Does Multi-hop Communication Enhance Localization Accuracy?

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***Abstract*—Estimating the location of sensor nodes in wireless sensor networks is a fundamental problem, as sensor node locations play a critical role in a variety of applications. In many cases the area covered is very large making it impossible to localize all sensor nodes using single-hop localization techniques. A solution to this problem is to use a multi-hop localization technique to estimate sensor node positions. Multi-hop localization techniques are classified into two main categories: range-based and range-free. Despite the numerous existing localization techniques, the fundamental behavior of multi-hop localization is yet to be fully examined. The aim of this paper is to study the effect of errors in a multi-hop localization environment and how this impacts localization accuracy. There has been a general belief that a fewer number of hops results in higher accuracy. Through different experiments on two generic localization techniques representing both categories of localization schemes, we show that such belief is not true in all cases, as in dense environments often using shorter hops gives better accuracy.**

***Index Terms*—Localization, Positioning, Multi-hop, DV Hop, DV distance, range based, range free.**

I. INTRODUCTION

Localization in Wireless Sensor Networks (WSNs) is attracting considerable research interest as identifying the position of Sensor Nodes (SNs) is required in numerous vital applications, including fire alarm systems, water quality monitoring, intrusion detection and commercial agriculture. Sending the sensed data to the central server is useless, if the locations of the events are not associated with the position of the received data. For this reason, a wide variety of localization techniques for WSNs have been recently proposed.

WSN Localization algorithms mainly estimate the position of unlocalized SNs with the aid of anchor nodes, i.e. SNs that have knowledge of their absolute position. Anchor nodes know their positions by either using a global positioning system (GPS), or by being attached to predefined locations with known coordinates. To localize SNs, anchor nodes broadcast their location with the operating instructions to SNs, and SNs use the received instructions to estimate their own locations.

Depending on the application and size of the sensed environment, localization techniques can either be single-hop or multi-hop. In single-hop techniques, un-localized SNs require a minimum of 3 anchor nodes in 2-D and 4 anchor nodes in 3-D within their transmission range in order to estimate their locations using one of the distance measurements: Received Signal Strength Indicator (RSSI), Time of Arrival (ToA), Phase of Arrival (PoA) or Angle of Arrival (AoA) [1]. However, if the area of the sensed environment is large such that not all the SNs can be covered by a single-hop, a multi-hop localization technique is used. There are two major categories of multi-hop localization techniques. The first category is distance-based that relays on the individual inter-sensor distance data. The second category, connectivity-based or range-free localization techniques, does not depend on any of the distance measurement techniques mentioned earlier. This approach is mainly based on connectivity information to estimate the locations of the un-localized SNs [2].

Regardless of the encouraging results of the previous proposed localization techniques, the proposed solutions provide an inaccurate position estimation, especially when used in multi-hop scenarios. Even in an ideal setup and ignoring the obstacles between SNs that can affect the localization process, a relatively small error in distance estimation can induce a much larger error in SNs location estimation.

Localization estimation errors can be broken down into extrinsic or intrinsic error [3]. An intrinsic error is usually caused by the imperfections of the sensor hardware and/or software, while an extrinsic error is attributed to the physical effects on the measurement channel and multi-hop communication. Savvides et al. [3] studied a range of intrinsic error characteristics for different measurement technologies, however they did not study the effect of extrinsic error. In this paper we are interested in studying the effect of extrinsic errors on multi-hop localization. A common belief by researchers in multi-hop localization techniques is: by increasing the number of hops between the anchor nodes and SNs, this will increase the localization error. However, in this study we show that this belief is not always the case. Indeed, there are conditions where using a larger number of hops gives a better localization accuracy than using a smaller number of hops.

The remainder of this paper is organized as follows. A background of multi-hop localization techniques used in this paper, multilateration and error modes is covered in Section II. Section III presents the performance evaluation setup. The results and discussion about the findings are discussed in Section IV. Conclusions are given in Section V.

