A Localization Algorithm for Wireless Sensor Networks Using One Mobile Beacon

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ABSTRACT

This paper proposes an accurate, low cost and power efficient localization algorithm for Wireless Sensor Networks (WSN). The algorithm uses a Received Signal Strength (RSS) measurement technique and a mobile anchor node equipped with a GPS and a directional antenna. The algorithm does not depend on specific ranging hardware requirements for sensor nodes, Moreover; the algorithm needs only one anchor node to achieve high localization accuracy. Performance evaluation of the proposed algorithm is done using MATLAB. The results show that the proposed algorithm achieves a high localization accuracy by reducing the localization error by **66.53%.** Moreover it extends the nodes' lifetime by reducing the reception energy consumption by **95.94%** compared to DIR localization algorithm introduced in [10].

Keywords: *Mobile Beacon, Beam-Width, Directional Antenna and RSS.*

1. INTRODUCTION

WSNs consist of many sensors deployed in a certain area to monitor or detect an event(s) depending on the application. WSNs are composed of hundreds, possibly thousands, of tiny low-cost and smart devices called Sensor Nodes (SN) that are capable of measuring various physical values. Sensor Nodes can detect temperature, humidity, pressure, motion, sound, etc. depending on application. These sensors are communicating with each other and organizing themselves in order to cooperatively achieve a desired task. It can provide opportunities for monitoring and controlling homes, cities, and the environment. WSNs can be used in many applications such as fire rescue [1], smart home [2], precision agriculture [3], environmental monitoring [4], volcano monitoring [5], structural monitoring [6], vehicle tracking [7], traffic control [8], site security and natural disaster detection [9]. The main challenges of a WSN design and implementation are power consumption constraints for nodes using batteries, scalability to large scale of deployment, ability to withstand different environmental constrains and ease of use. An important aspect in most sensor networks applications is localization of individual nodes; the measured data is meaningless without knowing the location from where the data is obtained. Moreover, location estimation may enable a myriad of applications such as intrusion detection, road traffic monitoring, health monitoring, reconnaissance and surveillance. Localization enables efficient routing; a typical sensor network has a large number of nodes that communicate at very short distance (a few meters), data sensed by a node has to be delivered to the central unit through several other nodes. Thus, multi-hop routing is necessary. In order to implement multi-hop routing it is necessary that nodes are aware of their locality, namely, they know their relative position with respect to their neighbors. Localization helps also in saving WSN energy, for example; in case of deploying a sensor network for pollution monitoring, the neighbor sensor nodes will have data which will not be dramatically different from each other. Thus to save power it makes sense to combine the data from neighboring nodes and then communicate the combined, reduced data set, thereby conserving power (since communication takes lot more power than local processing). In order to do this local data fusion, we will need the location information. Localization is useful in locating the source of data: In many applications, an event based sensor network is used; nodes are normally in sleep mode and when an event occurs (say sudden vibrations take place) the nodes are awakened, nodes then sense and transmit data. Such data requires a location stamp and therefore localization becomes necessary. From the previous examples, it could be seen that localization is indeed a necessity for sensor networks however choosing the suitable localization technique depends on the application.

This study introduces an algorithm called Beam width Related Motion algorithm (BRM) for locating static sensor nodes randomly deployed in a two dimensional coordinate system by using a mobile Beacon Node (BN) equipped with directional antenna and moves in a certain pattern. The performance of BRM algorithm is evaluated using MATLAB then compared with the performance of **Dir**ectional algorithm (DIR algorithm) [10]. The rest of the paper is organized as follows, Section 2 includes related work in localization field, Section 3 includes our work in details which is the BRM algorithm, and Section 4 includes conclusion and future work.

2. RELATED WORK

Localization in WSNs has attracted extensive studies and many localization techniques are introduced. The major studies in this field are summarized in the sections below.

