SIMULATION AND CALIBRATION OF RSSI BASED DISTANCE ESTIMATION FOR LOCALIZATION IN WSN

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ABSTRACT
Wireless Sensor Networks (WSNs) are extensively being used in various environments to implement different monitoring tasks such as search, rescue, disaster relief, target tracking and a number of tasks in smart environments. Various applications of wireless sensor networks need information about the physical location of each sensor node. So therefore self-organisation and localisation capabilities are one of the most significant requirements in sensor networks. In this paper, we proposed a distance based cooperative localization algorithm called Curvilinear Component Analysis mapping (CCA-MAP) for nodes position estimation within a WSN. This algorithm is based on distance measurements using Received Signal Strength Indicator (RSSI) technique. The performance of our approach is evaluated through simulations using MATLAB simulator and we also implemented it in a real system deployment in an indoor environment by performing an empirical measurement using Crossbow IRIS sensor motes. The simulation results obtained revealed that our approach delivers improved position accuracy.

KEY WORDS
WSNs, Localization, CCA-MAP, RSSI and Distance measurement.

1. Introduction
Research on Wireless Sensor Networks (WSNs) has attracted a lot of interest in recent times, and this interest is growing because it promise to be an enabling technology of the future owing to the fact that processors, sensors and wireless radios are becoming extremely small and inexpensive. A WSN is a network consisting of a large number of wireless radio nodes equipped with sensing devices and are densely distributed for specific applications. Each node is equipped with a transceiver to communicate with another node within its communication radio range [1].

Typical sensors incorporated into wireless sensor nodes are light sensors, sound sensors, ultrasound sensors, accelerometers, temperature sensors, pressure sensors, humidity, and touch sensors to name a few. Some of the applications of WSN include disaster and relief operations, biodiversity mapping for wildlife observation, intelligent building and bridges, military operations and health where motes may be deployed to collect vital information such as pulse and heart beat rate. Some WSN applications are seen underground for monitoring earthquake, soccer fields, locating people in a collapsed building, under water applications which are implemented for ocean sampling networks, disaster prevention, assisted navigation, pollution monitoring specifically for chemical and biological spillage and distributed tactical surveillance [1], [2].

In many applications of WSN, sensed information only becomes useful when it is accompanied by the location of the area and accurate distances of where such information is been sensed. Hence, sensor nodes need to know the distance between one another in order to calculate their positions. This need however drives the assumption that the location information of sensor nodes is available by some means such as Global Positioning System (GPS) or manual entry. The challenge faced in the entering of the position information of nodes manually is that it limits the size and scalability of a sensor network; as a result, it removes much of the strengths of WSNs. The problem with assuming GPS enabled sensor nodes is that the cost of the sensor nodes increases considerably, and the appropriate environment in which the sensor nodes can be deployed is limited. Moreover, the energy cost would be excessively large. As a result of the constraints of power consumption as well as the limitations that could be caused due to the lack of visibility of satellites require the need to propose an alternative solution. In this case, methods for self-determination of position information are required for achievable placement of wireless sensor nodes [3].

Many algorithms have been proposed in the literature to calculate relative and absolute positions among sensor nodes in wireless sensor networks (WSNs). The major challenges in all these methods lies in designing an effective and robust localisation scheme that takes cognisance of the form factor and computing power of the node, power usage at the minimum level, scalability of the network and of course accuracy of the localisation.

In this paper, we proposed a distance based localization algorithm called CCA-MAP algorithm. This algorithm is based on the RSSI model that estimates the RSSI signal propagation for WSN in order to estimate the distance of deployed sensor nodes in the network. The RSSI signal propagation model is currently of three types; Free Space propagation model, Two-ray ground Model and Log Normal Shadowing Model (LNSM) [4], [5], [6], [7]. The first two models have special requirements for the application environment while the third model which is considered in this paper is a more general signal propagation model.

The remainder of this paper is structured as follows. In section 2, the classification of localization algorithms in WSN is presented and section 3 focuses on our proposed approach which is the distance based CCA-MAP algorithm. In section 4,
the experimental setup and the calibration of the empirical measurement of the sensor nodes is analysed. Section 5 presents the simulation result which is the performance evaluation of our approach. Finally, the conclusion and future work of this research study are summarized in section 6.