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II. BACKGROUND

In this section, we provide a background about the main multi-hop localization techniques used in WSNs that cover range-based and range-free categories. After which we explain the multilateration process used to estimate nodes location, and lastly, we discuss the error components used in this paper.

A. Multi-hop Localization

In this paper, we adopt two generic techniques that represent the two major categories of multi-hop localization techniques. DV-Hop represents the connectivity based category, while DV-Distance represents the distance-based category [4]. In the following subsection, we will give a quick overview about DV-Hop and DV-Distance respectively.

1) DV-Hop Localization technique:

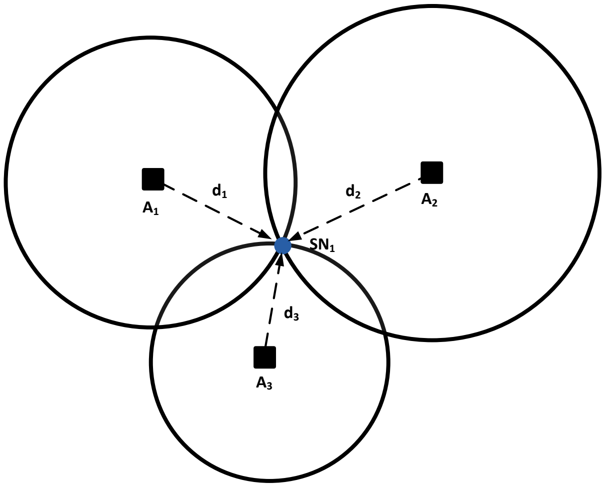
The DV-Hop localization technique has two stages. In the first stage the anchor nodes broadcast their actual positions to the SNs. The SNs keep the shortest number of hops to each anchor node along with the anchor node's position. Thus at the end of the first stage, each SN maintains a table of $\{x_i, y_i, h_i\}$, where x_i and y_i are the coordinates of anchor i and h_i is the shortest number of hops to reach anchor i. SNs exchange the shortest hop position messages only with their neighbors. When an anchor node receives a position message from other anchor nodes, it estimates the average distance for a single hop for the entire network. The average distance of a single hop of anchor i is calculated as follows

$$c_i = \sum_{j=1}^{M} \frac{\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}}{h_j}, \ \ where\ i \neq j. \qquad (1)$$

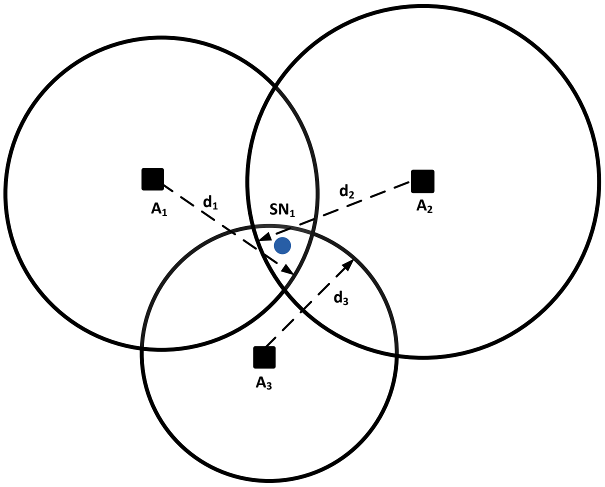
In the second stage, the anchor nodes broadcast their estimates of the average distance for a single hop. SN saves the average single hop from the closest anchor node and forwards it to its neighbors. The SNs use the received average distance for a single hop and multiply it with the total number of hops for each anchor node using the information saved in the table $\{x_i, y_i, h_i\}$. Finally, these values are then plugged in the multilateration equation described in the next subsection. The error in the DV-Hop localization technique appears since it assumes all hops to have the same value.

