Quadrant-Based Weighted Centroid Algorithm for Localization in Underground Mines

Nazish Tahir[1], Md. Monjurul Karim[2], Kashif Sharif[2(✉)], Fan Li[2(✉)], and Nadeem Ahmed[1]

[1] School of Electrical Engineering and Computer Science, National University of Sciences and Technology, Islamabad, Pakistan
{12msitntahir,nadeem.ahmed}@seecs.edu.pk

[2] School of Computer Science and Technology, Beijing Institute of Technology, Beijing, China
{mkarim,kashif,fli}@bit.edu.cn

Abstract. Location sensing in wireless sensor networks (WSNs) is a critical problem when it comes to rescue operation in underground mines. Most of the existing research on node localization uses traditional centroid algorithm-based approach. However, such approaches have higher localization error, which leads to inaccurate node precision. This paper proposes a novel quadrant-based solution on weighted centroid algorithm that uses received signal strength indicator for range calculation and distance improvement by incorporating alternating path loss factor according to the mine environment. It also makes use of four beacon nodes instead of traditional three with weights applied to reflect the impact of each node for the centroid position. The weight factor applied is the inverse of the distance estimated. Simulation results show higher localization accuracy and precision as compared to traditional weighted centroid algorithms.

Keywords: Localization · Centroid algorithm · RSSI
Sensor networks

1 Introduction

There has been an increasing demand for miner's safety that requires development of location sensing infrastructure [1]. WSNs are a potential solution that can provide vital localization information [2]. However, there is a need to develop fast and reliable localization algorithm that can work with a WSN based sensing infrastructure. Localization algorithms rely on the existing technologies, such as RFID, Wi-Fi, GSM, and the likes. However, these technologies have their

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limitations. For example, in the case of RFID, the card reading time causes delays if applied to multiple personnel. Besides, the localization accuracy is low and requires an additional RFID antenna in the existing WSN motes to build a workable algorithm [3]. Similarly, in case of Wi-Fi, the signal attenuation is very high in an underground environment. Therefore, the signals can never be relied on to be accurate in case of a mining incidents. There is also high computational cost involved while working with Wi-Fi signals, which is undesirable for wireless motes working in the underground environment [4]. Weak signal strength of GSM/4G technologies results in a significant reduction of localization accuracy for a cellular-based localization algorithm [5]. ZigBee is one technology that is more suited for underground environments due to its inherent characteristics [6]. ZigBee based WSNs have recently emerged as a flexible power capacity system that offers low energy consumption, small size, reliable performance in underground environments, and ease of use and deployment.

Many localization solutions based on WSNs already exist. Smart Dust [7], Pico Radio [8], and SCADDS [9], all address node localization with energy management in ZigBee. Works have been done in node localization at the application layer [10] as well. Therefore, ZigBee based WSN can be considered as a potential solution to the miner's localization issues [2]. Moreover the use of location information is not limited to WSNs only [11–14], and hence any improvement in localization algorithms benefits a larger application domain. In this paper, we introduce a novel localization algorithm that makes use of Received Signal Strength Indicator (RSSI) ranging and alternating path loss factor to correct and calculate possible distances between the nodes. We use four, instead of three of these nodes to compute the centroid position on a dedicated ZigBee infrastructure. Additionally, applied weights are used to estimate distances between the selected nodes and the unlocalized node.

The remainder of this paper is organized as follows. In Sect. 2, we discuss the related work. Section 3 presents the proposed quadrant-based weighted centroid algorithm. Section 4 presents performance evaluation, and Sect. 5 concludes the paper.

2 Related Work

A number of approaches have been introduced to address the localization-related fundamental issues and to improve the location precision by combining the ZigBee technology with RSSI based location algorithms. Some of the traditional proposed localization systems with minor alteration to WSNs are Centroid systems [15], APIT (Approximate Point in Triangulation) [16], and DV-Hop [17]. Their principal focus is on the improvement in location precision, reduction of the localization error and enhancement of the cost efficiency.