2. Classification of Localization Algorithms in WSN

Localization is the method of dynamically determining the position or location of sensor node in a network. There are different types of localization techniques to solve the problem of localization in WSN. These techniques can be differentiated based on the way in which they use the extracted signal information. Some localisation technique can be a centralised techniques or distributed technique while some techniques use the information to determine the absolute distance to a reference node (range based), others make no assumption that the absolute distance can be determined by the information provided (range free). Some techniques can also be anchor free or anchor based techniques in other ways some can also be mobile or stationary localisation technique. The exact approach one chooses depends highly on the application involved. The classification of localization algorithm in WSNs is presented in this section [8], [9].

2.1 Centralized versus Distributed Localization Algorithms

The classification of localization algorithms in WSN can be categorized into centralized [10] or distributed [11] algorithms based on the way the computation of the sensor nodes in the network are organized. In centralized algorithms, sensor nodes send all there information to a central node called sink where the computation of their positions are computed and sent back to them. The limitations of this algorithms is that their communication costs is very high and in large networks, they are inefficient because as the number of sensor nodes in the network increases, the delay in computation increases due to the fact that all the nodes in the network send their information to the sink for computation. In contrary to the centralized algorithms, distributed algorithms works in a way in which each sensor nodes in the network computes its position with the help of its neighbours by means of communication. So therefore, these algorithms can be used in large networks compared to centralized algorithms because the computational cost is very low and the delay in communication between the sensor nodes in the network is minimized.

2.2 Anchor-Based versus Anchor-Free Localization Algorithms

The classification of localization algorithms in WSN can also be categorized into anchor based algorithms and anchor free algorithms. In anchor based algorithms, anchor nodes are the nodes that know their position information by means of installing a Global Positioning System (GPS) receiver on them or by manual entering. These anchor nodes are used by other nodes called non-anchor nodes as reference nodes to provide their position information in the network [11], [12]. In anchor based algorithms, a fraction of the sensor nodes in the network must be anchor nodes or at least a minimum number of anchor nodes are required for accurate results. The limitation of anchor based algorithms is that they require a GPS receiver which is used to determine the position of the anchor nodes and if the anchor nodes are not in the visibility of a satellite to determine their position information, the algorithms may fail to work properly.

In contrary, an anchor free localization algorithm [13] does not need the services of anchor nodes to determine the position of the sensor nodes in the network but however provide node positions that reflect the position of the sensor nodes relative to each other. This is achieved in such a way that the next forwarding node in the network is chosen based on a distance metric which needs the next hop to be closed to the destination in a physical manner.

2.3 Mobile versus Stationary Node Localization Algorithms

The classification of localization algorithms in WSN can be categorized in such a way that the sensor nodes in the network are stationary or mobile. In a stationary network, the position of the sensor nodes are computed in a static form while in a mobile network, the problem of finding the position and tracking moving sensors in real time is determined. The number of applications that requires mobile sensor nodes in WSN has increased because the introduction of mobility have improved the overall network lifetime and the capacity of the data in the network by addressing the delay and latency problem [14], [15].

2.4 Range-Based versus Range-Free Localization Algorithms

The classification of localization algorithms can also be categorized into range free [16] and range based [17] localization algorithms. Range free localization algorithms estimate the positions of the sensor nodes in the network by using the connectivity information between the sensor nodes that are in the same neighborhood. This algorithm does not need any additional hardware to determine the position of the sensor nodes in the network but uses the proximity information of the sensor nodes. On the other hand, range based localization algorithms uses the ranging information to determine the position of the sensor nodes in the network by measuring the distances between two neighboring nodes. These algorithms used different range measurement techniques which are Time of Arrival (TOA), Angle of Arrival (AOA), Received Signal Strength Indicator (RSSI), and Time Difference of Arrival (TDOA) to estimate the distances between the sensor nodes in the network.
2.4.1 RSSI - Distance Estimation using Theoretical Model

There are four main ranging techniques for distance estimation for localization in WSN. In this paper we considered only RSSI technique because the use of it does not require any additional hardware but simply a radio transceiver compared to other ranging techniques.

