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Wireless sensor localization using enhanced DV-AoA algorithm

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Abstract: In this paper, we deal with the improvement of the positioning accuracy of distance vector (DV)-based positioning algorithms, which use angular information DV- angle of arrival (AoA). This algorithm belongs to an ad-hoc positioning system. We focus on the improvement of the algorithm and its enhanced version is presented. The angular information of particular nodes is obtained and processed by the original algorithm; however, the final position estimation is determined by the proposed novel algorithm using only a subset of all intersections. We assign weights to the individual intersections according to their positions and the positions of the RNs. For the final position estimation, only intersections with the highest weights are used. The performance of the proposed enhanced algorithm is verified by simulations and it is compared with the original DV-AoA algorithm.

Key words: Ad-hoc positioning system, angle of arrival, positioning accuracy, wireless networks, ad-hoc networks

1. Introduction

Research related to mobile positioning has been extensively studied. The requirements for the emerging location-based services (applications) cause it to be more and more important to provide low-cost and effective mobile positioning solutions. Furthermore, positioning may be necessary to increase network performance. For example, positioning in a wireless sensor ad-hoc network has a major role in the development of the geographically aware routing and multicasting protocols that result in new and more efficient ways for routing data in multihop networks. Most applications are associated with the geographic location of devices. However, acquiring these position data can be quite challenging.

Traditionally, there are 2 main approaches for mobile device positioning: the Global Navigation Satellite System (GNSS) and the utilizing of radio signal information. The GNSS can satisfy some of the requirements, but attaching a GNSS receiver to each device may be a significantly costly solution in terms of volume, money, and power consumption. Moreover, GNSS signal reception might be obstructed by climatic conditions or be impractical in indoor environments. Therefore, attention should be paid to GNSS-free solutions at the expense of decreased positioning accuracy. The second approach, mobile device location, is typically determined by utilizing radio signal information such as the received signal strength, time of arrival, and channel impulse response or angle of arrival (AoA) [1–28]. Several signal measurements from different reference stations, with the knowledge of their geographical locations, can be used for the determination of a mobile device location. The principles of particular methods are the same as those presented in the following: [21,24] (ad-hoc), [11] (cellular), [1–4,8,9,25,28] (sensor), or [10,15,16] (UWB), regardless of the implemented network's platform.

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The ad-hoc positioning system (APS) was first introduced by Niculescu and Nath [23]. Generally, it is not possible to implement common positioning methods into ad-hoc networks due to restrictions caused by the network architecture. The main restriction is that a node can only communicate with its immediate neighbors, which may not always be reference nodes (RNs). RNs are aware of their positions and possibly their orientation (direction).

The APS is a hybrid between 2 major concepts: distance vector (DV) routing and beacon-based positioning. The original APS concept was based on ranging [23]. In the next phase, it was extensively used for angle measurements [24]. In [24], a method was proposed for forward orientation, so that nodes that are not in direct contact with the RNs can still infer their orientation with respect to the RN. In that context, orientation means bearing, radial, or both. Two DV-AoA–based algorithms are examined: DV-bearing, which allows each node to get a bearing to the RN and DV-radial, which allows a node to get bearing radial to the RN. A detailed description of the algorithms can be seen in [24]. The final position estimation of a blindfolded node (BN) is calculated as an intersection of lines, which are defined by the angle between particular nodes.

However, this way is not always optimal, because the positioning accuracy is influenced differently by the various geographical distributions of the intersections. For illustration, 2 classes of intersections can be defined: 1st class, suitable intersections, and 2nd class, unsuitable intersections (see Figure 1). BN Estimation 1 is calculated from the 1st class intersections and BN Estimation 2 is calculated from all of the intersections, i.e. from the 1st class and 2nd class intersections. Obviously, BN Estimation 1 is more accurate compared to BN Estimation 2. This is because the unsuitable intersections (2nd class) are not taken into account.