2) DV-Distance Localization technique:

The DV-Distance localization technique has only one stage, in which the anchor nodes broadcast their positions to the entire network. The position message contains the actual position x_i, y_i of anchor node i and the total distance traveled d_i. The anchor node initializes the distance to 0. When a SN receives the packet, it estimates the distance the packet traveled for a single hop using either RSSI or ToA. After which the SN node adds the estimated distance to the total distance traveled field and forwards the packet. Thus, each SN maintains a table of $\{x_i, y_i, d_i\}$, where x_i and y_i are the coordinates of anchor i and d_i is the cumulative traveling distance estimated in meters from anchor node i. The DV-Distance technique is prone to distance estimation errors due to obstacles between SNs, multi-path fading, noise interference, and irregular signal propagation. However, the hops between SNs are not assumed to have the same distance.



(a) Noise free distance measurements



(b) Noisy distance measurements

Fig. 1: The difference between trilateration with noise free and noisy distance measurements.

B. Multilateration using Linear Least Square

Multilateration is the process that uses the estimated distance between anchor nodes and un-localized SNs to estimate the location of the SNs. In the ideal case, multilateration assumes that distance measurements are accurately estimated and noise-free. Figure 1(a) shows that the 3 circles intersects in a single point which represent the location of the SN.

However, such a situation is not usually applicable as the accuracy estimation of distance measurements are easily affected by surrounding noises. These inaccuracies prevent the circles to intersect in a single point making the localization process more challenging. Figure 1(b) shows that the 3 circles does not intersect in a single point. A possible solution to estimate the SN location is to use the least squares optimization [5].

C. Error components

The process of estimating the distance between a pair of SNs is the building block for ranging techniques. RSSI and ToA are the most common ranging techniques used in WSN localization. Both techniques introduce noise to the estimated distance [6]. RSSI is commonly used to estimate the distance between the un-localized SN and the sender based on the strength of the received radio frequency signal by either using RSSI profiling measurements or estimating the distance via the analytical model by mapping the RSSI to distance using the path-loss propagation model. In this case, the rate in which the signal attenuation over distance is assumed to be previously known and the distance is estimated using the following equation [2]

$$\hat{d}_{ij} = d_0 \left(\frac{P_{ij}}{P_0(d_0)}\right)^{-1/n_p} e^{\frac{\sigma^2}{2\eta^2 n_p^2}}, \tag{2}$$

where $P_0(d_0)$ is a known reference power value at a reference distance d_0 from the transmitter, P_{ij} is the RSSI measurement between a transmitter i and a receiver j, n_p is the path loss exponent that indicates the rate at which the RSSI decreases with distance, and $\eta = \frac{10}{ln(10)}$. RSSI is very sensitive to channel noise, interference, attenuators and reflections. All of which have significant impact on signal amplitude.

ToA estimates the distance by measuring the time the signal takes to travel between two SNs and multiplies it by the speed of the signal by assuming that such speed is constant. Since ToA relies on the speed of the signal rather than the signal strength, it is relatively immune to most sources of noise including signal attenuation and reflections. However, the estimated distance is affected when there is no line-of-sight between SNs, the processing time at the SNs and the queuing time of the packets.

In theoretical analysis and simulation, RSS and ToA are usually modeled with a noisy disk model, which is represented by two components: node connectivity and error. The node connectivity component represents the distance between the two SNs, while the noise component represents the noise distribution of the estimated distance and the actual distance. In most cases the noise is represented by White Gaussian process. The noisy disk model using the White Gaussian noise that defines the measured distance between the i^{th} and j^{th} SN can be represented as

$$d_{i,j} = d_{j,i} = r_{i,j} + \varepsilon_{i,j} \qquad \forall i, j = 1, 2, \ldots, M \tag{3}$$

where $r_{i,j} = \|\mathbf{x}_i - \mathbf{x}_j\|$ is the noise free distance between node i and j, and $\varepsilon_{i,j} \sim \mathcal{N}(0, \sigma_{i,j}^2)$ represents the uncorrelated noise, where $\sigma_{i,j}^2$ is assumed to be accurately estimated and is known a priori [7].

