Distance Based Transmission Power Control Scheme for Indoor Wireless Sensor Network

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Abstract. This paper proposes a Distance Based Transmission Power Control (DBTPC) scheme for selecting Optimal Transmission Power for Indoor Wireless Sensor Network. The proposed work consists of two phases namely Localization phase and data transfer phase. In Localization phase, the relative coordinate of the unknown sensor node with respect to anchor sensor node is estimated by the proposed Received Signal Strength (RSS) based localization algorithm. By performing neighbor discovery process, each node obtains the distance information of its neighboring nodes. Based on this information, in data transfer phase it dynamically controls its transmission power level to reach their neighboring node with acceptable RSS value. This is achieved by the proposed distributed Distance Based Transmission Power Control (DBTPC) scheme. The Optimal Transmission Power (OTP) can be adaptively selected by the proposed DBTPC scheme. This ensures energy efficiency in sensor node and thereby increases the lifetime of the network.

Keywords: Received Signal Strength based localization algorithm, Distance Based Transmission Power Control scheme and Optimal Transmission Power.

1 Introduction

In Wireless Sensor Network, location awareness is the key factor for many potential real time applications such as monitoring, target tracking, person tracking, and context-aware application [1]. The sensor nodes in the network are usually powered by limited batteries which in turn influences the network lifetime. In order to increase the lifetime of the network, localization has to be made power efficient and accurate. The ability of sensors to locate themselves using limited energy and computational resources pose new challenges that require novel solution.

The traditional Global Positioning System (GPS) method of localization is not suitable for Indoor Wireless Sensor Network (IWSN), as it is not accurate and cost-effective [2]. Hence an alternate method like Time of Arrival (ToA), Time Difference of Arrival (TDoA) and Received Signal Strength (RSS) may be used [2]. From the literatures [2], it is found that RSS-based localization method is cost-effective, but not very accurate. However, using appropriated error minimization techniques, this problem can be resolved.

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In this paper, an energy efficient RSS based distributed localization algorithm and Distance Based Transmission Power Control (DBTPC) scheme are proposed. The principal objective of the proposed algorithm is to improve the accuracy in relative coordinate estimation and minimize the energy cost incurred for transmitting information between nodes. The proposed localization algorithm consists of two stages namely, distance estimation and coordinates estimation. Estimation of accurate distance is done by one-dimensional Kalman filter estimator. The number of iterations of the Kalman filter estimator is limited by Cramer Rao Bound (CRB). Min-max bounding box algorithm estimates the coordinates of the unknown nodes more accurately as it considers the overlapping issues prevailing in tri-lateration techniques. The proposed DBTPC scheme, aims to minimize the energy consumption in the network by selecting the Optimal Transmission Power (OTP) for each node to reach their neighboring nodes.

The rest of the paper is organized as follows. Section 2 discusses the related work in preceding power aware localization methods for Wireless Sensor Network. The proposed RSS –based localization algorithm and DBTPC scheme is presented in section 3. Results and discussion of the proposed work are presented in section 4 and Section V concludes the paper with future work.

2 Related Work

The goal of localization algorithms in Wireless Sensor Network (WSN) is to determine the node's position. Number of approaches [3, 4, 5, 6, 7, and 8] has been proposed that formulate the localization problem as joint estimation problem. The estimators determine the unknown node's locations with reference to the anchor node's positions. [9] proposes RSS based localization algorithm with weighted centroid method for indoor Wireless Sensor Network which offers low communication overhead and low computational complexity. But the reduction in RSS measurement errors is achieved by antenna diversity technique. This requires two antennas thus results in increase of hardware complexity.

[5] Proposes a hop-distance algorithm for self-localization in WSN which is based on RSS and uses maximum likelihood estimator to achieve accuracy. [10] Proposed a localization scheme based on RSS and distributed weighted multidimensional scaling algorithm which allows sensors to calculate their own location by means of iterative optimization thus decreases the cost and improves the global coordinate estimate. This method is robust to large errors.

As sensor networks are mainly operated by batteries, transmission of data between nodes needs to consume less power. Dynamic transmission power control mechanisms are required. In [11], a collaborative energy efficient target-tracking algorithm is developed, where transmission power is adjusted based on the amount of mutual information a node wants to share with their neighbors. In this method, the power adjustment scheme depends on the network querying technique and it performs well only if the most informative node is queried. A decomposition algorithm which optimizes the sensor power levels to achieve higher utility factor for scheduling transmissions in Wireless Sensor Networks is proposed in [12]. In [13], an optimal common transmit power for Wireless Sensor Networks is investigated. The optimal transmit power derived in this paper can be applied only to some specific scenarios and also it does not consider the multipath effects. In [14], an optimum selective forwarding policy for data transmission is introduced that selects the messages with higher priority and discards that of low-priority. This method considers only the energy requirements and not the neighbor node's information.

