An Overview of Localization Techniques for Wireless Sensor Networks

A. R. Kulaib and R. M. Shubair
Khalifa University
Sharjah, UAE
Communication Engineering Department
Email: akulaib, rshubair,@kustar.ac.ae

M. A. Al-Qutayri
Khalifa University
Sharjah, UAE
Electronic Engineering Department
Email: mqutayri@kustar.ac.ae

Jason W. P. Ng
Khalifa University
AbuDhabi, UAE
Etisalat BT Innovation Centre
Email: jason.ng@kustar.ac.ae

***Abstract*—Localization of sensor nodes is an important aspect in Wireless Sensor Networks (WSNs). This paper presents an overview of the major localization techniques for WSNs. These techniques are classified into centralized and distributed depending on where the computational effort is carried out. The paper concentrates on the factors that need to be considered when selecting a localization technique. The advantages and limitation of various techniques are also discussed. Finally, future research directions and challenges are highlighted.**

I. Introduction

Sensor nodes usually consist of a low power processor, a small amount of memory, a wireless transceiver, and a sensor board. The size and price of sensor nodes decreased significantly over the past few years to the point that it is possible to build large WSNs. Such networks are becoming increasingly important as they enable the placement of sensors as close as possible to the event, which in turn provides better signal quality. However, the sensor data by itself, in many applications, is of low value unless the spatial information is known. This is because; the lack of location information can result in an incorrect interpretation of data. As a result, research interest in WSN localization has recently increased significantly. WSNs are used in a wide range of applications, such as habitat monitoring, smart environments, and target tracking. These applications require exact localization of nodes with respect to a global coordinate system in order to provide meaningful information and to be able to efficiently route data through the network [1], [2].

Localization is basically the process of determining the physical coordinates of a group of sensor nodes. In WSNs, nodes that have known coordinates are called beacon nodes or anchor nodes. These nodes provide their global coordinates either by hard coding it or by fitting them with a GPS receiver. Using anchor nodes simplifies the task of assigning coordinates to ordinary nodes. However, anchor nodes usually use a GPS, which is expensive, cannot be used indoor, and may face some difficulties if they are placed near obstacles such as tall buildings. The GPS also consumes significant battery power which is a limited resource in WSNs. Another option is to program the nodes with their locations before deployment. This method is impractical for large scale networks and impossible if nodes are deployed from an aircraft [1]. The coordinates in a network can either be absolute (global) or relative (local). Absolute location can be obtained using anchor nodes, while relative location can be determined using signal processing techniques such as multilateration or triangulation [2], [3].

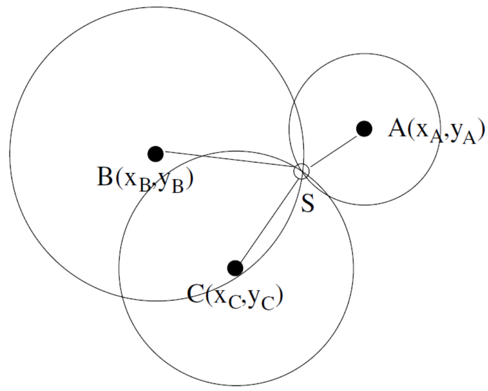

Fig. 1. Trilateration technique [4].

This paper is organized as follows. Location discovery techniques are highlighted in section II and evaluated in section III. After that, a classification of the localization algorithms is presented in section IV. Finally, section V presents the conclusions of this study, and highlights future research directions and challenges associated with localization in WSNs.

II. Location Discovery Techniques

There are three basic localization techniques that are used as a base to a more advanced techniques [4], [5]:

- **Trilateration:** This method determine the position of a node from the intersection of 3 circles of 3 anchor nodes that are formed based on distance measurements between its neighbours. The radius of the circle is equal to the distance measurement as shown in Figure 1. However, in a real environment, the distance measurement is not perfect; hence, more than three nodes are required for localization.
- **Triangulation:** This method is used when the direction of the node rather than the distance is estimated. It uses

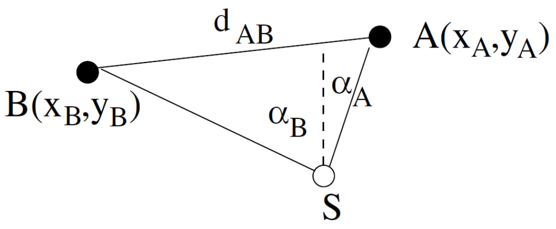

Fig. 2. Triangulation technique [4].