Jian and He-ping [18] propose a novel algorithm for wireless sensor networks based in a coal mine environment, that uses RSSI algorithm for distance measurements and weighted centroid algorithm for node localization. The improved algorithm uses multi-hop transmission and power control devices. That means if any beacon node is damaged in the network, the beacon node next to it will increase its transmission power to connect with the unknown node to participate in the localization process. The authors also propose that since the underground environment is harsh and the electromagnetic wave propagation becomes problematic in such a medium, the wireless signals face scattering attenuation. A polarization factor is added to the RSSI values to counter the vertical and horizontal polarization effect on electromagnetic waves. The unknown node archives the average RSSI received from each beacon node and selects three best RSSI values, which have the highest values received from the network. These values are converted into distance by formulas that include propagation loss in the underground mines. After that, weights are applied to improve the results. The least localization error recorded is 4.87 m from this improved version, which still needs considerable improvement, given the mine environment.

Fan et al. [19] propose a new scheme of weighted centroid algorithm designed for improved RSSI ranging. This algorithm uses the distance as well as RSSI values and corrects the distance between the beacon nodes. The RSSI and weights applied are reciprocal of the distance calculated. Additionally, this scheme uses the Free-Space model for the simulation environment to apply the traditional principles of weighted centroid algorithm. The RSSI ranging is accomplished by using the signal strength measurements and the distance between the beacon nodes, the coordinates of which are known. The results indicate that centroid algorithm with RSSI ranging shows better positioning and less localization error as compared to the traditional centroid algorithm. The results are improved by 10% as compared to traditional methods.

Another simple scheme has been proposed by Xie et al. [20], where none of the complexities related to path loss and distance between the anchor nodes are reflected. The scheme only relies on the received RSSI information to localize the unknown node. The authors establish the relationship between the received power at the unknown node from an anchor node and the transmission power of the two nodes placed one meter apart. By using the equation from path loss in a Free Space model, the authors calculate distance. After the distance calculation, normalized weights are assigned to the least distant nodes. The average localization error is improved as compared to the traditional weighted centroid localization algorithm. The least error recorded by is 4.32 m while the improved version had the least localization error of 3.75 m. The scheme also claims to be faster and efficient than traditional localization methods as it does not calculate β, the path loss factor, and the distances between the beacon nodes. Hence, this can preserve a significant amount of time and energy. However, this scheme can reasonably fail in the underground environment as path loss factor cannot be ignored in such harsh settings and avoiding the calculation of path loss can result in erroneous measurements. Although all the schemes mentioned above claim to perform better than the traditional weighted centroid algorithm, they can still undergo significant improvement to enhance localization accuracy.

3 Quadrant-Based Weighted Centroid Algorithm

In this article, we propose an improved localization scheme based on the weighted centroid algorithm. The design includes a set of static beacon nodes whose coordinates are fixed at the time of deployment. The deployed system is used to track an un-localized node carried by a mobile target. We have designed our network in a way that the beacon nodes are programmed to send beacon frames at a regular interval in the network. The un-localized nodes receive periodic beacon frames transmitted by the beacon nodes. These beacon frames contain information, such as beacon node ID and coordinates (X, Y) of each sender. The RSSI values are calculated at the receiving node. These values represent the signal strength in dBm.

As explained above, weighted centroid algorithm coupled with RSSI distance measurement provides promising results in an underground environment. We propose a localization algorithm that takes two essential aspects of the node localization in underground mines into account, namely; the path loss factor and an improved weighted centroid algorithm, both of which work together to give improved localization results as compared to other techniques. Our proposed scheme comprises of four phases: (a) path loss calculation, (b) distance estimation, (c) position estimation, and (d) quadrant calculation. We will give a brief overview on each of them in the following sections.

3.1 Pathloss Calculation

The path loss calculation phase involves finding the path loss in the vicinity of each beacon node. The existing literature on radio propagation model in different environments [21,22] suggests that a non-isotropic path loss exists because of the variation in the propagation medium and direction. Neglecting the path loss factor while considering underground environments can lead to highly erroneous results. The feasibility of any localization algorithm largely depends on the correct estimation of this constant, which varies based on the environment. Most of the models assume the path loss to be between $2-4$ when considering the underground environment. However, such assumptions do not always hold true due to the varying and harsh underground environment. Therefore, to analyze the radio propagation pattern, the irregularity of the path loss must be defined.

A series of calibrations performed in [23] show that keeping the path loss factor constant to compute distance despite the alternating factors in the underground environment exhibits certain drawbacks. This verifies that various mediums, such as walls, obstacles, glass, etc. affect the signal attenuation differently. Therefore, using a uniform signal propagation constant, neglects the interference properties of these materials. So calculating a single path loss factor for all beacon nodes may lead to high errors in the localization process.