In this paper, an efficient RSS based Localization Algorithm and Distance Based Transmission Power Control (DBTPC) scheme are proposed. The proposed RSS based localization algorithm, aims to estimate an accurate relative coordinate of a sensor node. The proposed DBTPC scheme concentrates on energy optimization in the node, by adaptively selecting the Optimal Transmission Power of a node to reach its neighboring nodes based on their distance.

3 Proposed RSS-Based Localization Algorithm and DBTPC Scheme

Consider a sensor network randomly deployed in an indoor environment with $(M+N)$ nodes, where M denotes the number of anchor nodes and N denotes the number of unknown nodes. All the nodes are assumed to be static and possess the capability of transmitting and receiving information by means of uni-cast communication.

The objective of the proposed RSS-based Localization Algorithm is to determine the relative co-ordinates of N unknown nodes using the distance and location information of M anchor nodes. The accuracy of the proposed algorithm is enhanced by one-dimensional Kalman filter estimator in distance estimation stage and min-max bounding box algorithm in relative coordinates estimation stage. The block diagram of the proposed RSS based localization algorithm is presented in Figure 1.

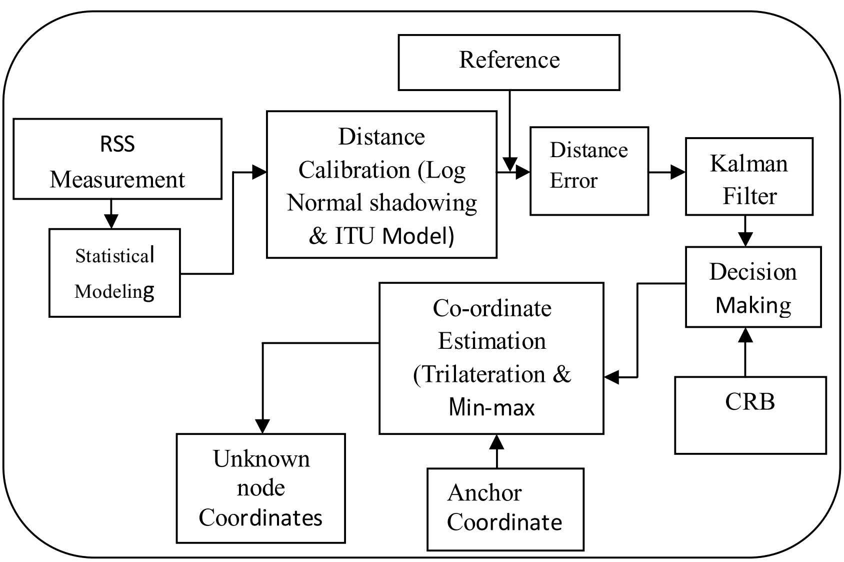

Fig. 1. Block diagram of proposed RSS based localization algorithm

Once every unknown nodes compute their relative co-ordinates through the proposed RSS based localization algorithm, they are termed as anchor nodes. Now, each node in the network performs neighbor discovery process to obtain the distance information of its neighboring nodes. With this information, the transmission power level at which each node need to be operated to reach their neighboring nodes with acceptable RSS is adaptively controlled by the proposed Distance Based Transmission Power Control (DBTPC) scheme. The block diagram of the proposed DBTPC scheme is presented in Figure 2.

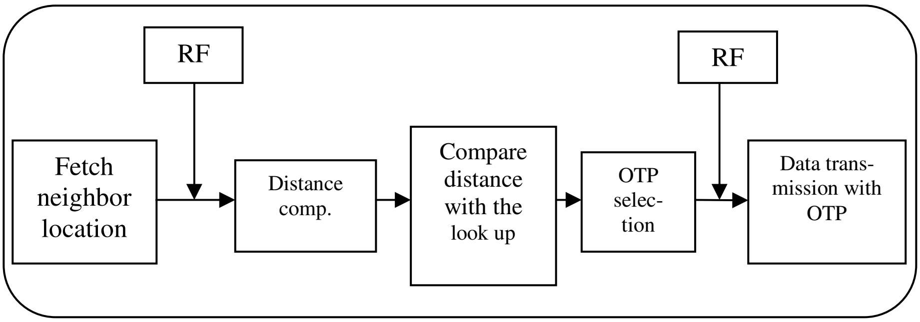

Fig. 2. Block diagram of proposed DBTPC scheme

3.1 RSS Based Localization Algorithm

The anchor node equipped with GPS receiver transmits signal with a particular transmission power to the unknown node, whose location is to be determined. The Received Signal Strength (RSS) value of the transmitted signal is measured in the unknown node. As the RSS values are fluctuating, more samples of RSS values are measured for different time instances. The above said procedure is repeated for different channels. The link qualities of all the channels are analyzed through statistical modeling. The channel possessing less Standard Deviation (*SD*) is concluded as the best channel. However, when the anchor node is operated at different transmission power level, then best channel selection depends on two other parameters like Packet Reception Rate (*PRR*) and Transmission Power (P_t).