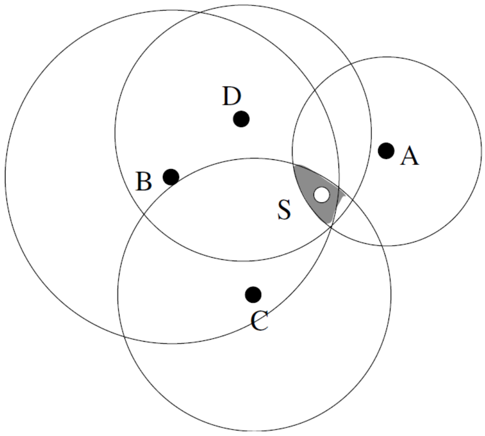

Fig. 3. Multilateration technique [4].

trigonometry laws of sines and cosines to calculate the nodes position based on the angle information from two anchor nodes and their positions as shown in Figure 2.

- **Maximum Likelihood Multilateration:** Trilateration technique cannot accurately estimate the position of a node if the distance measurements are noisy. A possible solution is to use the Maximum Likelihood (ML) estimation, which includes distance measurements from multiple neighbour nodes as in Figure 3. This method intends to minimize the differences between the measured distances and estimated distances.

Several localization or ranging techniques that are used to localize the position of sensor nodes have been proposed in the literature, they include Time of Arrival (ToA), Received Signal Strength (RSS), Radio Hop Count, and Angle of Arrival (AoA) [1], [3], [4], [6], [7].

A. *Time of Arrival Technique*

ToA is defined as the earliest time at which the signal arrives at the receiver. It can be measured by adding the time at which the signal is transmitted with the time needed to reach the destination (time delay). The time delay can be computed by dividing the separation distance between the nodes by the propagation velocity. In ToA, the nodes have to be synchronized and the signal must include the time stamp information [3]. To overcome these restrictions, Round-trip Time of Arrival (RToA) and Time Difference of Arrival (TDoA) are developed.

RToA is similar to ToA but it doesnot require a common time reference between nodes. It works by recording the time

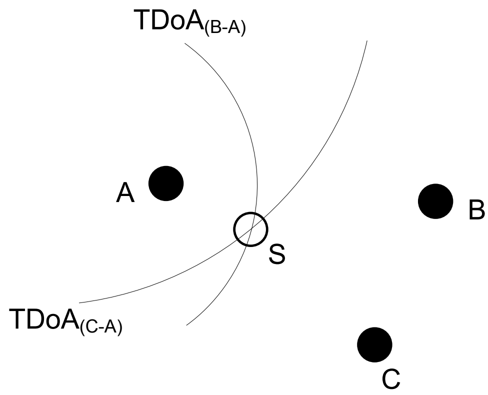

Fig. 4. Multi-node time difference of arrival method.

of transmission at node ‘A’ according to its own clock, then node ‘B’ records the reception time in its own time reference and transmits back to node ‘A’ after some time interval. Finally, node ‘A’ records the time of reception and uses the recorded timings to determine the distance between the two nodes [3].

TDoA is a well known technique to measure distance between nodes. TDoA techniques can be classified into two main types: multi-node TDoA, and multi-signal TDoA. The multi-node TDoA uses ToA measurements of signals transmitted from multiple anchor nodes. Three synchronized anchor nodes are required to accurately locate a node as shown in Figure 4. This technique works by measuring the difference in time between a pair of anchor nodes. This difference defines a hyperbola on which node S should lie. Two hyperbola is sufficient to pin point the location of node S. On the other hand, the multi-signal TDoA uses two different kinds of signals that have different propagation speeds to estimate its distance to another node. This technique requires additional equipments, a microphone and a speaker. In this technique it is possible to use ultrasound or audible frequency without changing the algorithm. It operates by sending a radio message and waiting for fixed interval t_{delay} and then produces a signal with a fixed pattern (chirps) using its speaker. On the other side, a node will register the current time t_{radio} when it detects the radio signal, then turns on their microphones and waits until it detects a chirp to register the current time (t_{sound}). Finally, the distance between the two nodes is calculated using (1) that is based on the fact that sound (s_{sound}) travels significantly slower than radio (s_{radio}) waves in air as shown in Figure 5.