2.1 Range-Based Techniques

Traditional range-based localization algorithms for WSNs such as RSSI, TDOA, and AOA [22], require at least three BNs to achieve acceptable localization accuracy. The beacons' antenna radiation should cover all the area. Otherwise, many nodes will not collect the required information to determine its location well. Time Difference of Arrival (TDOA) uses two different signals (like RF signal and ultrasound signal) and computes their time difference of arrival; it can estimate the distance using time difference of arrival value and the speed of the two different signals. Angle of Arrival (AOA) technique depends on measuring the angle of the direction from which the signal comes from. Based on the directions, the range between nodes can be estimated. Received Signal Strength Indicator (RSSI) depends on measuring the attenuation of the transmitted signal between the sender nodes and the receiver nodes then translates this attenuation value into distance. After that sensor nodes can use the appropriate localization method with the technique (RSSI, TDOA, or AOA) like trilateration, triangulation, etc. to estimate its position.

The algorithm introduced in [11] depends on stationary BNs, omnidirectional antenna and the received signal strength. A range-based localization algorithm is introduced using a high number of BNs; around 20% of the total nodes number. Each non-localized node collects information from its neighboring beacon. If the number of neighbor beacons is greater than or equal three, it determines its own location using trilateration. Otherwise sampling is carried out by the remained non-localized nodes based on the received beacon information at this stage the non-localized nodes know its initial position. Then, the non-localized node refines its initial position by genetic algorithm. No energy consumption studies are taken into consideration in this algorithm, however, energy is a very important issue in sensor networks as most of it works on DC batteries, which in most applications cannot be changed or charged. As soon as the battery becomes empty, the node becomes a dead node.

The algorithm introduced in [12] depends on Mobile Beacons (MB), omnidirectional antenna and RSS. An RSSI-based Geometric Localization (RGL) technique is introduced to estimate sensor nodes location using the received RSSI value from a MB equipped with GPS. The MB broadcasts messages periodically as it traverses in the WSN. The sensor nodes store a series of different MB positions and RSSI signal information after receiving a packet from a MB when sensor nodes are in the transmitting range of the MB. The sensor nodes use the maximum RSSI value and its related beacon position to estimate its position. Also [12] did not include any studies for energy consumption.

2.2 Directional Antenna-Based Techniques

Numerous localization algorithms use BNs equipped with Omni-directional antennas for transmitting Beacon Messages (BM) have been proposed. However, the radiated signal from an Omni-directional antenna is more susceptible to be interfered by noise than the radiated signal from a directional antenna which leads to greater localization error because the directional antenna concentrates the radiated signals on a particular direction with a high gain and narrow covering area. The directional antenna also has a higher transmission range than Omni-direction antenna as the directional antenna has a higher gain. Therefore, BN with directional antenna may transmit beacon information more effectively than that with Omni-directional antennas. [13].

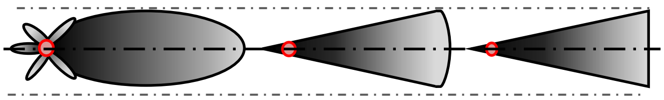

Figure 1.a Figure 1.b Figure 1.c

Figure 1 Directional Antenna Pattern.

In [10] the used directional antenna radiation pattern is similar to [14], [15], [16], and [17], it ignores the side lobes and approximates the antenna pattern as a conical section with an apex angle (i.e., Beam Width) as shown in Figure 1.b. In this study (i.e., BRM algorithm) the directional antenna radiation pattern is approximated to be a triangle as shown in Figure 1.c.

2.2.1 Stationary Beacon with Directional Antenna-Based Techniques

In [18] and [19] directional antenna-based, localization algorithms are-introduced. Using a set of stationary BNs each equipped with a single directional antenna and transmits the BMs; sensor nodes receiving this BM estimate their positions via a triangulation technique based on the AOA measurements and the received BMs of at least three BNs. Other studies introduce a single stationary BN but using both range and angle information as [20] and [21].

2.2.2 MB with Directional Antenna-Based Techniques

Localization using MB nodes is cost effective because a fewer MBs can cover all sensors' area more than using stationary beacons.

In [13] a localization algorithm using a MB with directional antenna is introduced to estimate the location of sensor nodes randomly deployed in a two-dimensional area. In this algorithm, the MB broadcasts BMs using a directional antenna, as it moves through the network. Using this message and a scheme called border line intersection localization (BLI) sensor nodes can estimate their location. In [13] a certain moving path for the MB is used.