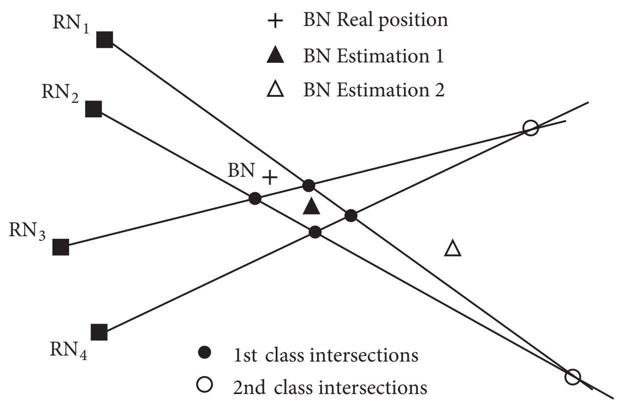

Figure 1. Intersections of the lines.

In light of this negative influence on DV-AoA algorithms (DV-radial, DV-bearing), we decided to improve the performance of these algorithms. Our proposal is more complex and it is based on the utilization of optimally situated intersections.

2. Proposal of the enhanced algorithm

The initial phase of the enhanced algorithm is fundamentally the same as the basic DV-bearing and DV-radial algorithms. These algorithms measure the orientation (angle) between BNs and RNs, or vice versa. What differs is the way in which the final position estimate is calculated from the set of intersections.

When calculating the position estimate, the enhanced algorithm does not take into consideration all intersections, but only the interesting ones that meet defined criteria. The final position estimate is then calculated only from the interesting subset.

We decided to assign weights to all of the individual intersection points according to their positions and the positions of the involved RNs. According to [21], the mutual positions of RNs used for BN position estimation have an impact on the positioning accuracy. The positioning error in this case is defined by the means of the root mean squared error (RMSE).

In this case, the signal-to-noise ratio (SNR) = 9 dB and the coordinates of the RNs are [50; 0] and [150; 0], i.e. they are located on the X axis and the distance between them is 100 m. The BN is situated at each point of the raster in Figure 2. The achieved positioning error is then calculated for each point in the area.

The white value in Figure 2 represents a RMSE higher than 50 m and means that the positioning error is very high. On the contrary, the black value represents the most accurate results. It is obvious that positioning errors can be divided into several areas (layers). The plane divided into layers at intervals of 5 m is shown in Figure 3.

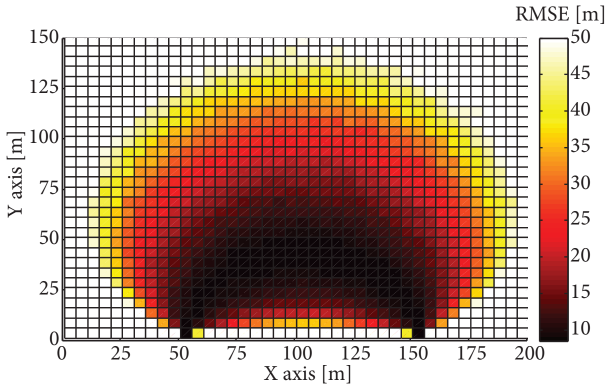

Figure 2. RMSE [m] versus BN position.

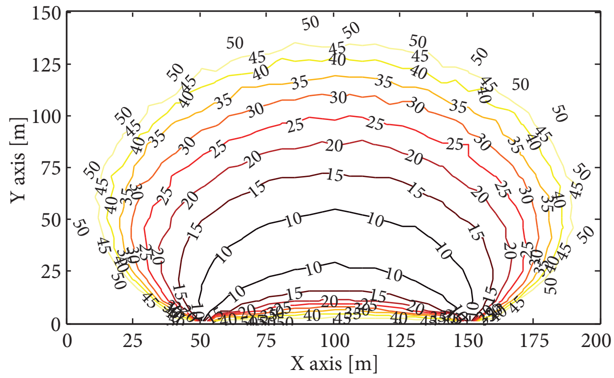

Figure 3. RMSE [m] versus BN position; distance between RNs = 100 m.