$$d = (s_{radio} - s_{sound}) * (t_{sound} - t_{radio} - t_{delay}) \qquad (1)$$

TDoA can also be measured based on the fact that the distances between the transmitter and different receivers are different. This means that the transmitted signal is delayed in time based on the distance to the receiver. The time delay between two receivers can be obtained by computing the correlation between the two signals. The location of the peak

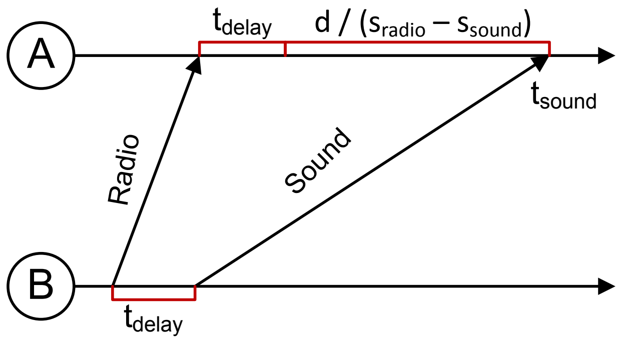

Fig. 5. Multi-signal time difference of arrival method.

in the cross correlation output is used to estimate the TDoA. Moreover, it is recommended to use the generalized cross correlation, since it is less vulnerable to noise, interference, and multipath [8].

B. Received Signal Strength Technique

RSS is a common technique in localizing sensor nodes; this is due to the fact that almost all nodes have the ability to measure the strength of the received signal. RSS technique benefits from the fact that radio signals diminish with the square of the distance from the signal's source. In other words, the node can calculate its distance from the transmitter using the power of the received signal, knowledge of the transmitted power, and the path-loss model. The operation starts when an anchor node broadcasts a signal that is received by the transceiver circuitry and passed to the Received Signal Strength Indicator (RSSI) to determine the power of the received signal. The RSS measurements of node i and j at time t can be calculated using the following equation [4]:

$$P_R^{ij}(t) = P_T^i - 10\eta \log(d_{ij}) + X_{ij}(t) \tag{2}$$

where P_T^i is a constant due to the transmitted power and the antenna gains of the sensor nodes, η is the attenuation constant, d_{ij} is the distance between the two nodes, and $X_{ij}(t)$ is the uncertainty factor due to multi-path and shadowing.

In addition, a technique similar to RSS called potentiometer can be used for sensor localization. This technique works by increasing the signal power in steps until the node receives three replies. Then it sends the data to a central receiver to compute the position of the sensor node using triangulation [9].

C. Radio Hop Count Technique

Radio hop count technique exploits the fact that if two nodes can communicate then the distance separating them is less than R, where R is the maximum range of their radios. For instance, if s_i and s_j are two nodes in a network then h_{ij} is the hop count that represents the shortest path between the two nodes, and d_{ij} is the distance between the two nodes, which is less than Rh_{ij}. In order to get a better estimate of the distance (3) is used if the expected number of neighbours per node is known (n_l) and is between 5 and 15. Above 15 nodes d_h approaches R, Thus, d_{ij} becomes approximately equal to $h_{ij}d_h$ [1].

$$d_h = R\left(1 + e^{-n_l} - \int_{-1}^{1} e^{-\frac{n_l}{\pi}(acos\ t - t\sqrt{1-t^2})} dt \right) \tag{3}$$

D. Angle of Arrival Technique

AoA technique can obtain angle data using radio array methods. It can estimate the AoA using multiple or directional antennas. In multiple antennas, it operates by analysing the time or phase difference between the signals at different array elements that have known locations with respect to the centre element. For example, the difference in arrival time Δ_t between two antenna elements is formulated in (4), where δ is the antenna separation, v is the velocity of the RF signal, and θ is the angle at which the signal arrives. In directional antennas, it operates by computing the RSS ratio between several directional antennas that are placed carefully, in order to have an overlap between their main beams. The AoA measurement from two anchor nodes can be combined with their locations (tringulation) to estimate the location of the node [3], [6].

$$\Delta_t = \delta / (v\ \cos\ \theta) \tag{4}$$

An alternative method is the beamforming technique that is used in array signal processing for a wide range of applications such as radar, sonar, communications, medical imaging, astronomy, and acoustics. There are many beamforming algorithms that have been reported in the literature. The choice of a beamforming algorithm depends on many factors such as the cost of the system, computational cost, performance, and robustness. It also depends on the application and the environment. Thus, the solution for one application may not be suitable for another.