Thus the Best Channel of Transmission (BCT) is expressed as,

$$BCT = fn(PRR, P_t, SD) \tag{1}$$

Where *PRR* - Packet Reception Rate.
P_t -Transmission Power
SD - *S*tandard Deviation

The distance of the unknown node with respect to anchor node is computed from the ensemble mean RSS value of the best channel using two models namely path loss log normal shadowing and ITU indoor attenuation models.

Let d_{mn} be the distance between anchor node *m* and unknown node *n* where *m* =1,2,….*M* and *n* =1,2,…..*N*.

The distance *dmn'* computed from log-normal shadowing model [15] is given below,

$$d_{mn}' = d_{ref}(10^{[(Pt(dBm)-\overline{PL}(d_{ref})-X_{\sigma}-Pr(d_{mn}')[dBm])/(10n_p)]}) \quad (2)$$

where $\overline{PL}(d_{ref})$ is the ensemble path loss at a short reference distance d_{ref} , X_{σ} is the zero mean Gaussian random variable with standard deviation σ and n_p is path-loss exponent, typically lies between 2 and 4.

The distance *dmn"* computed from ITU indoor attenuation model [16] is given below,

$$d_{mn}'' = d_{ref}(10^{[(Pt(dBm)-20\log f-L\log d_{ref}-P_f(f_{rmn})+28-X_{\sigma}-Pr(d_{mn}')[dBm])/(10n_p)]}) \quad (3)$$

Where L is the distance power loss coefficient, f is the frequency, f_{max} is the number of floors between the node m and node n, $P_f(f_{mn})$ is floor loss penetration factor.

The distance errors of the calculated distance by the two models are minimized by one-dimensional Kalman estimator [17].The convergence rate of Kalman filter estimator is decided based on the CRB (Cramer Rao Bound) [18].

Thus through one-dimensional Kalman filter estimator, the estimated distance $\hat{d}_{mn}$ is computed as given in equations below:

$$\hat{d}_{mn} = \left(\frac{d_{mn}'}{\sigma_1} + \frac{d_{mn}''}{\sigma_2}\right) \Big/ \left(\frac{1}{\sigma_1^2} + \frac{1}{\sigma_2^2}\right) \quad (4)$$

(Or)

$$\hat{d}_{mn} = (\mathrm{d_{mn}}'\sigma_2^2 + \mathrm{d_{mn}}''\sigma_1^2) \big/ (\sigma_1^2 + \sigma_2^2) \quad (5)$$

where $\sigma 1$ = standard deviation for d_{mn}' about the mean

$\sigma 2$ = standard deviation for d_{mn}'' about the mean

The above estimated distance can also be rewritten as

$$\hat{d}_{mn} = d_{mn}' + K(d_{mn}'' - d_{mn}') \quad (6)$$

where $K = \sigma_1^2 \big/ (\sigma_1^2 + \sigma_2^2)$ is defined as the Kalman gain.

The CRB value is given below,

$$CRB_{bound} = \frac{\sigma^2}{n_d} \quad (7)$$

where $\sigma = \frac{(\sigma_1 + \sigma_2)}{2}$

n_d =number of samples

Lateration is one of the most popular techniques for node positioning in Wireless Sensor Network. The lateration technique focused in this paper is tri-lateration. Assume that there are three anchor nodes with known positions (x_a, y_a) where a=1, 2, 3, a node at unknown position (x_u ,y_u) and estimated distance value $\hat{d}_{mn}$.

Using the model of multi-lateration [2], the 2-D coordinates of the unknown node can be determined as below:

$$\begin{bmatrix} x_u \\ y_u \end{bmatrix} = 2\begin{pmatrix} y_m - y_{m-1} & \cdots & y_1 - y_m \\ \vdots & \ddots & \vdots \\ x_{m-1} - x_m & \cdots & x_m - x_1 \end{pmatrix} \begin{bmatrix} (d_{1n}^2 - d_{mn}^2) & - & (x_1^2 - x_m^2) & - & (y_1^2 - y_m^2) \\ . & & . \quad . & & . \quad . \\ . & & . \quad . & & . \quad . \\ (d_{m-1}^2 - d_{mn}^2) & - & (x_{m-1}^2 - x_m^2) & - & (y_{m-1}^2 - y_m^2) \end{bmatrix} \tag{8}$$

where (x_u,y_u) be the coordinates of the unknown node, (x_a,y_a), a=1,2,….m be the coordinates of the known nodes, d*in*, i=1,2,…m be the distance between the node i and node n. Then from the point of intersection of all three anchors node's connectivity circles, the relative coordinates of unknown node is computed. But in real time scenario, overlapping circles may exist due to wireless medium constraints, this result in inaccurate relative coordinate estimation of unknown node. To resolve this problem an efficient min-max bounding box concept is used in the proposed algorithm. The connectivity circles of anchor nodes are modeled as square positioning Cells (PC). Then the Final Bounding Box (FBB) which is the overlapping box of all the square boxes is determined as below:

FBB is given by

$$FBB = \bigcap PC_n \tag{9}$$

3.2 Distance Based Transmission Power Control (DBTPC) Scheme

Let D represent the maximum coverage of (S=M+N) sensor nodes that are randomly deployed in indoor Wireless Sensor Network. After the Localization phase, each node is aware of its relative coordinates. Now each node broadcast a request message to obtain its neighbor's topological information. After receiving the network topological information, the proposed Distance Based Transmission Power Control (DBTPC) scheme placed in the transceiver module of the sensor node is switched ON. This DBTPC scheme, selects the Optimal Transmission Power (OTP) required to reach its neighboring node. This scheme minimizes the energy utilization in the node, thereby enhanced the lifetime of the network. The model used in the proposed DBTPC scheme is presented in the following section.

The DBTPC scheme present in the transceiver module of each sensor node controls its transmission power based on two factors namely distance information of its neighbors (d_i) where i=1, 2,..., (S-1) and its own residual energy (E_k) at K^{th} instant.

Thus the Optimal Transmission Power (OTP) can be expressed as,

$$OTP = \begin{cases} fn(E_k, d_i) & ; \quad E_k > e_t \\ 0 & \quad otherwise \end{cases} \tag{10}$$

Where e_t the total amount of energy is consumed per packet transmission and is given by [11],

$$e_t = P_t \times \frac{L}{R_b} (Joules) \tag{11}$$

where P_t - Transmission power, L - Packet size, Rb- the bit rate.

The proposed DBTPC scheme is validated by two models namely (i) Connectivity model and (ii) Energy model.

Connectivity model

Let d_k represent the connectivity information of a sensor node at instant. If neighboring nodes are within the connectivity of a sensor node, then d_k =1 else d_k =0. Let x_k be a variable that indicates the communication status of a sensor node such that,

$$x_k = \begin{cases} 1, & transmission\, occurs \\ 0, & no\ transmission \end{cases} \tag{12}$$

The necessary condition at which the proposed DBTPC scheme can be enabled in the sensor node is when both $d_k = x_k = 1$.

Energy model

The energy consumption in nodes can be the sum of energy spent in the sensing module, processing module and transceiver module. It is found from the literature [14] that energy consumption in sensing and processing is negligible compared to that of transceiver module. In transceiver module, the energy consumption can be controlled by adaptively selecting the transmission power to reach the neighboring nodes based on their distance. The proposed DBTPC scheme is designed to perform this task.

Let E_k be the residual energy in a node at k^{th} instant that can be expressed as,

$$E_k = E_{k-1} - x_k E_1(d_k) + (1 - x_k)e_i \tag{13}$$

Where E_{k-1} is the residual energy in the node at $(k-1)^{th}$ instant, e_i is the energy spent by the nodes when they are in idle state, $E_1(d_k)$ is the energy consumed when the node decides to transmit.

$$E_1(d_k) = pe_t \tag{14}$$

Where p - number of transmitted packets.

The lifetime of the node can be defined as the time taken to drain out of initial battery energy and is given by [3],

$$\tau = \frac{E_{batt}}{\lambda_t e_t} = \frac{E_{batt} R_b}{\lambda_t L P_t} (\text{sec}) \tag{15}$$

where λ_t - average transmission rate, E_{batt} - initial battery energy.

The expected power profile obtained by the proposed DBTPC scheme is given in Figure 3. Transmitting with a lower power reduces the communication range of the node. Hence the profile justifies that the communication between nodes that are closer to each other can be achieved with lower transmission power level of operation.

Consider each sensor node consists of an ordered set of transmission power levels, $P_t = \{P_1, P_2, ..., P_l)$ where l represents the number of power levels such that $P_1 < P_2 < .... < P_l$. Let d_{ij} be the distance between any two nodes that are within the maximum coverage D, Then the Optimal Transmission Power (OTP) is given in equation (16).

If each node has the maximum coverage D, it has the privilege to communicate with the maximum power, P_l. However, the proposed DBTPC scheme adaptively controls the transmission power P_l in accordance with its distance information. The Energy reduction is further ensured by enabling the DBTPC scheme in the transceiver module which in turn wakeup the RF module from idle to active state. Thus the proposed DBTPC scheme provides the energy saving mode of operation.

$$OTP = \begin{cases} P_1, & 0 \le d_{ij} < D - \frac{(l-1)}{l} D \\ P_2, & D - \frac{(l-1)}{l} D \le d_{ij} < D - \frac{(l-2)}{l} D \\ . & . \\ . & . \\ . & . \\ P_l, & D - \frac{(l-(l-1))}{l} D \le d_{ij} \le D \end{cases} \tag{16}$$