RSSI is defined as the amount of power present in a received radio signal. Due to radio-propagation path-loss, RSSI decreases as the distance of the radio propagation increases. Therefore, the distance between two sensor nodes can be compared using the RSSI values at the receiver assuming that the transmission power at the sender is either fixed or known [18]. Estimating distances based on RSSI samples drawn from a given channel, some model of the given channel that effectively defines the environment need to be developed. So therefore, this approach needs complete models of radio frequency propagation and does not account for any form of variations in the orientation of the receiver and its sensitivity.

When a signal propagation model is given, raw RSSI data can be mapped to specific distances. These distances can be used either directly in order to perform localization or given a probability and used in a learning based/probabilistic localization algorithm. Clearly, the accuracy of the distance estimation based methods rest heavily on the accuracy of the signal propagation model used for transforming RSSI values to distances. Example of the common radio propagation models is the log-normal shadowing model [19] and is given in Equation 1.

Log-Normal Shadowing model is a radio propagation model that estimates received signal strength inside a building or heavily populated environment over distance. The model is implemented in an indoor and outdoor propagation modeling.

\[ PL(d) = PL(d_0) + 10 \times n \times \log_{10}(d/d_0) + X_n \]  

(1)

Where \( d \) is the transmitter-receiver distance, \( n \) is the attenuation constant, \( X_n \) is a zero-mean Gaussian (in dB) with standard deviation \( \sigma \) (multi-path effects), \( d_0 \) is a reference distance and \( PL(d_0) \) is the power decay for this distance. The received signal strength \( Pr \) at a distance \( d \) is the output power of the transmitter \( Pr = Pt - PL(d) \), (all powers in dB) [20].

2.4.2 RSSI – Distance Estimation using Empirical Model

Received signal strength indicator measures the power of the signal at the receiver based on the known transmit power. The respective propagation loss can be calculated. Theoretical and empirical models are used to translate this loss into a distance estimate. This method has been used mainly for RF signals. The relationship between RSSI values and distances are derived as follows by [21].

The received signal power is inversely related to distance as;

\[ P \propto 1/D^n \]  

(2)

\[ RSS \propto 10 \times \log_{10}(1/D)^n \]  

(3)

\[ RSS = -10 \times n \times \log_{10}(D) + C \]  

(4)

\( D \) is the distance of deployed sensor and \( n \) is the path-loss exponent factor. \( C \) is considered to be a fixed constant. In more compact form, RSS can be represented as:

\[ RSS = -m \times \log_{10}(D) + C \]  

(5)

In equation 5, \( m \) is the slope of linear equation between RSS and \( \log_{10}(D) \). The path-loss exponent factor is given as:

\[ n = m / 10 \]  

(6)

3. The Distance based CCA-Map Algorithm

The approach in this paper is a distance based cooperative localization scheme called Curvilinear Component Analysis Mapping (CCA-MAP) and it has already been proposed in [12]. CCA-MAP algorithm was chosen among other localization algorithms because it has high accuracy with minimum number of anchor nodes and without any additional refinement process. CCA-MAP algorithm is also computationally efficient resulting in faster mapping process.

CCA-MAP technique is a cooperative node localization scheme that applies an efficient neural network non-linear projection method [22], to deliver accurate data dimension reduction and to localize nodes in WSN using distance measurement. CCA delivers accurate data dimension reduction while preserving distances between the data points during the reduction process at a computational cost that is the least among the various reduction methods. CCA looks for configuration of points in the output space that preserves the original distances as much as possible while focussing on small distances in the output space. This cooperative localisation scheme formulates the localization problem as a joint estimation problem and applies optimisation techniques to derive location coordinates considering all constraints on inter-node distances, rather than considering only constraints between the sensor nodes and anchor nodes. It uses a variant of the stochastic gradient descent method to create a mapping of data.