In the proposed scheme, when an un-localized node receives the beacon frames at predefined intervals, it calculates the RSSI values. This RSSI value is used to approximate the distance from each beacon node by using the path loss factor. Any error in path loss factor estimation will result in erroneous distance estimation. This first phase aims to improve the estimation process of path loss factor.

Beacon nodes are already aware of their coordinates as they are fixed at the time of deployment. The fundamental principle is that beacon nodes can exchange beacon messages with each other and calculate RSSI of the received beacon messages. As the actual distance between the respective beacon nodes is already known, RSSI can be easily related to the actual distances to calculate realistic path loss factor involved in the beacon message transaction. Each beacon node can calculate and advertise this path loss factor in its future beacon messages. The unknown node will receive the path loss factor from the beacon messages and can use it to improve the distance calculation based on RSSI. When the beacon frames are exchanged, beacon nodes calculate their relative distances compared to other beacon nodes by geometric line formula.

This distance is stored at each beacon node such that every beacon node in the network is aware of its neighbor's coordinates and their respective distances from each other. After determining each other's distances, beacon nodes calculate the path loss factor by the measured RSSI values and the relative distances by reversing the linear RSSI equation.

$$n_i = -\left(\frac{RSSI - A}{10\log_{10}d_i}\right) \tag{1}$$

The value of A is an absolute value calibrated by determining the signal strength between two nodes set at 1 m apart. In this phase, the path loss factor is calculated to be used in the distance estimation. After path loss calculation by each beacon node, we proceed to the distance estimation phase.

3.2 Distance Estimation

Since each beacon node in the network has estimated the path loss factor, it will propagate this information to other nodes within the beacon frame advertisement. The un-localized node can now receive beacon frames containing the information of their transmitted beacon node IDs, coordinates, and the path loss factor along with the RSSI values calculated upon the arrival of each beacon. The un-localized node upon receiving this information stores this information and averages the multiple path loss values received from various beacon nodes to obtain an average path loss factor value in the current environment.

Once the average path loss factor value is available, an un-localized node is capable of converting its RSSI measurements into the distance through the use of this average path loss factor. However, the principal challenge in using raw RSSI values is that it is prone to high sensitivity of its environmental variations. The fluctuating nature of RSSI measurement limits the accuracy of the distance estimation. Even when a mobile node is not changing its position and the whole network is static, RSSI values vary over time for the same distances. Thus, to reduce this complex wavering of the signals when the unknown node is mobile, RSSI smoothing is required. To smooth the RSSI values while the user moves arbitrarily in the network, we calculate the simple moving average of measured RSSI values for each beacon node as

$$RSSI_{avg(i)} = \frac{RSSI_{avg(i)} + RSSI_{new(i)}}{2} \tag{2}$$

where $RSSI_{avg}$ is the previously averaged and $RSSI_{new}$ is the newly received $RSSI$ from beacon node i. Averaged $RSSI$ values obtained using Eq. (2) are then converted into distance with estimated path loss factor derived from the phase 1 of our algorithm. The un-localized node now has calculated the distance to each beacon node from which it has received a series of beacon messages. The information of neighbor beacon nodes is stored at the un-localized node according to the calculated distance in ascending order.

3.3 Position Estimation

We select at least three reference nodes to determine the position of the unknown node. These three nodes are the three least distant beacon nodes from the un-localized node. A traditional weighted centroid algorithm is applied, which calculates the position of the ascending node based on range measurements from the three beacon nodes received at the same time. The algorithm requires the coordinates of these three reference nodes $(X_i,\ Y_i)$, the distances d_i between the un-localized node and the beacon nodes, which has already been calculated in the last phase and sorted according to the distance.

Now weights are applied based on the distance from each beacon node. From the weighted centroid principle, we have

$$X_{est} = \left(\sum_{i=1}^{n} \frac{X_i/d_i}{1/d_i}\right), Y_{est} = \left(\sum_{i=1}^{n} \frac{Y_i/d_i}{1/d_i}\right) \tag{3}$$

where X_i, Y_i are the x-coordinator, y-coordinator of beacon nodes and d_i is their respective distances. The weighing factor used is

$$w_i = \left(\frac{1}{d_i}\right) \tag{4}$$

In other words, we can say that the closer the distance, the greater the value of the weight. In this way, a node closest to the un-localized node will have more influence on the position estimate than a node that is farther away. After this phase has completed, we have an estimated position of the un-localized node.