III. Evaluation of Location Discovery Techniques

RSS measurement is not precise since radio propagation in real environments is extremely non-uniform. This is because real environments consist of different materials and have lots of obstacles that influence the radio propagation (shadowing and multipath modelled by the term $X_{ij}(t)$ in (2)). For example, the relation between distance and signal level in open space is $1/R^2$, near the ground is $1/R^4$, and in closed spaces like corridors is $1/R^{1.5}$. Moreover, a significant source of error is due to the lack of line-of-sight (LOS) between the anchor and the node. This error is more severe than multipath error and it cannot be corrected by taking multiple measurements. In addition, there are some difficulties in estimating the parameters for the channel model in (2). For instance, the power of transmission can be fixed for each anchor node, but the parameters associated with antenna gains may differ from node to node, and the attenuation constant η varies with the environment. However, it is possible to improve the accuracy of RSS measurement by calibrating the sensor

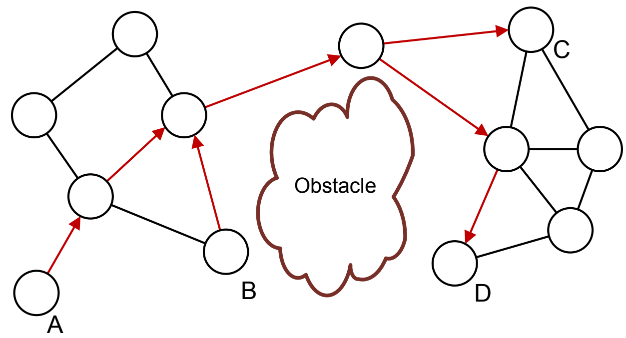

Fig. 6. Example of Radio hop count.

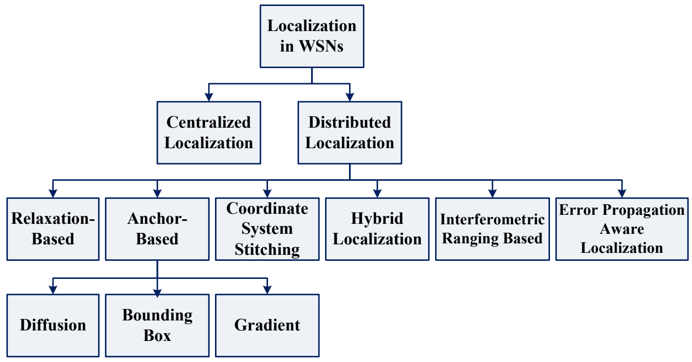

Fig. 7. Classification of various localization algorithms in WSNs.

radios and carefully analysing the radio propagation [1], [2], [4], [6].

Radio hop count technique can be used to assist localization when RSS is too inaccurate. However, it has some drawbacks in some situations, where obstacles prevent an edge from appearing in the connectivity graph as in Figure 6, leading to an inaccurate estimate. In this figure the number of hop count between A and C is equal to the number of hop count between B and D due to an obstacle, which increases the error in the measurement. In addition, the distance measurements are always integral multiples of d_h, which means that the error per measurement is high (0.5R). The accuracy of this technique can be increased further by averaging distances with neighbours, reducing the error to 0.2R [1], [2], [6].

ToA is influenced by two main sources of error, which are additive noise and multipath. Additive noise affects the accuracy of the signal arrival time. This issue can be tackled by implementing the TDoA instead of ToA, which is simply the maximum of the cross-correlation between the received signals. However, multipath is considered as the major source of error that is caused by two problems which are attenuated LOS, and early-arriving multipath. Multipath components arriving late behind the LOS signal can attenuate the LOS signal making it difficult to estimate the ToA, and multipath components arriving very soon after the LOS signal can cover the location of the peak in the cross-correlation output. The attenuated LOS problem can be solved by increasing the density of sensor nodes, which in turn increases the LOS signal power. On the other hand, early-arriving multipath problem results in smaller errors, but it is difficult to combat. AoA is also affected by the same source of errors that affects ToA. In addition, the lack of LOS can be more severe when compared to that of RSS or TDoA based techniques. Furthermore, AoA require a certain spacing to provide spatial diversity and additional hardware that consumes substantial amount of power [1], [4], [6].

IV. Classification of Localization Algorithms

Localization algorithms can be classified based on different criteria, such as single-hop vs. multi-hop, anchor vs. non-anchor, centralized vs. distributed *etc*. In this paper the localization algorithms are categorized into two main types, namely centralized and distributed algorithms as in Figure 7 [1], [5].