The goal of the CCA is to minimise a cost function shown in equation 7 based on inter-point distances between the original input space and projection output space [12].

\[ E = \frac{1}{2} \sum_{i,j} \left(A_{ij} - B_{ij}^2 \right)^2 f(B_{ij}, \lambda_j) \]  

(7)

\( A \) represents the distance matrix in the input space and \( B \) represents the distance matrix in the output space. \( A_{ij} \) stands for inter-point distance that forms a \( N \times N \) distance matrix of
\[ A_i = d(a_i a_j) = \sum_{k=1}^{N-i} (a_{ik} a_{jk})^2 \] in the input space and \( B_{ij} = d(b_i b_j) = \sum_{k=1}^{N-i} (b_{ik} b_{jk})^2 \) in the output space. The weighting function is often bounded and monotonically decreasing in time with each computing cycle in order to favour the local topology conservation. The decreasing exponential functions for \( F(\cdot) \) is chosen during the experimentation exercise of this technique.

CCA uses a modified stochastic gradient descent method to improve computation efficiency in its update cycle such that it pin one \( b_i \) and moves all other \( b_j \) around. This means that only the \( b_i \) distance from node \( i \) to other \( N-1 \) nodes are computed instead of all \( \frac{N(N-1)}{2} \) distances in the input and output spaces [14].

The updated cycle is:

\[ \Delta b_j = \alpha(t) F(B_{ij}, \lambda(t))(A_{ij} - B_{ij}) \frac{b_j - b_i}{B_{ij}} \quad \forall j \neq i \quad (8) \]

The decrease exponential function, \( F(B_{ij}, \lambda) = e^{-\lambda(t)} \) is selected with the fact that both \( \alpha(t) \) and \( \lambda(t) \) decreases with time along each computing cycle in order to conserve the local topology. The complexity in terms of adaptation cycle of all nodes is \( O(N) \) instead of \( O(N^2) \) as in most nonlinear mapping (NLM) algorithms. Contrast to most NLM technique, CCA minimisation allows the cost \( E \) to increase temporarily, but bind it to decrease on average. The computation applying CCA minimisation not only converges much faster, but it also escapes from local minima to reach a much deeper minimum.

CCA-MAP builds local map at each node within the sensor field and put them together to form a global map. CCA is employed in computing the node coordinates in the local map. In a situation where accurate ranging capability is implemented in the network, the distance between pairwise neighbour nodes will be measured and known, else connectivity information is solely implemented to allocate value of 1 to the edge between each neighbouring nodes. Finally the distance matrix \( D \) for all the nodes in the \( H \) hop neighbourhood of node \( I \) can then be constructed (for instance \( H = 2 \)) by using the shortest distance matrix to form an approximation of the distance.

The CCA-MAP requires no further optimization because the results obtained are largely optimized over the given distance information which is satisfactorily in this regard.

### 4. Experimental Setup

IRIS Motes are the motes used for our experimentation and they form part of the latest generation of Motes from Crossbow Technology, XM2110 (2400 MHz to 2483.5 MHz band). These enhancements provide up to three times improved radio range and twice the program memory over previous generation MICA Motes. The same MICA family, 51 pin input/output (I/O) connector, and serial flash memory is used; all application software and sensor boards are compatible with the XM2110 [23].

The radio used by the IRIS is an IEEE 802.15.4 compliant radio frequency (RF) transceiver designed for low-power and low-voltage wireless applications. It uses Atmel’s AT86RF230 radio that employs O-QPSK (Offset Quadrature Phase Shift Keying) with half sine pulse shaping. The 802.15.4 radio includes a DSSS (Digital Direct Sequence Spread Spectrum) baseband modem providing a spreading gain of 9 db and an effective data rate of 250 kbps [23].

RF transmission power is programmable from 3dBm to –17.2dBm. Lower transmission power can be advantageous by reducing interference and dropping radio power consumption. The RF received signal strength indication (RSSI) is read directly from the AT86RF230 Radio and sent with every radio packet received. The type of antenna used by IRIS mote is called a monopole antenna and its gain is ground plane dependent. The antenna length of IRIS mote is 1.2inches [23].

![Image](image.png)

**Figure 1.** Figure taken from [23], XM2110 IRIS mote with standard antenna and its respective block diagram

### 4.1 Experimental Analysis

The experiment was carried out in an indoor environment using Crossbow Iris Motes. The motes were programmed before performing any forms of measurements. One end of the Universal Serial Bus (USB) extension cable was connected to an available USB port on the laptop and the other end to the gateway USB connector. Each node was programmed by mounting them on the Gateway. The Gateway used was MIB520 Interface board by crossbow. Application software called mote-view which acts as an interface between the user and the deployed wireless sensor nodes was also installed on the laptop and it provides the tools to simplify deployment and monitoring; it also makes it easy to connect to a database to analyze and to graph sensor readings. In the classroom where the experiment was conducted, there were tables, chairs, walls,
projectors and laptop which introduce multipath fading and shadowing effect to the channels.

