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Enhancing Location Accuracy by Minimizing RMS Using RSS-AMLE in WSN

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Abstract

Over the past decade, there has been significant growth in wireless sensor networks, particularly in the context of industrial applications. Mobile sensor networks have garnered research interest due to their ability to facilitate communication between various devices. Still, the mobility of these nodes gives rise to challenges such as network coverage and connectivity issues. Addressing these challenges necessitates accurate estimation of sensor node locations, a critical factor in network performance. Numerous methods, such as Angle of Arrival (AOA) and Time of Arrival (TOA), have been proposed for node localization. Still, these methods are plagued by localization errors and high implementation costs. To overcome these localization errors in wireless sensor networks, we present an adaptive approach based on the Received Signal Strength (RSS) model. This model views localization as a non-convex problem and employs an adaptive maximum likelihood estimation to minimize localization errors. An extensive simulation study is carried out to measure the performance of the intended approach in minimizing the localization error. The results unequivocally demonstrate that our localization scheme achieves higher accuracy in locating sensor nodes while reducing deployment costs. Comparative analysis against existing methods further underscores the significance of our approach.

Keywords

Wireless Sensor Networks (WSNs), Received Signal Strength (RSS) model, non-convex problem, localization errors

1. Introduction

A Wireless Sensor Network (WSN) consists of hundreds, or even more sensory devices designed to observe the surroundings, carry out basic computations, and transmit the collected data to other sensors or a central unit for data collection. These sensor devices are characterized by their limited battery life, cost-effectiveness, compact size, and are primarily intended for a wide range of sensory applications. These applications encompass areas such as military surveillance systems, environmental monitoring, search and rescue missions, disaster management, wildlife habitat counting in forests, fire detection, and safety alarms, among others [1]. In many such applications node localization is an important criterion to report the origin of events, to query the sensor nodes, routing, and the network coverage for providing better and effective service to the end users. Over the past few years, these sensor nodes have been enhanced with wireless interfaces, enabling them to establish connections with one another, forming a wireless network infrastructure. These sensor devices gather and store relevant data in their local vicinity and then transmit this sensory data over a remote medium to central information gathering nodes, often referred to as Base stations or Sinks. At these information gathering nodes, the collected data is analyzed with the aim of determining the overall status of the sensed area. There are many locations-based approaches to localize the nodes. The straightforward solution is to add a global positioning system (GPS) to every sensor node in the network, but it is not feasible as mountains, dense forest and other obstacles block the line-of-sight from GPS satellite. High power consumption due to the use of GPS has a negative impact on the lifetime of the entire network. Similarly, the production and implementation cost of GPS for large sensor nodes is very high [1]. For these reasons an alternative solution that is cost effective, easily deployable and can operate in diverse environments is required. The localization method based on Time of Arrival (TOA) framework [2], necessitates the use of additional devices or hardware to ensure that the transmitting and receiving devices are synchronized. Crucially, even a small error in time estimation can lead to a significant deviation in the ranging measurements. Moreover, the localization technique relying on Time Difference of Arrival (TDOA) encounters similar challenges as TOA frameworks, as they both entail considerable costs for hardware. Both TDOA and TOA methods also require the deployment of a larger number of sensor devices because their signal propagation range is limited. On the other hand, Angle of Arrival (AOA) frameworks have the potential to offer superior localization accuracy. However, they may not be well-suited for large-scale or highly dense sensor networks due to their intricate design and the associated implementation expenses [3-6].

This research introduces a cost-effective and highly efficient localization approach that relies on Received Signal Strength (RSS). Unlike the limitations discussed earlier, RSS-based localization methods provide effective solutions to these issues. The core concept of RSS techniques is to utilize Radio Frequency (RF) signal propagation models, which can be derived from theoretical, hypothetical, or empirical sources, to analyze RSS data and estimate distances without requiring additional ranging hardware. These systems are not only economical but also straightforward to implement, as the majority of RF IC-chips used in wireless sensor network devices can directly furnish RSS data [7-8].

Present study shows that, implementation of RSS based localization technique with error minimization and approximation methods gives better results in terms of location accuracy of sensor nodes. In this direction, we have implemented RSS based localization technique with adaptive approach for maximum likelihood estimation to increase the location accuracy of sensor nodes by reducing the localization error in wireless sensor networks.