In Figure 4, the same dependency is shown, but the interval between the RNs is changed to 20 m. This demonstrates the fact that the decrease of the distance between the RNs signifies the decrease of the positioning error. The obtained RMSE is significantly lower, but the shape of the curves (layers) is pretty much the same. These results are crucial for the next processing. In light of these results, 2 important facts come into consideration:

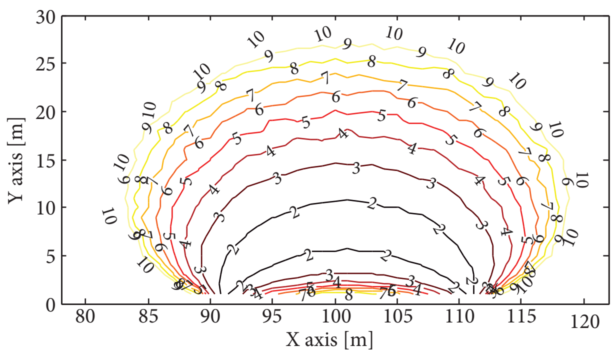

Figure 4. RMSE [m] versus BN position; distance between RNs = 20 m.

1. The position of the BN against the RNs is important and it can be associated with the defined error.
2. The mutual distances between the RNs have an impact on the positioning accuracy.

The relation between the positioning error in particular layers and the distance between the RNs will be utilized for weighting of the particular intersections. The process of the final position estimation can be divided into 3 phases.

In the first phase, weights are assigned to the individual intersections with respect to the layer that they are situated in. The layer width (L_W) is given by a distribution of the RMSE localization error. It can be defined on the basis of the distance between the involved RNs (RN_d). We use 8 layers, which corresponds to 5% of the RN_d:

$$L_W = 0.05 \times RN\_d. \quad (1)$$

The step of 5% of the RN_d is sufficient for this purpose. The layer with the lowest error is the 1st layer and the layer with the highest error is the 8th layer. The greater the layer index, the narrower the layer and the greater the error. The algorithm uses only these 4 interesting layers (see Figure 5):

- First layer: contains the area where the localization error is the smallest and the RMSE ranges up to 10% of the distance of the RNs (layer bounded by blue curves).
- Second layer: contains the area where the RMSE ranges up to 15% of the distance of the RNs (layer bounded by red curves).
- Third layer: contains the area where the RMSE ranges up to 20% of the distance of the RNs (layer bounded by green curves).
- Eighth layer: contains the area where the RMSE ranges up to 45% of the distance of the RNs (layer bounded by cyan curves).
- Outside layer: outside of the 4 defined layers and black collinear lines.

Figure 5 displays how the weights are assigned. Only the intersections that are situated between 2 black collinear lines that cross RNs have a nonzero weight assigned to them. These lines are defined for simplified but sufficient area determination. Table 1 displays the weights used for the individual layers.

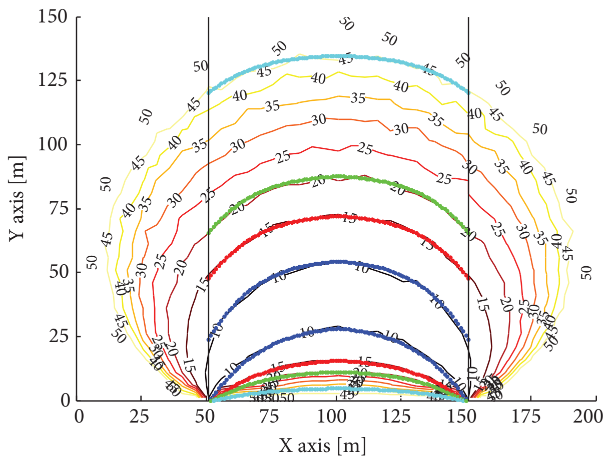

Figure 5. Defined layers.

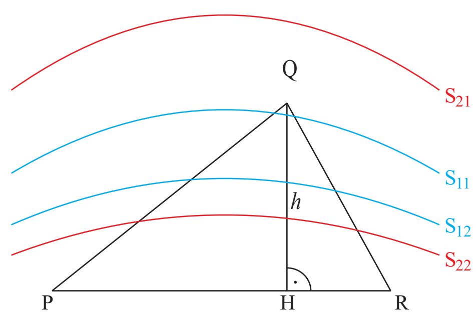

Figure 6. Principle of layer selection.