Table 1
This table from [23] summarizes the details regarding IRIS XM2110 Crossbow mote

<table>
<thead>
<tr>
<th>Mote Hardware Platform</th>
<th>Platform Types</th>
<th>IRIS XM2110</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCU</td>
<td>Chip Type</td>
<td>AT Mega 1281 7.37 MHZ, 8Bit 128 8</td>
</tr>
<tr>
<td></td>
<td>Program Memory(KB) SRAM(KB)</td>
<td></td>
</tr>
<tr>
<td>Sensor Board Interface</td>
<td>Type 10Bit ADC UART</td>
<td>51 Pin 7, 0V to 3V Input 2</td>
</tr>
<tr>
<td>RF Transceiver (Radio)</td>
<td>Chip Radio Frequency(MHZ)</td>
<td>RF 230</td>
</tr>
<tr>
<td></td>
<td>Max Data Rate (Kbits/sec) Antenna Connector</td>
<td>2400 250 MMCX</td>
</tr>
<tr>
<td>Default Power Source</td>
<td>Type Typical Capacity(mA-hr)</td>
<td>AA, 2^2 2000</td>
</tr>
</tbody>
</table>

These sensor nodes were programmed at a transmitter power of 3.2dBm in which the RSSI has a sensitivity of -102dBm. Only two sensor nodes were used for performing the experimentation, one node act as the transmitter and the other as the receiver. The effects of the antenna orientation of the sensor nodes were taking into consideration so therefore all the sensor nodes are resting on their bases with antenna pointing vertically upwards. RSSI measurements are prone to noise and interference which leads to error in measurements. Hence, in order to avoid these errors and to provide ideal environment for the measurements, measurements were taken in such a way that no other device working in the range of 2.4GHz were present in the vicinity of experimental location and it was ensured that the deployed sensor nodes are in line of sight with the base node and no obstacles were present between them.

The RSSI readings taking from the measurements is shown in figure 2 and the readings were taken at a fixed distances at different time intervals in order to take into consideration the effect of shadowing due to the fact that RF channels vary with time.

4.2 Calibration of RSSI Measurements

Since the measured RSSI values vary randomly with time, the mean values of the RSSI were considered for calculating the distances of the deployed sensor nodes. We conducted an experiment for generating the calibration equation relating RSSI to distance and is shown in figure 4.

Figure 2. Plot of RSSI Values at each Distance

Figure 3. Plot of the mean of the measured RSSI values in an Indoor Environment

Figure 4. Calibration Equation Relating RSSI to Distance
Table 2
This table shows the mean, variance and the standard deviation of the RSSI values in an indoor Environment.

<table>
<thead>
<tr>
<th>Distance(m)</th>
<th>Mean</th>
<th>Variance</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-10.9000</td>
<td>0.9889</td>
<td>0.9944</td>
</tr>
<tr>
<td>2</td>
<td>-25.4000</td>
<td>5.3778</td>
<td>2.3190</td>
</tr>
<tr>
<td>3</td>
<td>-24.2000</td>
<td>0.8444</td>
<td>0.9189</td>
</tr>
<tr>
<td>4</td>
<td>-36.4000</td>
<td>8.7111</td>
<td>2.9515</td>
</tr>
<tr>
<td>5</td>
<td>-24.7000</td>
<td>2.3333</td>
<td>1.4944</td>
</tr>
<tr>
<td>6</td>
<td>-24.1000</td>
<td>0.1000</td>
<td>0.3162</td>
</tr>
</tbody>
</table>

The plot in figure 4 shows the data used for calibration. It was obtained with RSSI(dBm) along the Y-axis and $\log_{10}$(Distance) along the X-axis. The calibration equation and curve were fitted with MATLAB’s basic fitting tool which shows a linear curve between RSSI and $\log_{10}$(Distance).