In [10] another localization algorithm called **DIR** algorithm (the first three letters of word **Dir**ectional) is introduced to estimate the location of randomly deployed sensor nodes in a two-dimensional area using MBs with directional antennas. In this algorithm eight mobile BNs are used, each equipped with four directional antenna and moves randomly in the deployment area. Two of the antennas are orientated such that they are parallel to the horizontal axis (i.e., the X axis), while the other two antennas are positioned such that they are parallel to the vertical axis (i.e., the Y axis). A compass is used to ensure that antennas are always parallel to horizontal and vertical axes as the beacon moves in the deployment area.

Our proposed algorithm does not depend on specific ranging hardware requirements for the sensor nodes, sensor nodes do not need to communicate with each other they only need to receive BM from the BN. Moreover, the algorithm needs only one BN to achieve high localization accuracy by reducing the localization error and long node lifetime by reducing the energy consumption.

BRM algorithm combines the advantages of both Range-Based techniques and MB with Directional Antenna-Based techniques.

3. THE PROPOSED ALGORITHM

The proposed algorithm called **B**eam-width **R**elated **M**otion (**BRM**) algorithm. In **BRM** algorithm a hybrid localization technique is used; hybrid between Range-Based technique and MB with Directional Antenna-Based technique.

BRM is a localization algorithm designed for locating static sensor nodes randomly deployed in a two-dimensional coordinate system by using a mobile BN with the following characteristics:

- The MB is equipped with a directional antenna with a radiation pattern assumed to be as shown in Figure 1.c.
- The MB is equipped with a GPS receiver to detect its position as it moves through the sensing field.
- The MB moves in a certain pattern as shown in Figure 2.
- The MB transmits a message called Beacon Message (BM) at certain points along the moving path.

The BM contains the following information:

- Beacon position at the moment of the transmission (B_x , B_y)
- Transmitting power P_i , Reference power value P_0 , Reference distance d_0 and path loss exponent n_p.

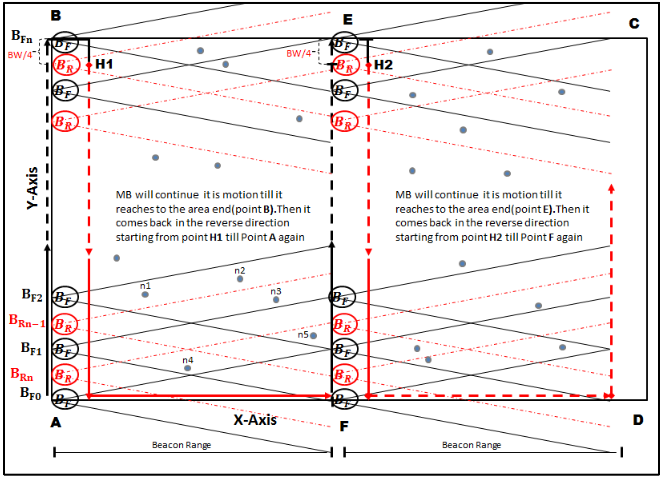

Figure 2 MB Movement Pattern.

The MB movement pattern is described as follow:

In Figure 2, MB moves forward from point A to point B and transmits BM every half Beam-Width (BW) distance where $\mathrm{BW} = 2\mathrm{R}\tan\frac{\theta}{2}$ meters, θ is the directional antenna main beam angle in degrees and R is the maximum range of the directional antenna in meters. Then MB moves in the reverse direction from point B to point H1; the distance between point B and point H1 is equal to BW/4. MB then transmits BMs every BW/2 starting from point H1 till it comes back to point A so that the position of BM transmission will be the solid lines for the **forward path** (i.e. B_F positions) and the dashed line for the **reverse path** (i.e. B_R positions) as shown in Figure 2 . After that MB moves from point A to point F without radiating BM; this distance is equal to the MB range R, then MB moves from point F to point E and transmits BM every BW/2 distance in meters while it moves from F to E, afterwards the MB moves in the reverse direction from point E to point H2; the distance between point E and point H2 equals BW/4, then MB transmits BMs every BW/2 starting from point H2 till it come back to point F and so on till it covers all the deployment area ABCD.