A. *Centralized Algorithms*

Centralized algorithms require plenty of computational power in order to run their operations on central machines. This high amount of computational power enables the algorithms to execute complex mathematical operations. This advantage comes with a communication cost, since all sensor nodes in the network will send their data to the central receiver and computed positions are sent back to respective nodes. There are different types of centralized algorithms depending on the way they process data at the central receiver. Such algorithms include Semidefinite Programming (SDP) [10] and Multidimensional Scaling (MDS) [11]. This paper concentrates on distributed algorithms as they are considered more efficient than centralized ones.

B. *Distributed Algorithms*

Distributed algorithms run their operations using the computational power of each node. This type requires massive inter-node communication and parallelism to be able to perform similar to centralized systems. Distributed algorithms can be divided into six main groups, which are anchor-based, relaxation-based, coordinate system stitching, hybrid localization, interferometric ranging based localization, and error propagation aware localization algorithms.

The first group is the anchor-based distributed algorithms. As the name implies, this type of algorithm uses anchors to find the position of unknown nodes. The nodes start by obtaining a distance measurement to few anchors and then determines their location based on these measurements. There are several anchor-based algorithms in the literature, such as diffusion [12], bounding box [13], gradient [14], and Approximate Point In Triangle (APIT) [15] algorithms.

The diffusion algorithm [12] is a simple algorithm that only uses radio connectivity data. It assumes that the node is most probably at the centroid of its neighbours' positions. There are two different alternatives to this algorithm. The first option developed by Bulusu *et al* [16] averages the positions of all anchors that can communicate with the node using radio, in order to localize the position of that node. The second option developed in [12] considers both anchors and normal nodes in

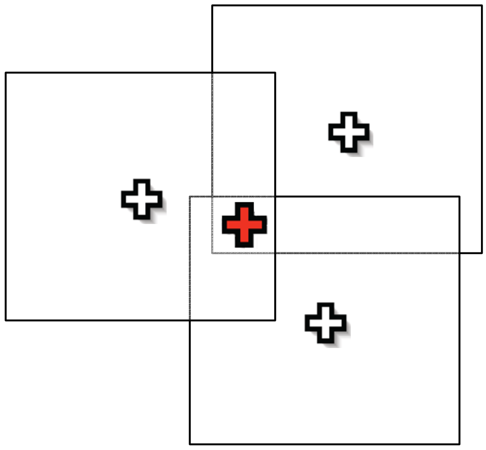

Fig. 8. An example of the intersection of bounding boxes.

determining the position of the node at centre. The advantage of the algorithm in [12] is that it requires fewer anchors than the one in [16].

The bounding box algorithm [13] calculates the position of the node based on the ranges to several anchors. Each anchor has a box and the intersection between these boxes determines the position of the node as shown in Figure 8. The box of an anchor is placed at the centre of the anchor position. Its size depends on the distance between the node and the anchor, where the width and height is twice the distance between the node and the anchor. This algorithm is used when sensor nodes cannot perform a lot of computation, and when the node is close to the centre of their anchors, since the accuracy is higher in such situation.

Another approach is the gradient algorithm [14] which starts by sending a message from anchor nodes to their neighbours. This message contains the anchor position and a count set to one. Then each node will send the same message to it neighbours after incrementing the counter. After that each node will keep the lower counter value and will use it to calculate the estimated distance using radio hop count technique. Finally, multilateration is used to compute the position of each node by combining the estimated distance from all anchor nodes. The gradient propagation of one anchor is shown in Figure 9, where each dot represents a node, and the color of the node represents its gradient value. This algorithm can easily adapt to the addition or death of normal nodes or anchors. However, it requires substantial node density to reach an acceptable accuracy level.

A different approach is the APIT algorithm [15] that is based on an area approach which forms triangles of arbitrary anchors. Each node selects three anchors in its radio coverage area, and then decides if it is inside or outside the triangle based on signal strength measurements with nearby non-anchor neighbours. After testing all triangle combinations, the node position is the centroid of the intersection region of the anchor triangles as shown in Figure 10. The advantage of this algorithm is that it requires smaller amounts of computation

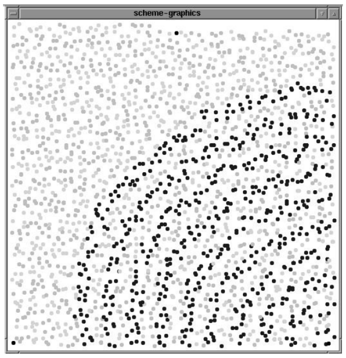

Fig. 9. Gradients propagating of one anchor placed at the lower right corner [1].

