [17]. There, unlike conventional DV-hop where nodes consider only the nearest hop-size, unknown nodes calculate their own hop-size as a weighted average of all anchor hop-sizes.

In [18], another improved version of DV-Hop was proposed in three processing steps. Some anchors are first of all deployed at the borders of the sensor field. Then each unknown node uses an average weighted hop-size to estimate its position by a 2D hyperbolic method. Finally, the estimated positions are corrected by particle swarm optimization.

In yet another variant of DV-Hop developed in [19], the hop-size at each anchor is calculated as a weighted sum of all average one-hop distances to all anchors. The weight of each anchor is the inverse sum applied at the distance difference between its initial hop-size estimate and those calculated at the other anchors.

III. Our Enhanced DV-Hop Technique

In DV-Hop, localization errors are due on one hand to the computation algorithm of the hops number and the hop-size of each anchor and on the other hand to the localization estimation method. In order to make the DV-Hop technique more accurate, we manage to work on the two last steps, i.e., the hop-size computation and the localization estimation method. Hence, only the first task of our improved solution remains the same as the original one. Each node determines the closest anchor as requiring the smallest number of hops.

In the following, we begin by detailing the hop-size computation method and then introduce our new location estimation approach.

A. Hop-size and Weighted Correction

Each anchor computes its hop-size using (1), and estimates the distance between itself and other anchor nodes using (2). The root mean square error (RMSE) is then determined as follows:

$$E = \frac{1}{N_a - 1}\sum_{i\neq j}(\||\|\hat{X}_i - \hat{X}_j\|\|| - d_{ij}) \ , \quad (9)$$

where d_{ij} between anchors i and j. According to the minimum square error (MSE) criterion, hop-size estimation errors at each anchor node i can therefore be reduced as follows:

$$\bar{h}_i^s = \frac{\sum_{i\neq j} \bar{h}_{ij}^c \||\|\hat{X}_i - \hat{X}_j\|\||}{\sum_{i\neq j} {\bar{h}_{ij}^c}^2}. \quad (10)$$

In DV-Hop, each unknown node exploits only the hop-size calculated by the nearest anchor to estimate its own location. However, in practice, all nodes are randomly distributed and the distance between them is not a straight line. Hence exploiting the hop-size estimate from one anchor only, presumably the nearest one, does not take advantage of the rest of the hop-size estimates to obtain even more accurate coordinates of the nodes' location. That is in our improved version referred to as IWDV-Hop for inversely weighted DV-Hop [13], we choose to exploit the hop-size estimates calculated at all anchors. Indeed, in likely cases where the true distance between the unknown node and the closest anchor is larger than the hop-size estimate times the hop-count value, then the localization errors would be very important. In contrast, a farther anchor with the appropriate hop-size estimation could provide more accurate node coordinates. However, granting the same level of importance or reliability to all anchors would be infructuous. In fact, after calculating the hop-size estimate using (10), we weight each anchor node as follows:

$$W_i = \frac{\frac{1}{h_{iu}^c}}{\sum_{k=1}^{N_a}(\frac{1}{h_{ku}^c})} \ , \quad (11)$$

This weight depends on the hop-count since the nearest anchor would provide more precise location than the others. This way, we improve the hop-size accuracy.

After we calculate the hop-size of all anchor nodes by (10), we can determine the hop-size of every unknown node:

$$\bar{h}_u^s = \sum_{i=1}^{N_a} W_i \bar{h}_i^s \ . \quad (12)$$

Instead of using (10), (12) will be used to estimate the distance separating a node from each anchor.

B. Location Estimation Method

Instead of applying the ML method to calculate the positions of the unknown nodes, we adopt the hyperbolic location algorithm of [20] in order to obtain more accurate locations.

If (x_i, y_i) denote the coordinates of the anchor node i and (x_u, y_u) the coordinates of the unknown node u, then the true distance d_{iu} between them is

$$d_{iu}^2 = (x_i - x_u)^2 + (y_i - y_u)^2. \quad (13)$$

If $A_i = x_i^2 + y_i^2$ and $B_u = x_u^2 + y_u^2$, we have the following formula:

$$d_{iu}^2 - A_i = -2x_i x_u - 2y_i y_u + B_u. \quad (14)$$

which can be rewritten as:

$$JU = I, \quad (15)$$

where

$$J = \begin{bmatrix} -2x_1 & -2y_1 & 1 \\ -2x_2 & -2y_2 & 1 \\ \vdots & \vdots & \\ -2x_n & -2y_n & 1 \end{bmatrix}, \quad (16)$$

$$I = \begin{bmatrix} d_{1u}^2 - A_1 \\ d_{2U}^2 - A_2 \\ \vdots \\ d_{nu}^2 - A_n \end{bmatrix}, \quad (17)$$

$$U = \begin{bmatrix} x_u & y_u & B_u \end{bmatrix}^T \quad (18)$$

According to (15), U can be estimated by the LS estimation method as follows::

$$\hat{U} = (J^T J)^{-1} J^T \hat{I} \quad (19)$$

And so the coordinates of the unknown node are:

$$\hat{x}_u = \hat{U}(1),$$
$$\hat{y}_u = \hat{U}(2).$$

IV. Simulation Results and Comparaison

In this section, we report on many simulations results that assess the localization accuracy of our new IWDV-Hop technique versus (vs.) the variations of communication radius, the anchor percentages, and the number of nodes. We also compare it in accuracy performance to the original DV-Hop [13] and its best improved variant HWDV-Hop proposed in [19]. We use MATLAB as a simulation tool and calculate each performance average over 100 Monte-Carlo realizations. As illustrated in Fig. 1, we randomly place uniformly all the nodes in a square area of 50×50 m^2 and assume that all anchors and unknown nodes have the same radio range R of 15 m.