Example to show forward path and reverse path BM transmission locations:

- Assuming that deployment area size is $100\,\mathrm{m} \times 100\,\mathrm{m}$, MB starts its movement from point (0,0), antenna range is $20\,m$ and BW is $2\,m$ (i.e. $\theta = 5.7248$ Degree).

Forward path BM transmission locations will be (0, 1, 2, 3, 4, ……, 98, 99, 100).

Reverse path BM transmission locations will be (99.5, 98.5, 97.5, 96.5, 95.5, ….., 2.5,1.5, 0.5).

3.1 Location Estimation

To estimate a sensor node's (n_i) location in a 2-D system just the node 2-axes coordinates are needed to be estimated (i.e., node (X_i, Y_i)). BRM uses two different simple concepts to estimate X_i and Y_i.

3.1.1 X_i Estimation

From the moving pattern shown in Figure 2 MB moves vertically and transmits BM every BW/2. In range, nodes n_i receive the BM and estimate its X_i coordinate using BM information and Equation (1). From [22] it is possible to conclude that given the RSS measurement P_{ij} between a transmitter i and a receiver j, a maximum likelihood estimation of the distance, d_{ij} between the transmitter and the receiver is:

$$d_{ij} = d_0\left(\frac{P_{ij}}{P_0(d_0)}\right)^{-1/n_p} \quad (1)$$

where P_0 is a known reference power value at a reference distance d_0 from the transmitter, n_p is the path loss exponent that measures the rate at which RSS decreases with distance and the value of n_p depends on the specific propagation environment so a calibration stage is needed to estimate the path loss exponent n_p.

3.1.2 Y_i Estimation

The in range nodes n_i that had received the BM are considered on the same horizontal line with the BN. Consequently its Y_i coordinate is equal to MB Y coordinate B_y (i.e. $Y_i = B_y$) at the time of receiving that BM. If a sensor node n_i receives more than one BM it will estimate X_i and Y_i for every BM, calculates the average value for all X_i values and calculates the average value for Y_i values. Then it will consider the final X_i and Y_i average values are its estimated coordinates.

Example:

In Figure 2 when the MB arrive to position B_{F2} nodes n_1 and n_2 and will be considered to have the same Y coordinate equal to B_{F2} (i.e. $Y_1 = Y_2 = B_{F2}$). n_3 will receive two BMs at positions B_{F2} and B_{Rn-1} so n_3 will consider its Y coordinate $Y_3 = \frac{B_{F2}+B_{Rn-1}}{2}$, n_5 will receive four BMs at positions B_{F1} , B_{F2} $B_{Rn-1}$and B_{Rn}

So n_5 will consider its Y coordinate $Y_5 = \frac{B_{F1}+B_{F2}+B_{Rn-1}+B_{Rn}}{4}$.

3.2 Performance Evaluation

Performance of BRM localization algorithm is evaluated by performing a series of simulations using MATLAB.

3.2.1 Simulation Settings

The simulations performed in this study consider the following settings:

- Sensors environment is an ideal environment with a clear line-of-sight (LoS) in every direction.
- 100 sensor nodes were randomly distributed in a 100 m × 100 m region.
- Each sensor node is equipped with an omnidirectional antenna for receiving the BMs from the MB.
- Only one MB equipped with a directional antenna with a beam width of θ degrees or the equivalent BW in meters is used.
- MB broadcasts a BM every BW/2 meter.
- The radio range of both omnidirectional and directional antenna is specified as $R = 20$ m.
- For energy consumption settings, the transmission of one BM is assumed to consume $6\mu J$ and the reception of one BM consumes $4\mu J$. [10]

3.2.2 Simulation metrics

BRM algorithm is simulated using MATLAB and compared to DIR algorithm.

The performance of BRM and DIR algorithms are evaluated using two metrics.