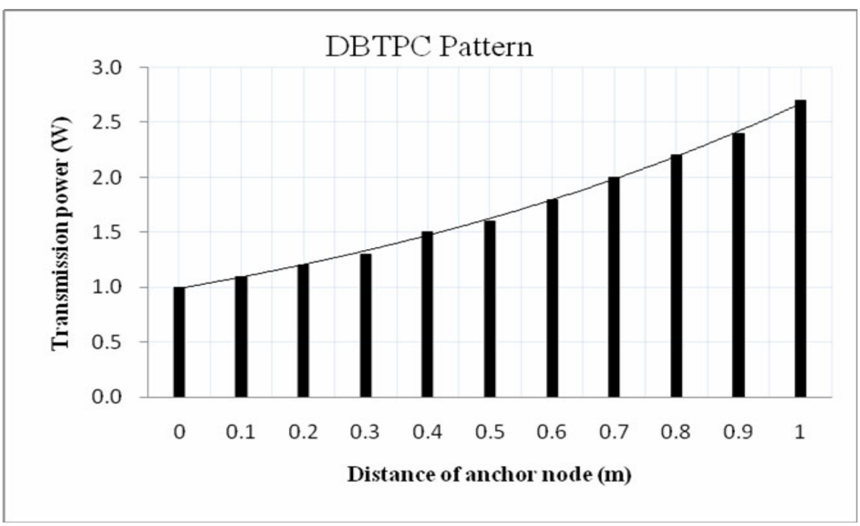

Fig. 3. Power Profile of the Proposed DBTPC scheme

4 Results and Discussions

The proposed RSS based Localization algorithm is analyzed using Matlab version 7.0. The results of analysis are given below.

4.1 RSS Analysis

The experimentation is done in the indoor environment using Zigbee series 1 RF module and the associated X-CTU software of MAXSTREAM. The experiment has been repeated for five different channels (B, C, D, E and F) with five different frequencies. The experimental observations recorded in indoor environment are presented in Table 1. The table shows 20 samples of RSS (Received Signal Strength) values measured at 20 different time instances for a specific distance. Figure 4 illustrate the relationship between distance and RSS measurement for channels B with frequency values shown in Table 1. It is seen that the Received Signal Strength of the unknown node decreases as distance between the anchor and unknown node increases. Similar relationship between Distance and RSS measurement is also found for remaining four channels (C, D, E, and F).

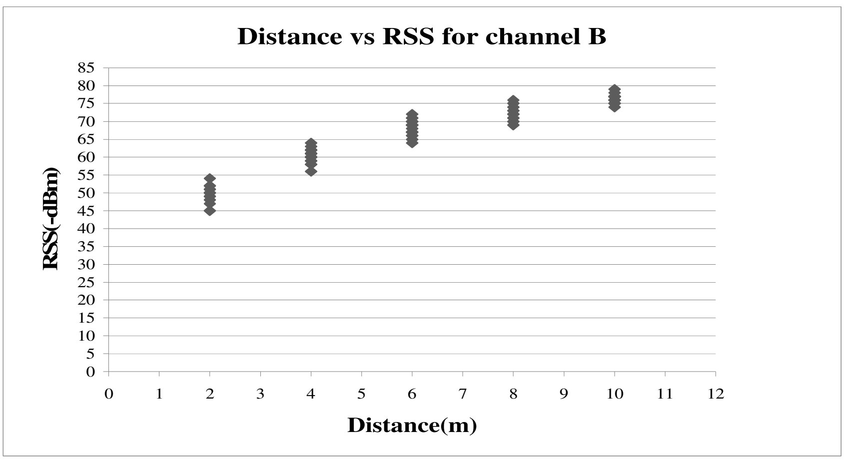

Fig. 4. Distance vs RSS for channel B

The statistical modeling is done to find the best channel. The results are presented in Table 2. It is found that the channel E is selected as the best channel for distances 2m, 4m and 10m as it possesses low standard deviation. For distances 6m and 8m, channel D is selected as the best channel of transmission. The average RSS value of channels D and E are computed.

From log normal shadowing path loss model and ITU attenuation model, the distance between the anchor node and unknown node is calculated as illustrated in Figure 5. It is seen that the calculated distance is closer to the actual distance in case of log normal shadowing path loss model than ITU attenuation model.