The mathematical principle of how the layer to which a certain intersection belongs is identified can be explained in the following way. In Figure 6, points Q and R represent 2 involved RNs, point P represents the intersection (estimated position of the BN by the above mentioned RNs), and point H is obtained as an intersection of line |QR| and triangle height |PH| (h).

The curves that define layers for the weights are given as:

$$\begin{array}{l} s_{i1} = (a_{i1} \cdot p) - (b_{i1} \cdot p) \cdot (x/p)^{n_{i1}}\,;\ i = 1, \ldots, 8 \\ s_{i2} = (a_{i2} \cdot p) - (b_{i2} \cdot p) \cdot (x/p)^{n_{i2}}\,;\ i = 1, \ldots, 8 \end{array}, \tag{2}$$

where a_{i1}, a_{i2}, b_{i1}, and b_{i2} are parameters that define the position of the curves for the lower and upper boundaries of the ith layer; root parameter n defines the shape of the curves; i is the index of the layer; p represents distance |QR|; and x stands for the lengths of distances |QH| and |HR|. Parameters a, b, and n are exactly defined constants for each curve. According to these facts, it is clear that curve s_i is the function of the coordinates of point H and the distance between the RNs p. Eq. (2) is derived by fitting the contour of the curve.

According to Eq. (2), the coordinates of intersections S_{i1} *and* S_{i2} between the straight line given by points P and H, and each of curves s_{i1} *and* s_{i2}, which define the boundaries of the layers of the weights, are computed. These intersections represent constraints for the weighting algorithm. The distance between point H and intersection S_i is computed and compared with height h. The layer is then selected according to the result in the following way. The height of triangle h is compared to the distance between point H and intersections S_{i1} and S_{i2}, which belongs to the ith layer. The layer is selected when the following criterion is met:

$$|HS_{i1}| < h < |HS_{i2}|\,;\ i = 8, \ldots, 1. \tag{3}$$

Using Eq. (3), the layer with the lowest possible error is selected. Based on this selection, the weight of the selected layer can be assigned to the given intersection. The weights (W_L) for all of the layers used are shown in the Table 1. These values of the weights are empirically assigned according to preliminary simulations.

Table 1. Weights for the individual layers.

Layer	1	2	3	8	Outside
W_L	10	6	3	1	0

During the second phase, the distance between the RNs, which is used for the creation of the intersection, is also taken into account. The existing weights are modified according to the rule that the shorter the distance, the greater the weight. The distance between the RNs is easy to calculate from their coordinates. This information is available.

The distances between the individual RNs are compared using relative numbers, which is more general and allows the algorithm to be implemented into networks of all sizes (small, medium, or large). For example, the relative distance (RD) could be derived from the radio range of the network nodes or the size of the network area. For simplicity, we assume that the network covers a square area and that the length of the square side is L. The RD is then calculated from the absolute distance RN_d as:

$$RD = RN\_d/L. \tag{4}$$

The weight values with respect to the RD are shown in Table 2. Weights can be also calculated using:

$$W = W_L + \sum_{m=1}^{5} W_D\,[RD < (1 - 0.2\,(m-1))], \tag{5}$$

where W_L is the weight of the layer achieved in the first phase of the algorithm; W_D is the step of the weights based on the distance, where after the experiments we use $W_D = 3$; RD represents the relative distance; m is the number of the steps in which the weight is increased; and $[.] = 1$ if it is true, otherwise 0. We use 5 steps of weights based on the distance between the RNs.

Table 2. Weights for the individual distances.

RD	0.2	0.4	0.6	0.8	1
W_D	15	12	9	6	3

The particular W_L and W_D values are empirically assigned according to preliminary performed simulations. The suitability of the weight values will be tested in the section devoted to the simulation results.

After weights are assigned to individual intersections, the third phase has to be performed, and that is the final position estimation.