1- *Localization Error*: defined as the average distance between estimated location (x’ , y’), and actual location (x , y) of all sensor nodes. [10]

$$\text{Localization Error} = \frac{\sum_{i=1}^{N}\sqrt{(x_i' - x_i)^2 + (y_i' - y_i)^2}}{N}$$

(2)

where N is the number of localized nodes, (x_i', y_i') are the estimated coordinates of the i^{th} sensor node, and (x_i, y_i) are the actual coordinates of the sensor node.

2- *Energy consumption*: Total energy consumption in the localization process. (i.e. Energy consumption due to transmission and reception of the BMs).

3.2.3 Simulation Results

To ensure the reliability of the simulation results, about 50 simulations were performed for each set of simulation conditions, with different initial random deployment of the sensor nodes in every case, theta varies from 5 to 50 degrees. Every point on the simulation curves represents the corresponding value to the average of 50 simulation trials.

1- *Impact of Antenna Beam Width on Localization Error:*

Figure 3 shows three curves for average error, one phase BRM algorithm curve which is the average localization error curve for BRM algorithm after forward path only, two phases BRM algorithm curve is the average localization error curve for BRM algorithm after both forward and reverse paths and DIR error curve is the average localization error curve for DIR algorithm. From the three curves shown in Figure 3 the average localization error increases as theta increases but BRM algorithm reduces the average localization error than the DIR algorithm especially after the MB completes its motion for both forward and reverse paths (i.e. two phases BRM curve). BRM algorithm reduces the average localization error more than the DIR algorithm because BRM algorithm uses RSS technique to estimate X-axis coordinate, which depends on an initial calibration stage in addition to relating the BMs transmission locations to the antenna BW in a predefined organized moving pattern for the MB to estimate Y-axis coordinate. Two phases BRM algorithm reduces the average localization error more than one phase BRM and DIR algorithm because it uses the reverse path in addition to the forward path to transmit BMs. However, transmitting BMs in two paths consume more power, localization error decreases.

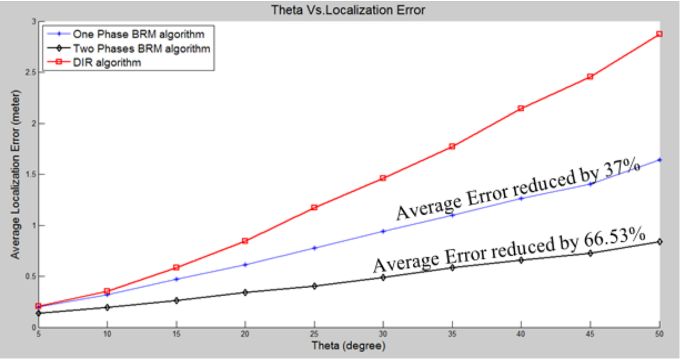

Figure 3 Theta verses Average Localization Error.

The mean of the three average error curves is computed to check localization accuracy enhancement ratio. The mean for one phase BRM, two phases BRM and DIR error curves are 0.8733, 0.4640 and 1.3864 respectively. So compared with DIR algorithm one phase BRM enhanced the localization accuracy by **37%** and two phases BRM enhanced the localization accuracy by **66.53%** as shown in Figure 3.

2- *Impact of Antenna Beam Width on Energy Consumption:*

Figure 4 and Figure 5 show that for DIR algorithm, the average transmission energy consumption changes from 12.9005 to 13.4861 mJ, while the average reception energy consumption goes up from 1.3181 to 13.4717 mJ. This result is reasonable since the number of sensors that fall in the antenna's coverage range and receive the BM increases as the beam width increases. For one phase BRM and two phases BRM algorithm, the average energy consumption due to receiving BMs remains about 0.3 mJ and 0.6 mJ respectively, while the average transmission energy consumption for one phase BRM algorithm goes down from 3.45 mJ to 0.33 mJ and goes down from 6.9 mJ to 0.66 mJ for two phases BRM algorithm. So it can be concluded that BRM algorithm reduced both average transmission and reception energy consumption. The average reception energy consumption for BRM algorithm is much lower than the DIR algorithm and it also saturates near 0.3 mJ, while for DIR it increases as theta increases it reaches 13.4717 mJ, consequently, BRM algorithm increases the sensor nodes lifetime as it has lower average reception energy consumption than DIR algorithm.