Several recent works in localization adopt the noisy disk model to mathematically derive the maximum likelihood for localization, study lower bounds on localization error and/or to evaluate and compare different localization techniques using simulation [6]–[10]. To better estimate distance errors, the variance used in the estimation should be a function of distance and SNR. We hence represent the variance as $\sigma_{i,j}^2 = d_{i,j}^2/SNR$. This makes the variance dependent on distance and SNR. Earlier studies of multi-hop localization [8], [10] have adopted such formulation.

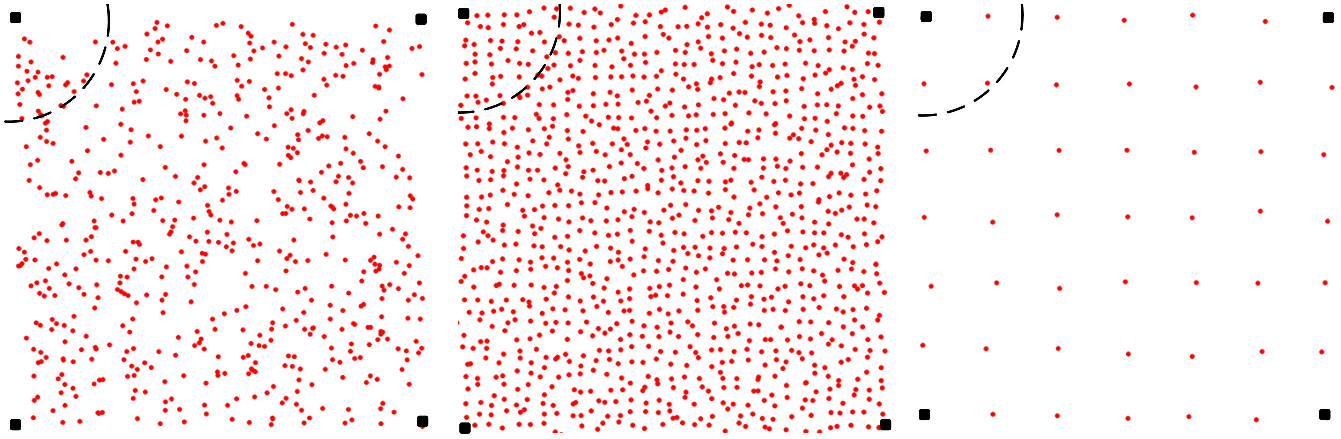
III. PERFORMANCE EVALUATION SETUP

In the simulation, we use NS3 [11] to study the effect of multi-hop on DV-Hop and DV-Distance localization schemes. The WSN is deployed with N un-localized SNs and 4 anchor nodes. Different numbers and locations of anchor nodes have been experimented with and resulted in similar observations. The simulation area is set to be $200 \times 200\ m^2$. To minimize the effect of the anchor nodes position on localization accuracy and to overcome the collinearity effect, the 4 anchor nodes are placed at the 4 corners of the simulation area. The collinearity problem appears when the anchor nodes are on the same line [12]. In this case, it is hard to identify whether the SN is on the left or right of the anchor nodes, which causes the position of the SN to be flipped [13]. The range measurement noise $\varepsilon_{i,j}$ used in estimating the distance for DV-Distance is a zero-mean White Gaussian process with variance $\sigma_{i,j}^2 = d^2/\text{SNR}$, where SNR is the signal-to-noise ratio received by the node [10]. We use two values for SNR: SNR $=$ 10 db is used to represent a communication channel with a high noise and SNR $=$ 30 db is used for a communication channel with low noise. All results are averages of 10 different independent runs with distinct random seeds.