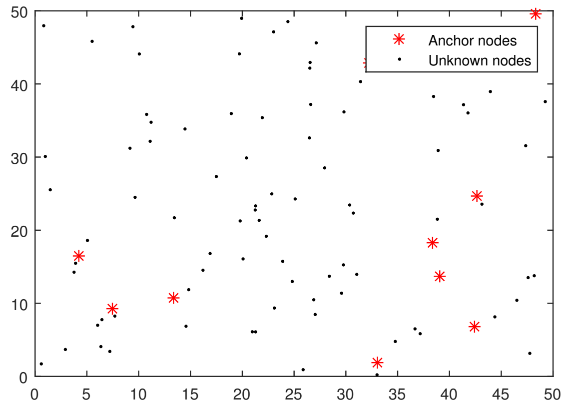

Fig. 1. An illustration of a uniformly random distribution of 100 nodes with 10% of anchors.

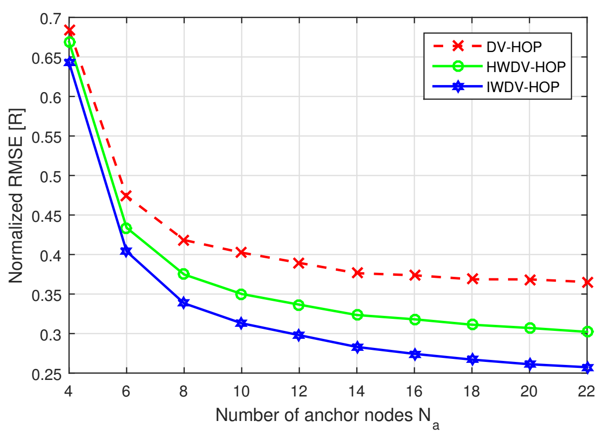

Fig. 2. Normalized localization error vs. the number of anchor nodes N_a.

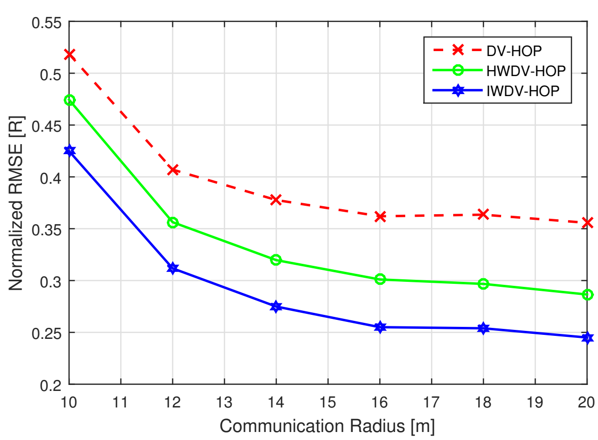

Fig. 3. Normalized localization error with different radio range of sensor nodes.

Firstly, we compare the performance in Fig. 2 of the three algorithms with different anchor node ratios

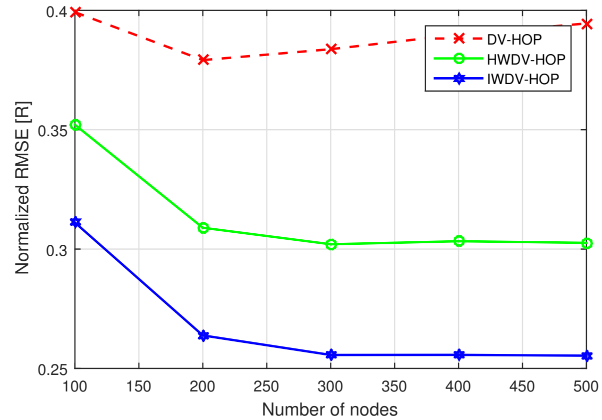

Fig. 4. Normalized localization error vs. the total number of nodes with 10% of anchors.

ranging from 4% to 22% of the total number of nodes. As expected, the accuracy of all three algorithms improves with an increasing number of anchors. Yet unambiguously our proposed version is constantly the most accurate and outperforms the two other benchmarks.

Fig. 3 shows the average localization error when the communication range gradually increases from 10 m to 20 m. In this scenario, we have 20% of anchors among 100 nodes. And once again, as expected, the localization accuracy of all three algorithms improves with increasing values of the radio range R. However, our new IWDV-Hop technique clearly outperforms both the original DV-hop and its best improved HWDV-Hop variant.

The third criterion is to calculate the average error of different number of nodes having the same R (15m). For this purpose, we choose to change this number from 100 to 500, while we keep the anchor ratio fixed at 10 % of total number of seniors.

Fig. 4 depicts the localization accuracy performance when the number of nodes increases from 100 to 500 with the same 10% ratio of anchor nodes. It shows yet again the expected improvement and most importantly the superiority of the new proposed localization technique over the original benchmark and its best improved variant.

V. Conclusion

Localization is one of the most challenging operations in WSNs since several applications need high localization accuracy of sensor nodes. In this paper, we presented a new enhanced version of range-free technique using a novel weighted hop-size expression. The simulation results indicate an improvement of the performance in terms of accuracy.

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