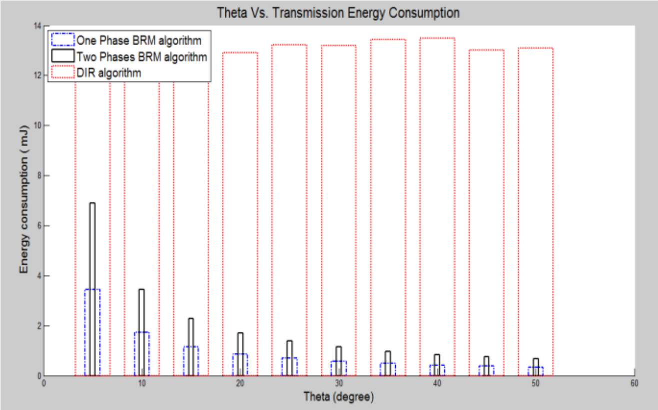

Figure 4 Average Transmission Energy Consumption versus Theta.

Mean values for BRM and DIR algorithms average energy consumption bars shown in Figure 4 and Figure 5 are computed to check the average energy consumption enhancement ratio (ratio of average energy consumption reduction relative to DIR average energy consumption).

The mean for one phase BRM, two phases BRM and DIR average transmission energy consumption bars are 1.0080, 2.0070 and 13.1905 respectively. So compared with DIR algorithm one phase BRM enhanced the average transmission energy consumption by **92.3581%** and two phases BRM enhanced the average transmission energy consumption by **84.7845%**

The mean for one phase BRM, two phases BRM and DIR average reception energy consumption bars are 0.3001, 0.6032 and 7.3948 respectively. So compared with DIR algorithm one phase BRM enhanced the average reception energy consumption by **95.9417%** and two phases BRM enhanced the average reception energy consumption by **91.8429%**

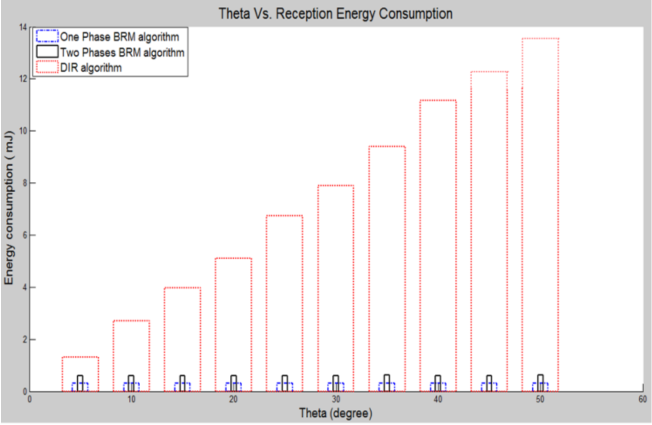

Figure 5 Average Reception Energy Consumption versus Theta.

Figure 6 shows that for DIR algorithm, the overall average energy consumption due to both transmitting and receiving BMs increases as theta increases and it goes up from 14.4101 to 26.5560 mJ. This result is reasonable since the number of sensors that fall within the antenna's coverage range and receive the BM increases as the beam width increases and the MB transmits BMs every fixed distance (1m) regardless the theta value. However for one phase BRM algorithm and two phases BRM algorithm the overall average energy consumption decreases as theta increases. This result is reasonable since in BRM algorithm the MB transmits BMs every BW/2 so as theta increases the MB transmits BMs every larger distance consequently the number of BM transmissions decreases. The overall average energy consumption for one phase BRM goes down from 3.7516 to 0.6306 mJ. For two phases BRM the overall average energy consumption goes down from 7.5033 to 1.2668 mJ. Therefore, it can be concluded that BRM algorithm has much lower overall average energy consumption than DIR algorithm.

The mean for one phase BRM, two phases BRM and DIR overall average energy consumption bars are 1.3081, 2.6102 and 20.5853 respectively. So compared with DIR algorithm one phase BRM enhanced the overall average energy consumption by **93.6455%** and two phases BRM enhanced the overall average energy consumption by **87.3201%**.