To study the effect of multi-hop communication on localization accuracy, we estimate the location of the SNs using 5 different transmission ranges for SNs, ranging from 20 meters to 100 meters with a step of 20 meters. To understand the effect of multi-hop on localization accuracy, we considered 3 different deployment scenarios. Fig. 2 shows the different deployment scenarios used in the simulation when the transmission range is set to 50 meters. The first scenario, represents a practical scenario, where SNs are deployed randomly in the sensor area as shown in Fig. 2(a) with a total of 1000 SNs. The second and third scenarios, represents controlled environments, enabling a better understanding of the effects of the errors. In the second scenario, the SNs are deployed in a fixed grid with a 10 meters step between SNs with a total of 1000 SNs as shown in Fig. 2(b). In the third scenario, the SNs are deployed in a dynamic grid, where the number of SNs and their placement are changed based on the SN transmission range as shown in Fig. 2(c). The number of SNs used in the dynamic grid is calculated using the following equation

$$= \left(\frac{\sqrt{(\text{Sim. Width})^2 + (\text{Sim. length})^2}}{\text{trans. Range}} + 2\right)^2, \tag{4}$$

while the vertical step is calculated using the following equation



(a) Random Deployment (b) Fixed Grid Deployment (c) Dynamic Grid Deployment

Fig. 2: Example for the different deployment strategies used for WSNs. The transmission range of SNs in this example is 50 meters.

$$= \frac{\text{Sim. width} \times \text{tran. Range}}{\sqrt{(\text{Sim. Width})^2 + (\text{Sim. length})^2 + \text{trans. Range}}} \qquad (5)$$

and horizontal step is calculated using:

$$= \frac{\text{Sim. length} \times \text{tran. Range}}{\sqrt{(\text{Sim. Width})^2 + (\text{Sim. length})^2 + \text{trans. Range}}}. \qquad (6)$$

To make the fixed grid deployment more realistic, we assume that there is randomness in the deployment of individual SNs. The randomness is modeled by a random error disk with a radius of 1 meter [14]. The second scenario represents a dense deployment for SNs, in which more SNs are covered by increasing the transmission range. While, the third scenario represents a non dense deployment where SNs are only covered by the boarder of the maximum transmission range. For example in Figure 2(b) when the transmission range is 50 meters, there are more than 50 SNs covered, where 3 or 4 of them are within 10 meters away from the anchor nodes, while there are around 10 SNs that are almost 50 meters away and the rest of the SNs are in between. This variant of distance increases the overall localization error. Where as in Figure 2(c) when the transmission range is 50 meters, we only have 3 nodes which are approximately 50 meters away from the anchor node.

IV. RESULTS AND DISCUSSION

For all the experiments we performed, it is clear that DV-Hop localization technique outperforms DV-Distance technique when the SNR is low. Previous works have also pointed to such findings such as [15]. However, when the SNR increases the performance of DV-Distance improves. In the following subsections, we discuss the results for random deployment, fixed grid and dynamic grid.

A. Random deployment

Figure 3 shows that using shorter hops gives a higher accuracy, for both DV-Hop and DV-Distance localization techniques. The average accuracy decreases when we increase the transmission range of the SNs for both DV-Hop and DV-Distance. However, the decrease in accuracy of DV-Hop is larger than DV-Distance when we increase the transmission range. The accuracy of DV-Hop decreased by 11% while the accuracy of DV-Distance decreased by 8%, for SNR = 10 db and 3% for SNR = 30 db when the transmission range of the sensor nodes increases from 20 meters to 100 meters.

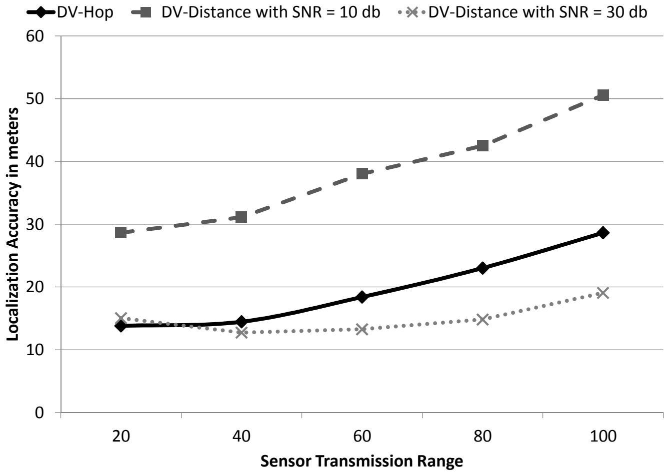


Fig. 3: The localization accuracy using random deployment for sensor nodes.