The number of intersections depends on the number of RNs in range. As mentioned above, not all of the points of the intersections have a positive impact on the positioning accuracy. In order to prevent using all of the points of the intersections with equal significance for calculations, the weights are assigned. The points of intersections classified as suitable intersections have a higher value of weight and the points of intersections classified as unsuitable intersections have lower values of weight (see Figure 1). The final position estimation is calculated as follows:

$$[x_{est}; y_{est}] = \left[\sum_{i=1}^{NUI} x_i W_i / \sum_{i=1}^{NUI} W_i ; \sum_{i=1}^{NUI} y_i W_i / \sum_{i=1}^{NUI} W_i \right], \qquad (6)$$

where $[x_{est};\ y_{est}]$ are coordinates of the estimated position of the BN, $[x_i;\ y_i]$ are coordinates of the ith intersection, W_i is the weight of the ith intersection, and NUI is the number of utilized intersections. We assume that the value of the NUI influences the localization error in a small way, because individual intersections are weighted.

If there is no intersection with a nonzero weight, the final position estimation is determined by the basic DV-radial algorithm, and thus without optimization.

3. Simulation results

This section analyzes the simulation results obtained by the original DV-radial and enhanced DV-radial algorithms. The positioning accuracy is compared by means of statistical parameters such as the median and cumulative distribution function (CDF) of the RMSE for each trial.

The simulation model takes into consideration a network of 3 kinds of nodes: RNs (aware of their positions), BNs (not aware of their positions or with a position to be estimated), and angular nodes (ANs; only aware of their orientations to the RN). The positions of all nodes are randomly generated with uniform distribution in an area measuring 100 $\times$ 100 m. The radio range of all nodes is 30 m. This limit means that the final angle estimation between the BN and RN is done by more hops (using neighbor nodes). The results are based on 1000 independent runs.

The radio channel is modeled as an additive white Gaussian noise (AWGN) channel, i.e. it consists of 2 parts: the path loss and white Gaussian noise. The second part, i.e. the AWGN, has a more significant impact on the channel properties. An increased value of the AWGN decreases the SNR. The properties of the radio channel are directly modified by the AWGN, and the SNR is affected, as well. The AWGN (SNR) is not dependent on the distance between the transmitter and receiver.

The following criteria are investigated:

- The impact of the SNR on the AoA estimation error.
- The impact of the SNR on the positioning accuracy.
- The impact of RN allocation on the positioning accuracy.
- The impact of the number of RNs used for the position estimation on the positioning accuracy.

In this model, the channel parameters mean only 1 direct error source in the positioning process. Therefore, it is necessary to observe the AOA estimation error versus the SNR dependency. The distance between the 2 nodes (transmitter and receiver) is 30 m.

On the basis of the simulation results (Figure 7), it can be concluded that the AOA estimation error is an exponential function of the SNR. An ascending value of the SNR means a decreased AOA estimation error.

In the next experiments, the basic properties of the proposed enhanced DV-radial algorithm are examined. The impact of the number of utilized intersections, the NUI for the BN position estimation on the positioning accuracy (RMSE), is investigated. This is important for the verification of the appropriate weight assignment. The final position estimation is calculated according to Eq. (6). In this case, SNR = 9 dB and the number of RNs is 10. The achieved results are shown in Figure 8.

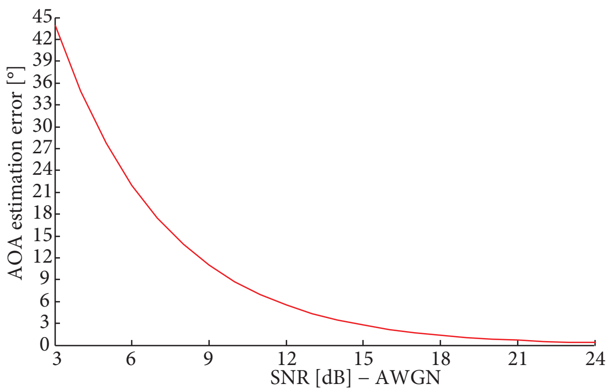

Figure 7. AOA estimation error [°] versus SNR [dB].

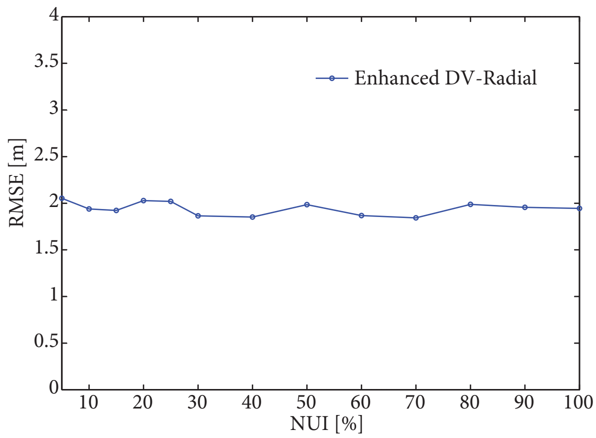

Figure 8. RMSE versus NUI.