The calibration equation and curve shown in figure 4 is for the indoor RSSI measurement. It gives the relationship between RSSI(dBm) and the actual distance and is derived below

$$y = -19x - 15$$  \hspace{1cm} (9)

$$RSSI = -19 \cdot \log(D) - 15$$  \hspace{1cm} (10)

From equation 9, the distance equation can be derived which is given in equation 11. This equation was used to in the simulation environment to calculate the distances between the wireless sensor nodes after getting the RSSI values from each node in the network.

$$D = \frac{RSSI + 15}{-19}$$  \hspace{1cm} (11)

5. Simulation Result

This section demonstrates the results obtained by the simulation of our proposed localisation algorithm using the theoretical model and empirical model of distance estimation which was described in section 2 above and we evaluated there performances based on the localisation error. In the theoretical model, the following assumptions were imputed to the parameters in equation 1; $P_t = 3.2$dBm; frequency =2.4GHz; IEEE 802.11a or g, $d_0 = 1$; $n = 2$, $X\sigma$ with $\sigma = 0.1$, represents the standard deviation of the received signal strength due to shadowing effects and is invariant with the distance. $X\sigma$ follow a zero mean normal distribution. So therefore, from equation 1, the distances between the sensor nodes are calculated.

We assumed that the maximum Radius used for this type of network to be 3 meters in order for the nodes to connect to its neighbours in its range. The Sensor Nodes connect to its neighbours if they are in the same specified network radio range and does not connect it its less than the network radio range. The full distance matrix was calculated between the pair-wise sensor nodes that are in the same radio range and the log-normal shadowing model was used to calculate the power received between the sensor nodes that are in the same range. The relationship between the received power and the distance is shown in figure 6.

Figure 4. Calibration curve of the linear regression based on the mean of the measured RSSI values in an Indoor Environment.

Where $y$ represents RSSI(dBm) and $x$ represent $\log_{10}$(D), where $D$ is the distance.

Figure 5. Network Topology Graph of a Randomly Deployed 50 Sensor Nodes
According to the simulation result shown in the figure 5, the sensor nodes are randomly deployed in an area of 10 meters by 10 meters and the nodes connect to its neighbours in the range of 3 meters. Using LNSM (log Normal shadowing model), we could observed in figure 6, the relationship between the RSSI of the sensor nodes and their respective distances. This however shows that as the distance between the two sensor nodes in the same range increases, the received signal strength reduces.

So however, we were able to compute the distance between the sensor nodes in the network theoretically by using the Lognormal Shadowing model in equation 1 and empirically by using the calibration equation derived from the RSSI measurements in an indoor environment.

This distance information is now imputed into our distance based CCA-MAP algorithm in order to compute the relative and position of the sensor nodes in the network. Three sensor nodes were designated as the anchor nodes to compute the absolute positions of the non-anchor nodes in the network. Anchors are sensor nodes that know there positions while non-anchor nodes are sensor nodes that does not know there positions in the network.

After computing the absolute position of the sensor nodes in the network using the distance measurement derived from the theoretical and empirical technique, we then evaluate the performance of our approach by calculating the error distribution of the estimated absolute coordinates of the sensor nodes in the network and it’s shown in figure 7.

Figure 7 shows the comparative simulation result of the mean localisation error of the proposed distance based CCA-Map localisation algorithm using the RSSI theoretical model and using the RSSI empirical model at different network size.

From the simulation results obtained, our approach delivers improved position accuracy because it has very low localization error. Localization error is the distance between the estimated position of the sensor nodes after applying our proposed algorithm and the real positions of the sensor nodes.

6. Conclusion and Future Work

In this paper, a comprehensive performance evaluation of the distance based CCA-Map localization algorithm was done using Matlab simulator. In the network configurations simulated with different network size when ranging capability is employed which is calculated theoretically and empirically using the Receive Signal Strength Indicator technique (RSSI), our approach achieved an accurate node position estimates with an average error less than 10%R where R is the radio range of each node in the network. So therefore our approach delivers improved position accuracy.

Currently, research work is in progress in implementing our distance based CCA-Map algorithm on a real test-bed and in the near future we planned to expand our approach to be able to localise mobile sensor nodes in WSN.
References