Table 1. Experimental results in indoor environment

Dist. (m)	RSS Measurements (dBm)				
	Channel B (2.404-2.406) GHz	Channel C (2.409-2.411) GHz	Channel D (2.414- 2.416) GHz	Channel E (2.419-2.421) GHz	Channel F (2.424-2.426) GHz
22	-50,-48, 47, -45,-45,-51, -53,-54,-52, -49,-49,-51, -52,-50,-52, -51,-50,-49, -50,-48	-50,-50,-47, -49,-51,-52, -45,-55,-50, -50,-49,-48, -49,-47,-49, -50,-51,-51, -52,-50	-50,-50,-49, -48,-47,-50, -51,-53,-54, -55,-47,-55, -49,-48,-47, -51,-52,-47, -48,-50	-49,-51,-49, -50, -50,-49, -49,-51, -49, -48,-51,-50, -51,-50,-51, -50,-49,-49, -49,-50	-49,-51,-50, -52, -53,-50, -48,-50, -49, -50,-50,-51, -52,-54,-52, -49,-47,-49, -50,-51
4	-59,-60,-62, -60,-58,-61, -62,-63,-64, -58,-56,-60, -61,-62,-61, -60,-61,-62, -59,-60	-59,-60,-61, -62,-60,-60, -61,-60,-56, -61,-59,-60, -60,-58,-56, -61,-62,-61, -60,-59	-60,-59,-61, -58,-59,-60, -60,-61,-60, -59,-59,-58, -61,-62,-61, -63,-61,-64, -61,-61	-59,-60,-61, -60,-59,-61, -60,-61,-59, -60,-61,-62, -60,-59,-60, -61,-62,-63, -60,-61	-60,-61,-63, -60,-59,-58, -61,-60,-58, -60,-61,-59, -61,-62,-59, -63,-60,-61, -60,-59
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4.2 Kalman Analysis

Figure 6 shows the relationship between actual distance and estimated distance estimation obtained with and without one-dimensional Kalman filter. It is seen that with kalman, the estimated distance is very close to the actual distance. The percentage of accuracy improved by kalman and the number of iteration taken to achieve them is

Table 2. Standard Deviation for five channels

DIST. (m)	B (2.404-2.406) GHz	C (2.409-2.411) GHz	D (2.414-2.416) GHz	E (2.419-2.421) GHz	F (2.424-2.426) GHz
2	2.39	2.13	2.62	0.92	1.69
4	1.87	1.65	1.53	1.23	1.38
6	2.13	1.67	1.26	1.37	2.05
8	1.98	1.29	1.04	1.31	1.92
10	1.11	1.44	0.96	0.61	1.18

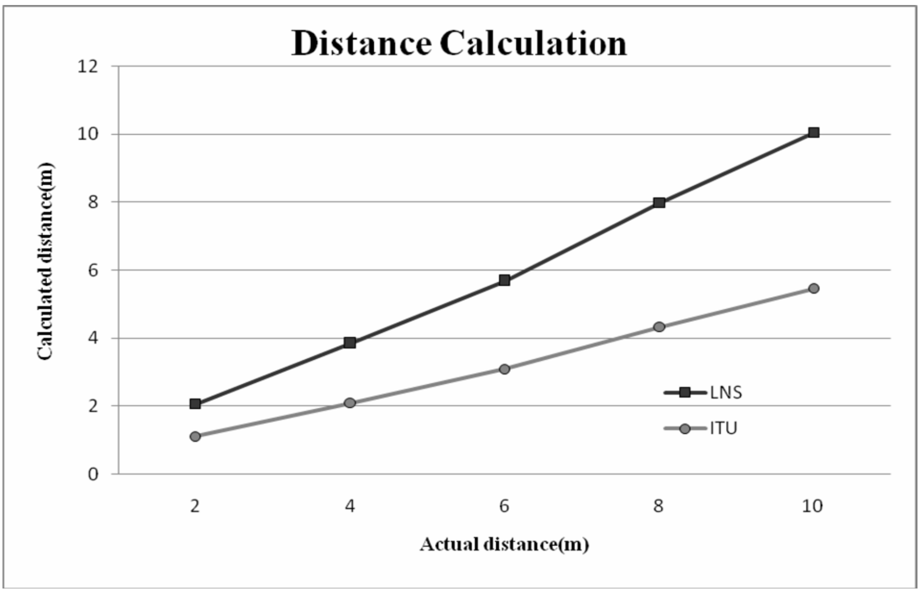

Fig. 5. Distance Calculation

presented in Table 3. It is inferred that percentage of accuracy improvement is gradually increased as the distance of separation between nodes is increased with the cost of number of iteration.

4.3 Trilateration Analysis

The relative coordinate of the unknown node is determined by trilateration and the accuracy is improved using min-max algorithm. Figure 7 shows the results of trilateration with min-max algorithm.