3.4 Quadrants Estimation

Once the estimated position is calculated, the partially-localized node will use this position to divide its surrounding area and nodes into four quadrants. Each quadrant will be a mathematically calculated area based on the coarse calculation of X and Y for the unknown node. These quadrants are calculated by the unknown node through sorting the X and Y of the neighboring beacon nodes into four squares from four directions. For this purpose, the unknown node will run a query on its existing beacon information to separate $X_{beacons} > X_{est}$ and $Y_{beacons} > Y_{est}$into first quadrant, $X_{beacons} > X_{est}$and $Y_{beacons} < Y_{est}$into second quadrant, $X_{beacons} < X_{est}$ and $Y_{beacons} < Y_{est}$into third quadrant, and $X_{beacons} < X_{est}$ and $Y_{beacons} > Y_{est}$into fourth quadrant. After this division, the unknown node will select the least distant node from each quadrant, so that now it has four nodes, one from each quadrant to perform the weighted centroid algorithm. The four nodes selected will undergo the position estimation again in which the weighted centroid algorithm will be applied to get a new estimated position.

The idea behind the division of the wireless sensor network into four quadrants is that the un-localized node should be localized from four directions in a 2D tunnel plane. A node which is going to be located through the information received from all directions will achieve better accuracy in localization as compared to a node using three least distant nodes as is the usual practice of a typical weighted centroid localization algorithm.

4 Performance Evaluation

The proposed algorithm has been simulated in Network Simulator(NS) 2.34 at the lower stack MAC level. Transmission power is set to be 0.008 W. The calibration constant A is set at -22.628 dBm, which is an absolute value obtained when the nodes are set at 1 m apart. Results are compared in two different scenarios. The first scenario includes the physical dimension of the outdoor environment, i.e., $100\,\mathrm{m} \times 100\,\mathrm{m}$. A maximum total of 40 reference nodes are scattered or randomly placed in the square test area. During the simulation, a user carrying an unknown node walks from an initial point with coordinate (10, 10) to a finish point with coordinate (60, 60). This movement is directed diagonally across the plane of the simulation. The speed of the movement is set at 3.5 m/s. The movement is tracked at every second interval of the simulation. The second scenario sets up the simulation area of $5\,\mathrm{m} \times 100\,\mathrm{m}$, which is the closest possible dimension of a mine tunnel as shown in Fig. 1. A total number of 40 nodes are placed at an equal distance of 5 m apart around the walls of the tunnel. The coordinates of these nodes are fixed and known by the system. The unknown node will start moving from its source point (2, 10) to its destination point (2, 80). The movement is set at the speed of 3.5 m/s.

First, a round of traditional WCL (Weighted Centroid Localization) algorithm is applied to the simulation area followed by the quadrant-based weighted centroid algorithm. Figure 2 shows the comparison of position estimation for both traditional weighted centroid algorithm and the quadrant-based weighted centroid algorithm for an open area. The error is recorded as soon as the simulation starts with the unknown node moving diagonally across the simulated area.

The localization error over the course of time is observed to be lesser for the quad-based weighted centroid algorithm with the maximum error observed of

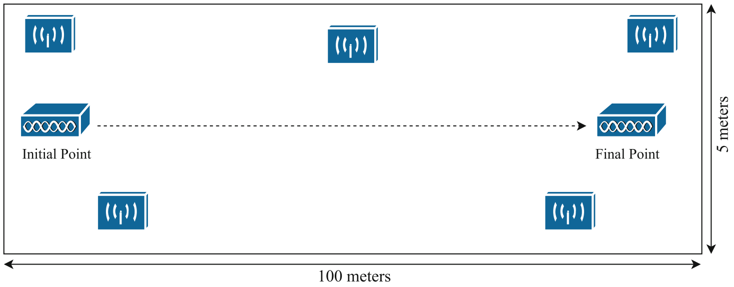

Fig. 1. Topology of 5 m × 100 m mine tunnel with 40 nodes placed 5 m apart.

3.62 m and the minimum of 0.39 m as shown in Fig. 2. Around 50% improvement in localization accuracy is observed as compared to the traditional weighted centroid algorithm. RSSI refinement through the use of path loss factor improves the position accuracy of the mobile node.

Similarly, simulations were performed with a setup of 5 m × 100 m, which closely depicts a mine tunnel dimensions. The error is recorded as soon as the simulation starts with the unknown node moving straight over the simulated area which depicts a miner walking straight inside a mine tunnel.