This results show that in highly dense environments it is better to have a larger number of hops with shorter transmission ranges than to have a small number of hops with larger transmission ranges. These findings are in contrast to an earlier belief that using shorter hops would give better accuracy. In order to understand the reason for such behavior, we use the two controlled experiments: fixed grid and dynamic grid explained in Section III.

B. Fixed Grid

Figure 4 shows the accuracy for localizing SNs when the SNs are placed in a fixed grid. The number of SNs is not changed, when we increase the transmission range for SNs. The accuracy of DV-Hop localization is reduced by 27% when

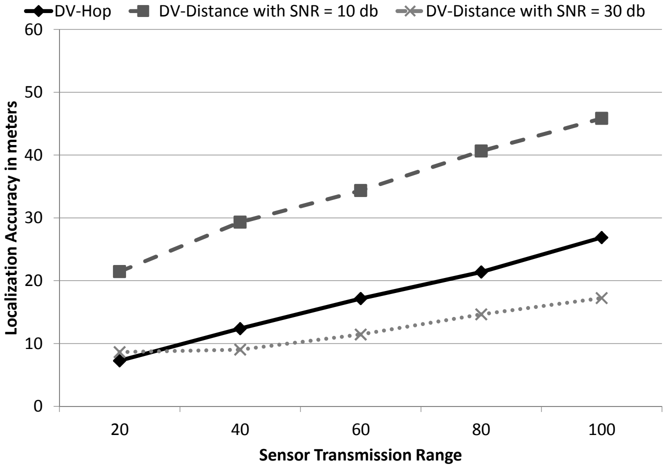
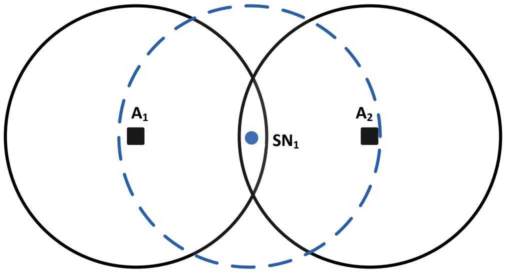
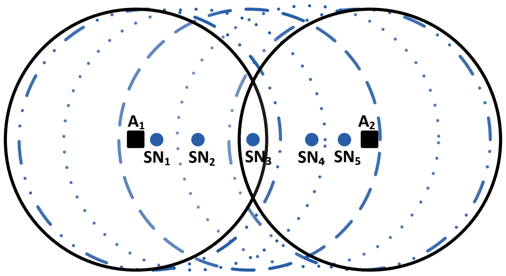


Fig. 4: The Localization Accuracy using Fixed Grid Deployment for Sensor Nodes.



(a) Non dense Environment



(b) Dense Environment

Fig. 5: Explain the difference between dense and non dense environment for DV-Hop

the transmission range is increased from 20 meters to 100 meters. Whereas the accuracy of DV-Distance only decreases by 12% and 10% for SNR = 10 db and 30 db respectively.

The reason that the localization accuracy decreases for DV-Hop as we increase the transmission range (decreasing the number of hops) is explained in Figure 5. If we assume the the distance between A_1 and A_2 is 100 meters. In the ideal case when there is 1 SN between the two anchor nodes as shown in Figure 5(a), both anchor nodes calculate that the average hop distance is 50 meters as the message reached A_2 in 2 hops. Thus when N_1 multiples the average hop distance which is 50 by the number of hops which is 1, we get 50 meters which is a highly accurate estimation. However, this is not the case in a dense environment. Figure 5(b) shows that there are 5 SNs between the two anchor nodes. The number of hops taken to reach A_2 is 3 hops through N_1, N_2, N_4 and N_5 and 2 hops through N_3. Thus the shortest number of hops is 2 hops. Thus the average hop distance is 50 meters. When N_1, N_2 and N_3 multiply the average hop distance which is 50 meters by the number of hops which is 1, as all of them are covered by a single hop, we get 50 meters which is an accurate estimation for N_3 only.