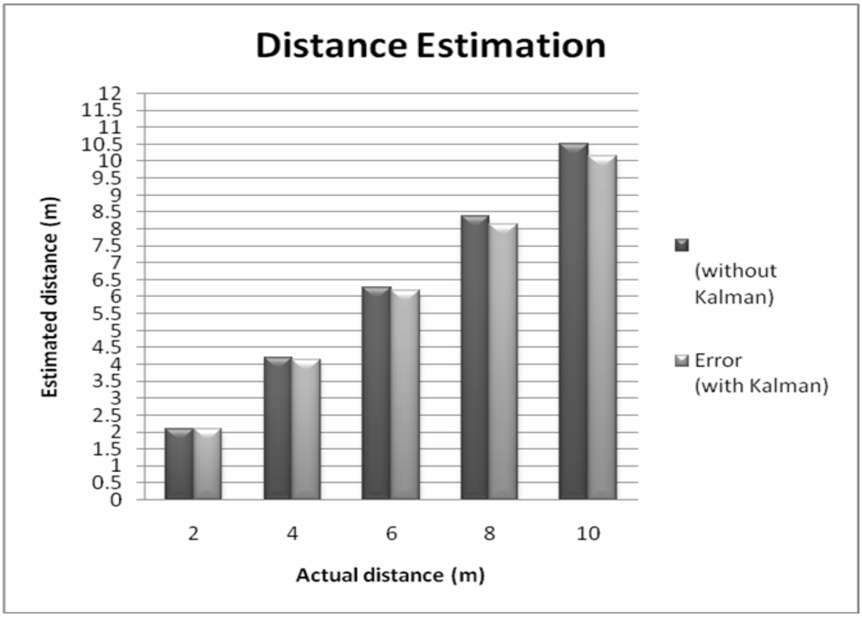

Fig. 6. Distance Estimation

Table 3. Kalman Filter Analysis

Act. Dist(m)	Error (with-out Kal-man)	% of error With out Kalman	% of acc. With out Kalman	Error (with Kal-man)	% of error With Kalman	%of acc. With Kalman	% of Impro-ved acc.	No. of itera-tion
2	0.10	5.06	94.93	0.08	4.47	95.52	0.59	1
4	0.19	4.84	95.15	0.13	3.30	96.69	1.55	2
6	0.27	4.61	95.38	0.19	3.21	96.78	1.40	2
8	0.37	4.62	95.37	0.14	1.77	98.22	2.85	3
10	0.52	5.28	94.72	0.16	1.68	98.32	3.6	3

Table 4 shows the result obtained with and without min-max bounding box algorithm. It is found that accuracy is improved through min-max bounding box algorithm.

4.4 Real-Time Experimentation Transmission Power Analysis

In real time, RSS values are measured between pairs of nodes for five different transmission power levels and the distance estimation is done using the proposed RSS

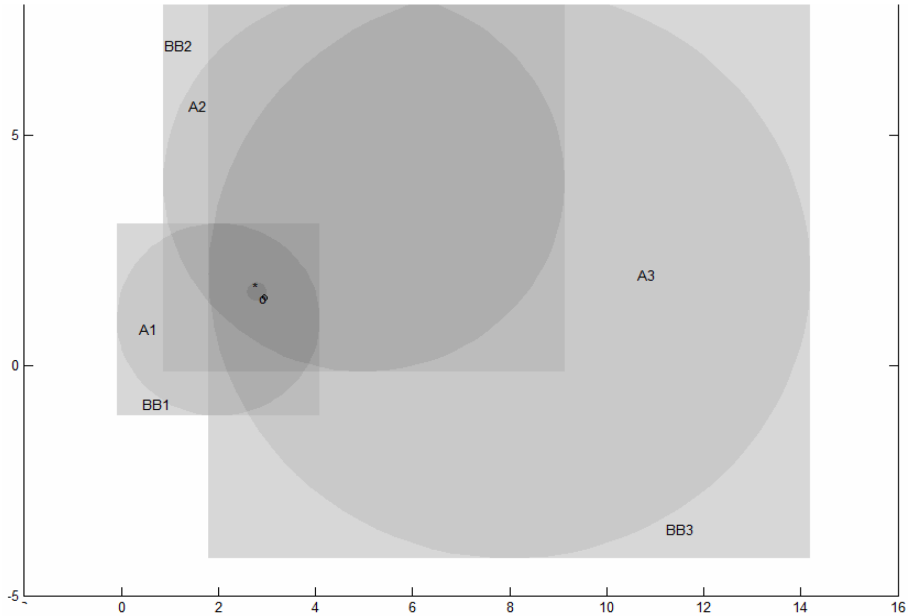

Fig. 7. Coordinates of unknown node estimated using min-max algorithm

Table 4. Co-ordinates Estimation

Anchor coordinates (x,y)		Distance between anchor node and unknown node(m)	Coordinates of the unknown node without min-max algorithm (x,y)	Coordinates of the unknown node with min-max algorithm (x,y)	Actual Coordinate
1	(2,1)	2.089	(2.12,1.75)	(2.94,1.47)	(3.3, 1.7)
2	(5,4)	4.132			
3	(8,2)	6.192			

localization algorithm. To analyze the energy consumption per packet transmission, a simple experimental setup is developed using zigbee series 1 RF module as illustrated in Figure 8. The various transmission power levels supported by zigbee series 1 RF module are lowest (0.16mW), low (0.25mW), medium (0.39mW), high (0.63mW) and highest (1mW). One experimental scenario is shown in Figure 8, in which two nodes A and B are kept at 8m distances apart.