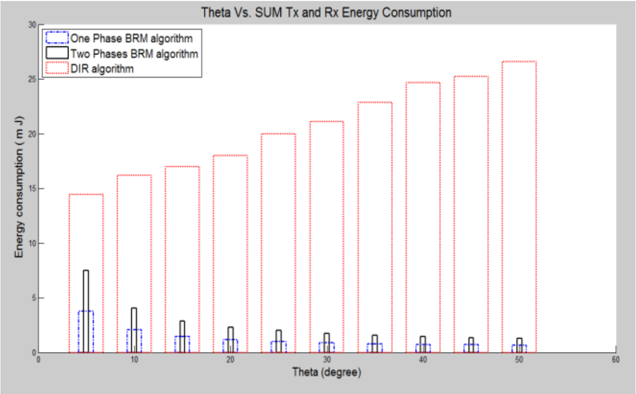

Figure 6 Overall Average Energy Consumption versus Theta.

3- *Impact of Antenna Beam Width on Localized Nodes Number:*

Figure 7 Shows that the percentage of average localized nodes number for two phases BRM algorithm remains about 88.21%, for one phase BRM algorithm it remains about 75.0140 % and for DIR algorithm the percentage of the localized nodes number increases from 48.0800% to 85.9800 % as theta increases. So it can be concluded that for lower theta values BRM algorithm can localize higher number of nodes than DIR algorithm but for high values of theta both BRM and DIR algorithms nearly can localize the same percentage of nodes.

Mean for one phase BRM, two phases BRM and DIR average localized nodes number bars are 75.0140, 88.21% and 74.3520 respectively. So compared with DIR algorithm one phase BRM enhanced the average localized nodes number by **0.8904%** and two phases BRM enhanced the average localized nodes number by **18.6384%**.

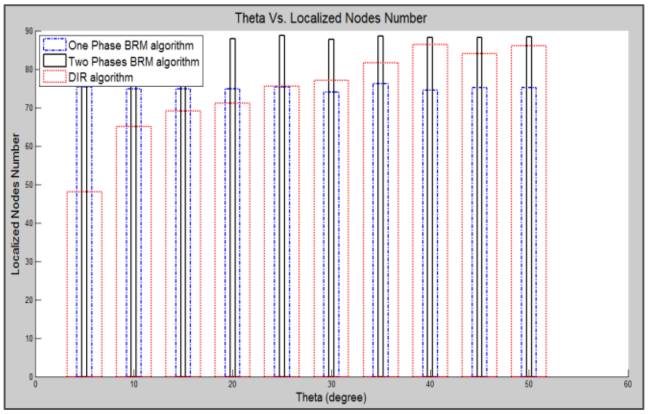

Figure 7 Number of Localized Nodes versus Theta.

4. CONCLUSION AND FUTURE WORK

This paper has proposed an efficient low cost, low power consumption and accurate localization algorithm for wireless sensor networks called BRM algorithm. The proposed algorithm needs only one MB node with one directional antenna, which transmits BMs as it moves through the sensing field. The sensor nodes receive these BMs and applies the statistical median to compute their coordinates based on the information included in these BMs. No specific hardware requirements for sensor nodes are needed and can be implemented using simple omnidirectional antennas. The performance of the proposed localization scheme has been evaluated by performing a series of numerical simulations using MATLAB. Simulation results have shown that the localization performance of BRM depends on the beam width of the directional antenna. Also it shows that BRM algorithm outperforms DIR scheme in terms of localization error, energy consumption and number of localized nodes. The future work will investigate the effect of the localization on routing process.

Table 1 summarizes the simulation results of BRM algorithm compared to DIR algorithm

Parameter	**One-Phase BRM**	**Two-Phases BRM**
Average Localization Error reduced by	37%	66.53%
Average Transmission Energy Consumption reduced by	92.3581%	84.7845%
Average Reception Energy Consumption reduced by	95.9417%	91.8429%
Overall Average Energy Consumption reduced by	93.6455%	87.3201%
Average Localized Nodes Number increased by	0.8904%	8.6384%

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