It is evident that, in Fig. 3, the proposed quadrant-based weighted centroid algorithm outperforms the traditional weighted centroid algorithm. The localization error is much reduced now with around 1.25 m to be maximum and 0.07 m to be minimum. Around 70% improvement in localization accuracy is observed as compared to the traditional weighted centroid algorithm. This accuracy is a significant improvement as the localization error has dramatically reduced while keeping beacon nodes orientation and the estimated path loss factor into account.

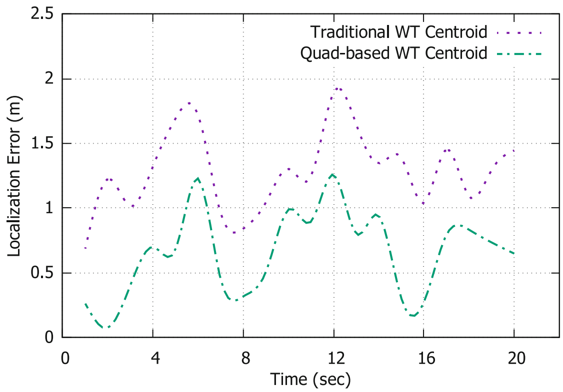

Fig. 2. Comparison of traditional weighted centroid algorithm with Quadrant-based weighted centroid localization error in 100 m × 100 m area.

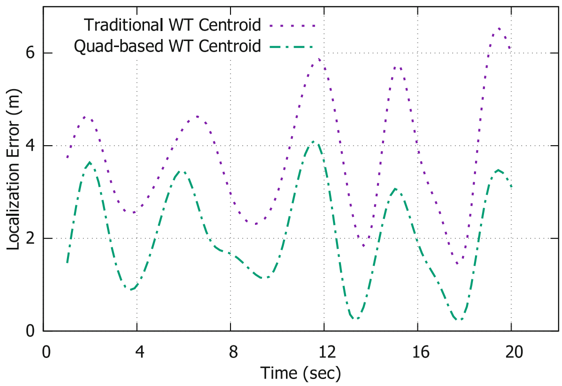

Fig. 3. Comparison of localization error of traditional weighted centroid algorithm with Quadrant-based weighted centroid algorithm in a mine tunnel.

It can be seen that results obtained in the mine tunnel are better than that of the open area. This is because the mine tunnels are narrow and close spaces in a width of 5 m where a miner would always be in proximity of the nodes placed in the tunnel. The path loss factor observed in a mine tunnel is less than 1.94 m on average. On the other hand, in an open area where the nodes are randomly deployed, a person will sometimes be surrounded by closely spaced nodes and, in other instances, he will have the beacon nodes placed far apart from him. This difference in the topology creates the differences in the RSSI values received. The path loss estimation in an open area is observed to be around 1.85 on average. However, the division of the area under consideration into quadrants still significantly improves the results.

In comparison with other RSSI-based location algorithms, our proposed system exhibits resemblance of calibration of the propagation constant, but the alternating path loss calculation is not suggested in other schemes. The accuracy of the localization is immensely improved as compared to other proposed systems by using the path loss and the quadrant division by our algorithm.

5 Conclusion

We have proposed a novel localization algorithm that makes use of RSSI ranging and alternating path loss factor to correct and calculate possible distances between the existing nodes. Besides, this method enables extended functionality by using four instead of three of these nodes to compute the centroid position on a dedicated ZigBee infrastructure. It has been observed that the localization error can be reduced by performing distance correction through the use of alternating path loss factor and dividing the area into four quadrants to pin down the un-localized node. The results obtained by our proposed algorithm exceed in accuracy as compared to the results obtained by the traditional weighted centroid algorithm. The accuracy has been improved up to 50% in open space and 70%

in the underground mine tunnels. The results can be further improved by implementing the algorithm in real underground environment, and some extensions can be applied to the proposed quadrant-based weighted centroid algorithm to improve the localization accuracy further. In our proposed algorithm, the path losses advertised by beacons are the *inward* path losses. However, this may be different from the path losses in other directions. Therefore, in future, more work will be carried out on calculating the accurate path loss factor. The impact of using various propagation models can also be applied so that more accuracy can be achieved if real-time RSSI values of underground mines are used in the simulation. We plan to implement our proposed algorithm on real sensor network hardware to ascertain its performance in real mine conditions.

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