The maximum distance (D) that can be covered by node A when operated at the highest transmission power in indoor environment is found to be 15m. Node A can communicate with node B as it is within its coverage, but it will definitely leads in reduction of its lifetime if it is continuously operated at the highest transmission

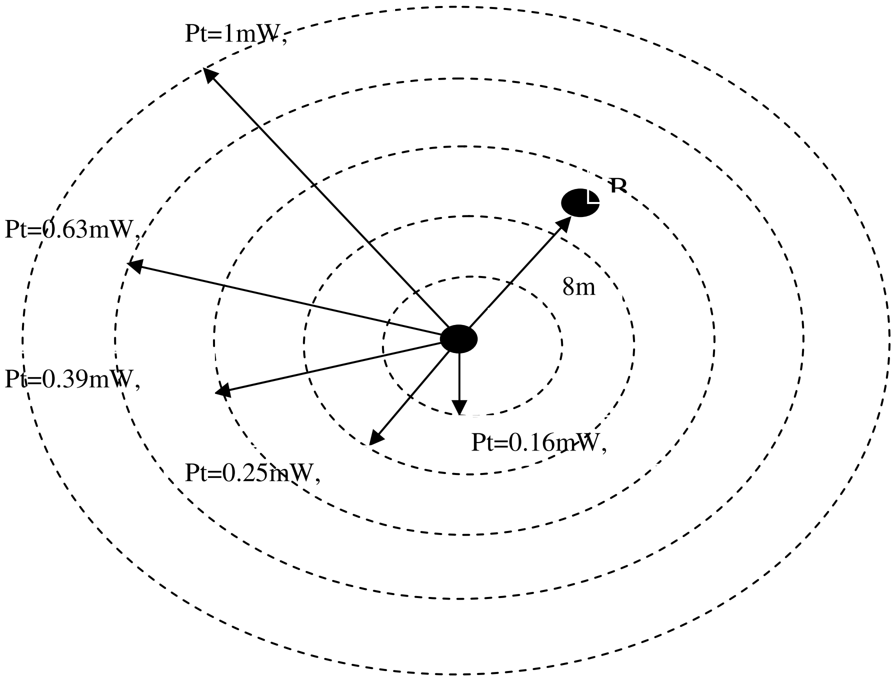

Fig. 8. Experimental setup to analyze the energy consumption

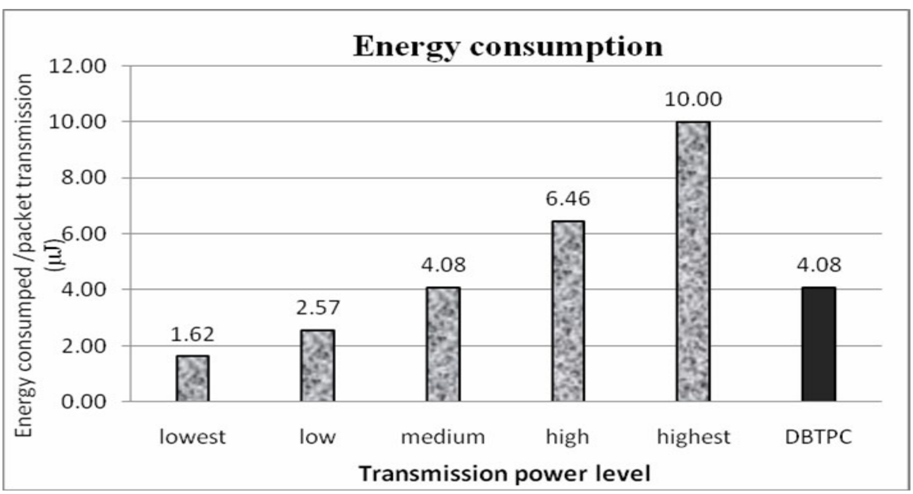

Fig. 9. Energy consumption vs Transmission Power level

power. By applying the proposed DBTPC scheme, node A dynamically adjusts its power level to medium power level to reach node B. Using equation 11, the energy consumed per packet transmission is computed for all the five power levels and plotted as shown in Figure 9. From the experimental result, it is found that by applying the proposed scheme, energy consumed per packet transmission is reduced to around 145%, when node A is operated in medium power level than in highest power level.

5 Conclusion and Future Work

In this paper, an efficient RSS based distributed localization algorithm and DBTPC scheme are proposed. The inaccuracies incurred in the RSS based localization algorithm are refined using Kalman filter estimator and trilateration with min-max algorithm. The energy consumption in the node for data transmission among neighboring nodes are reduced by the proposed DBTPC scheme which selects the Optimal Transmission Power based the distance information of the neighboring nodes. Hardware design and embedding the proposed DBTPC scheme in the transceiver module of the sensor node are under progress.

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