The obtained results confirm that the NUI does not have an impact on position accuracy when particular weights are appropriately defined. This result also has a significant impact on the computing requirements, because the enhanced DV-radial algorithm does not need to consider a large amount of existing intersections. Only intersections with the highest weights are considered for the final position estimation.

Figure 9 shows the influence of the SNR on the positioning accuracy. The network consists of 60 nodes + 1 BN, and the rate of RNs is 50%, i.e. number of RNs = number of ANs = 30, and SNR = 9 dB. There is an observed direct dependency between the positioning error (RMSE) and AOA estimation error. Increasing the value of the SNR yields more accurate positioning results caused by a more accurate AOA estimation. The enhanced algorithm achieves more accurate results compared to the original DV-radial by approximately 50%.

In Figure 10, to gain more insight into the statistical view of the proposed algorithm with respect to the positioning error, the corresponding curves represent the CDF of the localization error. We consider the same parameters for the simulation model as in the previous simulation.

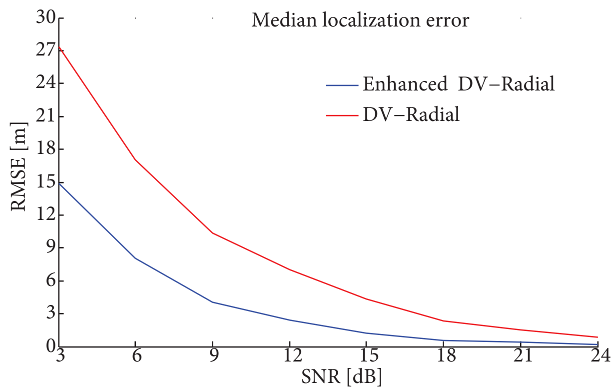

Figure 9. Impact of the SNR on the positioning accuracy.

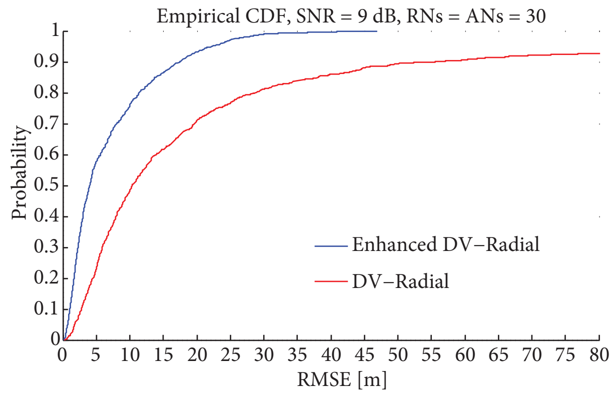

Figure 10. Comparison of original and enhanced algorithms.

As shown by the simulation results, the enhanced DV-radial performs better than the original DV-radial. The enhanced algorithm cuts down on the extreme cases that occur in the case of the original algorithm. These extreme situations are caused by the fact that all of the mutual intersections of the lines of the positions are taken into account in the case of the DV-radial.

Finally, a complex view of the performance of both algorithms is taken. The mutual impact of the number of all nodes in the network and the rate of RNs from all nodes in the network is investigated.

The obtained results shown in Figures 11 and 12 confirm the facts from previous simulations, i.e. the enhanced algorithm achieves more accurate and more stable results compared to the original one. The number of nodes in the network has an impact on the RMSE. Fewer nodes in the network mean that the angular information has to be estimated for a longer distance (RN-BN) and it means a bigger AOA error (positioning error). If the rate of RNs of all nodes is higher, the probability that the RN is in the range of a BN is also higher, and the angle can be directly estimated from the RN and not by means of the ANs. This causes the RMSE to be lower in the case of a higher rate of RNs.