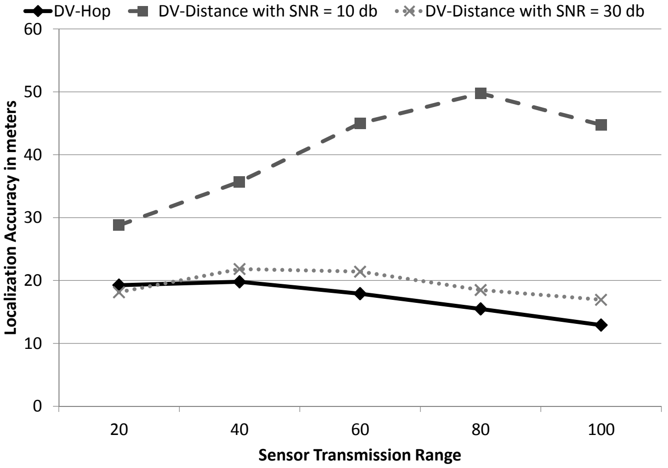
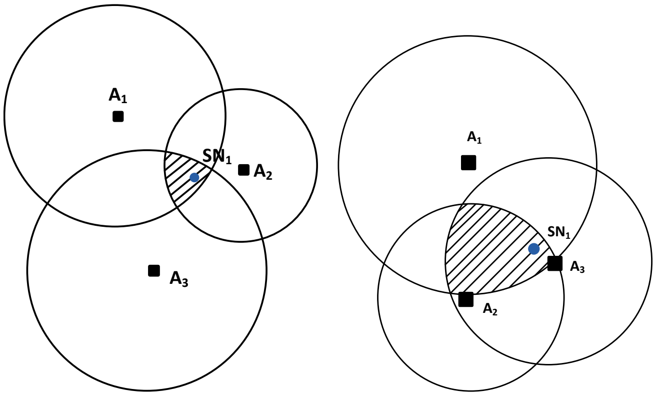


Fig. 6: The localization accuracy for dynamic grid deployment for sensor Nodes.



(a) Small Area (b) Large Area

Fig. 7: The area used in multilateration to estimate the node position.

C. Dynamic Grid

When using a dynamic grid, i.e. decreasing the number of SNs as we increase the transmission range, we find that localization accuracy improved when we decrease the number of hops for both DV-Hop and DV-Distance using SNR = 30 db as shown in Figure 6. This result was as expected, however, the accuracy decreased dramatically when we used DV-Distance using SNR = 10 db.

To explain why DV-Distance with high noise (low SNR value) has poor accuracy in a non dense environment when using longer transmission ranges, refer to Figure 7. When the distance between the anchor nodes and the SN is accurately estimated the area we perform multilateration is relatively small, which increases the localization accuracy as shown in Figure 7(a). However, when the error for the estimated distance is high, the area on which we perform multilateration is larger. This increases the error for the estimated position. Thus when we use DV-Distance in an environment that has a high noise level in the channel it is better to use shorter hops with a shorter transmission range than to use a long transmission range.

V. CONCLUSION

In this paper, the effect of number of hops in multi-hop localization techniques is investigated. There has been a belief in the literature that the smaller the number of hops the grater the accuracy is. We assess such belief for representative generic schemes of range-based and range-free localization. We consider a number of sensor nodes deployment and anchor node placement scenarios. Deployment scenarios considered include random, fixed grid, which represents a controlled dense environment, and dynamic grid, which represents a controlled non-dense environment. Our results show that using a larger number of hops with a shorter transmission range in dense environments may provide higher accuracy than using a small number of hops with a larger transmission range. In less dense environments with a noisy channel it is also better to use a large number of hops with a shorter transmission range for a range-based localization technique. In general, range-free localization performs better than range-based localization under noisy communication channels. The findings of this paper show that the choice of localization techniques (with or without multi-hopping) is dependent on deployment setting and channel conditions.

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