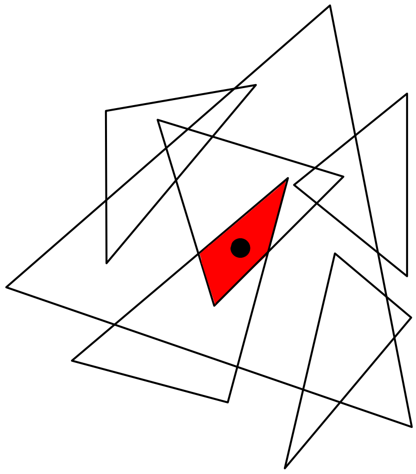

Fig. 10. Illustartion of Approximate Point In Triangle (APIT).

and less communication when compared to other anchor based algorithms. However, it requires longer range anchors, relatively high ratio of anchors to nodes, and RSS has to be calibrated.

The second group is relaxation-based distributed algorithms [17]. This group fuses the computational advantages of distributed schemes with the precision of centralized schemes. It starts by estimating the position of the nodes using one of the above distributed techniques. Then the positions are refined from position estimates of their neighbours, which are considered temporary anchors. The refining step is performed using local neighbourhood multilateration or an equivalent technique called the spring model [18], which represents distance between nodes with resting springs. It uses an optimization technique that will change nodes position in every iteration, until all nodes have zero forces acting on them. The advantages of this algorithm is its ability to operates without anchors, it is fully distributed, and concurrent. However, it cannot guarantee avoiding local minima, especially in larger scale networks.

The third group is coordinate system stitching algorithms [19]. It consists of three main steps. The first step is to split the network into small overlapping subregions which are usually a single node and its one-hop neighbours. In the second step a local map of each subregion is computed. Finally, the third step places all the subregions into a single global coordinate system using a registration procedure. The first two steps in this process differ between one algorithm and another while the third step is common for all.

The fourth group is hybrid localization algorithms. It simply combines two existing techniques to get a better performance, such as using both multidimensional scaling and proximity based map [20].

The fifth group is interferometric ranging based localization algorithms. It works by creating an interference signal using two transmitters emitting radio waves simultaneously at slightly different frequencies. The signal will arrive at the two receivers with a phase offset, which is a function of the relative positions of four nodes. The advantage of this algorithm over other algorithms is its high accuracy with long range measurements, but it requires a considerably larger set of measurements, thus it is limited to small networks [21].

Finally, the error propagation aware localization is important since error propagation can degrade the performance of an algorithm. There are two types of error, range and position error. Combining information about error characteristic with the algorithm can result in increasing the accuracy and the robustness of the algorithm. The basic idea of the algorithm is that nodes use the available information to transform into anchors in an iterative method, taking in consideration the minimization of position error and error propagation. The advantage of this algorithm is that it is more precise than other localization schemes, since its uses ranging and position information obtained from each involved anchor [22].

V. Conclusions and Future Directions

Localization algorithms in WSNs are growing continuously due to the fact that WSNs are used in a wide range of applications that require exact node location. The performance of any localization algorithm is affected by several factors such as the amount of resources available in the network (*e.g.* memory, processing power, and battery life), the node density, the shape of the network, and the environment where sensor nodes are going to be deployed. Therefore, it is important to study all these factors before designing an algorithm.

Localization in WSNs is an active research area that can be improved considerably. One of the problems that require further study is the ability of an algorithm to adapt to the movement of sensor nodes even if the nodes have high mobility. This task is important since node mobility can affect the localization accuracy of the moving and the non-moving node by averaging several measurements taken while moving, and can be used to enlarge the sensing coverage area. In addition to that, all the localization algorithms are designed to operate in two dimensions, which is not the case in real world application. Hence, it is recommended to investigate localization algorithms that can localize sensor nodes in three dimension space. Another issue that requires additional study is the ability of an algorithm to accurately localize the position of sensor nodes in real time, even if the number of nodes is increased substantially. Furthermore, the introduction of a large set of nodes may increase the security risks for the overall system. One possible security risk is the presence of malicious nodes that feed the wrong information about their location. In all such cases security measures need to be introduced to safe guard the integrity of the information being exchanged between the nodes including their location.