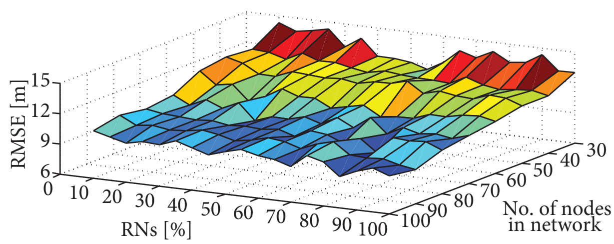

Figure 11. RMSE versus percentage of RNs and number of nodes in the network (DV-radial).

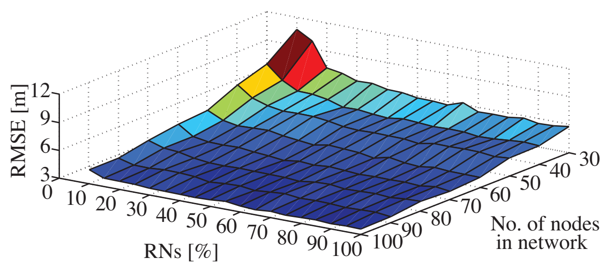

Figure 12. RMSE versus percentage of RNs and number of nodes in the network (enhanced DV-radial).

In the last simulation, the impact of the proposed algorithm on localization using the simple AoA algorithm is investigated. In this scenario, 10 RNs are placed in a localization area measuring 100 $\times$ 100 m. In the simulation, it is assumed that the radio signal from all of the RNs can be detected everywhere in the area. The SNR in the AWGN radio channel is set to 9 dB. The achieved results are shown in Figure 13 as the CDF of the RMSE.

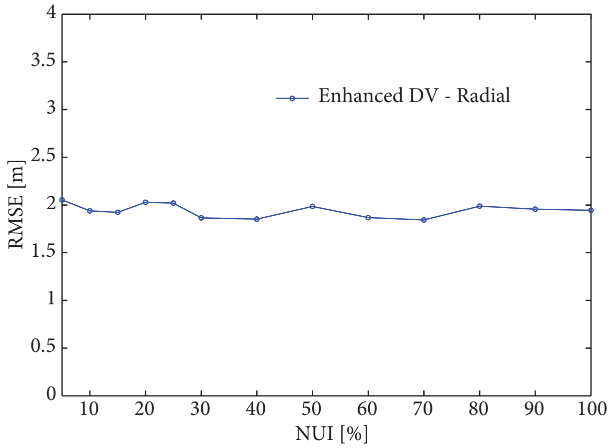

Figure 13. CDF of RMSE achieved for basic and enhanced AoA algorithms.

From the achieved results, it can be seen that the proposed algorithm can improve the localization accuracy of the AoA localization algorithm, and a significant difference in the positioning error is observed, especially with a higher probability. The enhanced AoA algorithm cuts down on many of the extreme cases that occur during the positioning process with the AoA algorithm. A RMSE of higher than 70 m could be marked as an extremely high error, because it is half of the communication range of the considered nodes. For example, for the enhanced AoA, the 95% probability corresponds to 5 m of localization error, which is contrary to that of the basic AoA, where it is approximately 70 m. These extreme localization errors are caused by the fact that all of the mutual intersections of the lines of the positions are taken into account in the case of AoA.

4. Conclusion

We proposed and verified the properties of an enhanced DV-radial positioning algorithm. The algorithm selects only the subset of all intersections for the final position estimation of a BN. It then assigns weights to individual points of intersection, according to their positions and the positions of the RNs. For the final position estimation, only intersections with the highest weights are used.

The distinguished advantage of this localization algorithm compared to the basic DV-radial is its higher accuracy. Simulations show that the enhanced algorithm brings more accurate results, regardless of current conditions (SNR and the number of RNs). The proposed optimization algorithm can be adapted to any other localization algorithms that use AoA measurements to estimate the position of a BN. This was proven in the simulations performed for 2 localization algorithms based on the AoA principle.

Some additional work could be done to emphasize the advantages and drawbacks of our algorithm, such as an analysis of the behavior of our algorithm in more realistic networks. Future works could lie in the algorithm's optimization to decrease the computing requirements.

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