References

[1] I. Stojmenovic, *Handbook of sensor networks: algorithms and architectures*. John Wiley and Sons, Oct. 2005.

[2] C. Raghavendra, K. Sivalingam, and T. Znati, *Wireless Sensor Networks*. Kluwer Academic, Jul. 2004.

[3] H. Wymeersch, J. Lien, and M. Win, "Cooperative localization in wireless networks," *Proceedings of the IEEE*, vol. 97, no. 2, pp. 427–450, 2009.

[4] I. F. Akyildiz and M. C. Vuran, *Wireless Sensor Networks*. John Wiley & Sons Inc, Aug. 2010.

[5] A. Pal, "Localization algorithms in wireless sensor networks: Current approaches and future challenges," *Network Protocols and Algorithms*, vol. 2, no. 1, pp. 45–74, 2010.

[6] N. Patwari, J. Ash, S. Kyperountas, A. Hero, R. Moses, and N. Correal, "Locating the nodes: cooperative localization in wireless sensor networks," *IEEE Signal Processing Magazine*, vol. 22, no. 4, pp. 54–69, 2005.

[7] G. Mao, B. Fidan, and B. D. O. Anderson, "Wireless sensor network localization techniques," *Computer Networks*, pp. 2529–2553, 2007.

[8] F. Gustafsson and F. Gunnarsson, "Positioning using time-difference of arrival measurements," *ICASSP*, vol. 6, pp. 553–556, 2003.

[9] M. Terwilliger, "Localization in wireless sensor networks," Ph.D. dissertation, Western Michigan University, Kalamazoo, MI, USA, 2006.

[10] L. Doherty, K. Pister, and L. Ghaoui, "Convex position estimation in wireless sensor networks," *Twentieth Annual Joint Conference of the IEEE Computer and Communications Societies*, vol. 3, pp. 1655–1663, 2001.

[11] Y. Shang, W. Ruml, Y. Zhang, and M. Fromherz, "Localization from mere connectivity," *Proceedings of the 4th ACM international symposium on Mobile ad hoc networking & computing*, pp. 201–212, 2003.

[12] S. Fitzpatrick and L. Meertens, "Diffusion based localization," *private communication*, 2004.

[13] S. Simic and S. Sastry, "Distributed localization in wireless ad hoc networks," *University of California Technical Report*, 2002.

[14] J. Bachrach, R. Nagpal, M. Salib, and H. Shrobe, "Experimental results for and theoretical analysis of a self-organizing global coordinate system for ad hoc sensor networks," *Telecommunication Systems*, vol. 26, no. 2, pp. 213–233, 2004.

[15] T. He, C. Huang, B. Blum, J. Stankovic, and T. Abdelzaher, "Range-free localization schemes for large scale sensor networks," *Proceedings of the 9th annual international conference on Mobile computing and networking*, pp. 81–95, 2003.

[16] N. Bulusu, V. Bychkovskiy, D. Estrin, and J. Heidemann, "Scalable, ad hoc deployable rf-based localization," 2002.

[17] C. Savarese, J. Rabaey, and J. Beutel, "Locationing in distributed ad-hoc wireless sensor networks," *ICASSP*, vol. 4, pp. 2037–2040, 2001.

[18] N. P. Hari, H. Balakrishnan, E. Demaine, and S. Teller, "Anchor-Free distributed localization in sensor networks," *MIT Laboratory for Computer Science, Technical Report*, 2003.

[19] D. Moore, J. Leonard, D. Rus, and S. Teller, "Robust distributed network localization with noisy range measurements," *Proceedings of the 2nd international conference on Embedded networked sensor systems*, pp. 50–61, 2004.

[20] K. Cheng, K. Lui, and V. Tam, "Localization in sensor networks with limited number of anchors and clustered placement," *Wireless Communications and Networking Conference*, pp. 4425–4429, 2007.

[21] N. Patwari and A. O. Hero, "Indirect radio interferometric localization via pairwise distances," *Proceedings of 3rd IEEE Workshop on Embedded Networked Sensors*, pp. 26–30, 2006.

[22] N. Alsindi, K. Pahlavan, and B. Alavi, "An error propagation aware algorithm for precise cooperative indoor localization," *IEEE Military Communications Conference*, pp. 1–7, 2006.