2. Proposed Sensor Devices Localization Model for WSN

This section presents proposed approach for wireless sensor node localization based on Received Signal Strength (RSS) information. In order to carry out this work, we have developed a measurement model for WSN that is used for network modeling. Figure 1 depicts WSN network topology with different number of sensor nodes, paired nodes which are capable of communicating with each other directly or by using an edge. Here, node connectivity is an important parameter which affects the performance of localization. Connectivity can be defined at initial stage based on their node density or it can be assigned dynamically by adjusting communicating node's parameters.

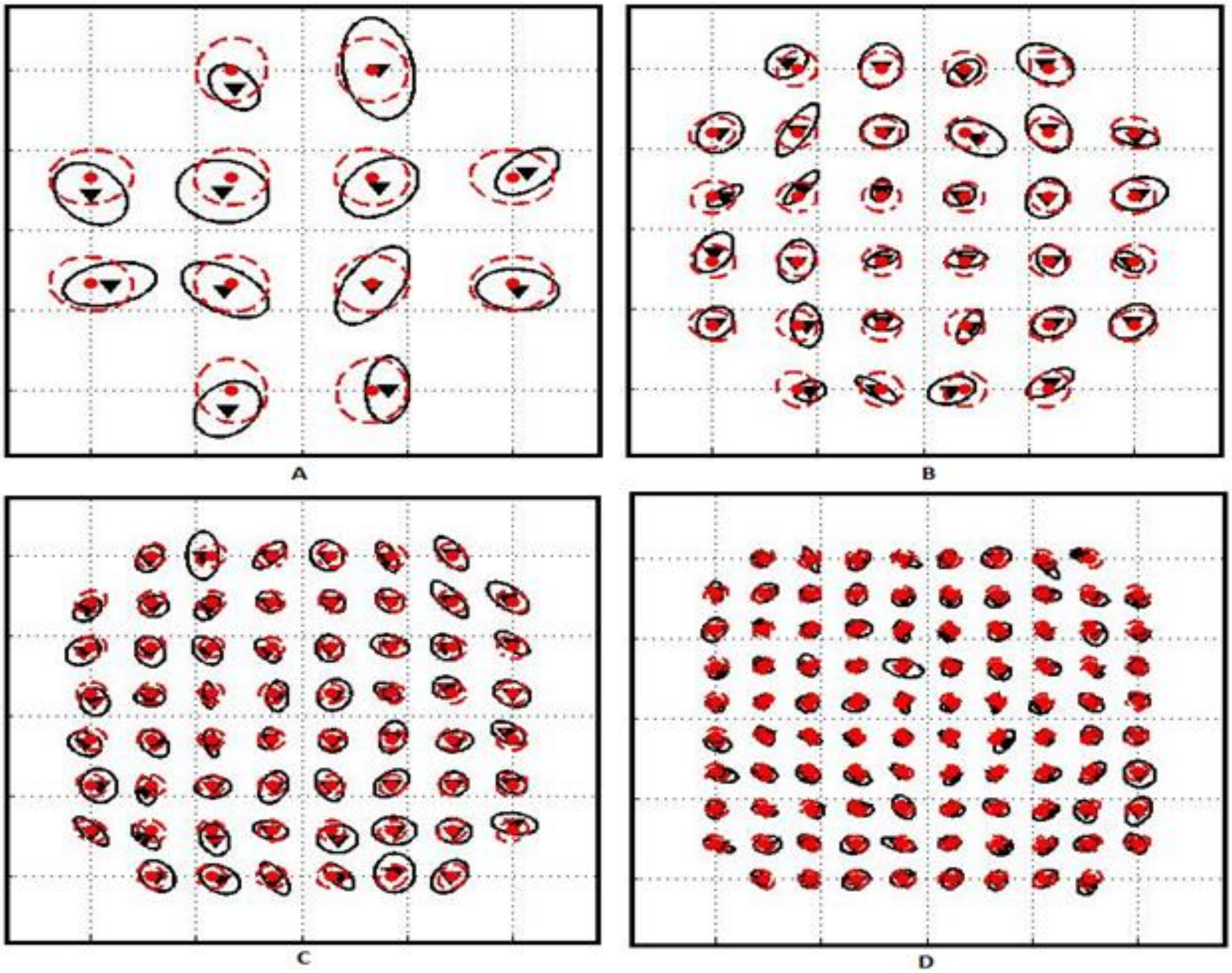

Figure 1. Network topology with different number of sensor nodes A) 4 B) 6 C) 8 D) 10

3. Problem Formulation

Let W be a wireless sensor network which consists of anchor node and target nodes set or it can be denoted as

$$W = |\mathcal{T}| + |\mathcal{A}| \quad (1)$$

Where $\mathcal{T}$ denotes target nodes and anchor nodes are denoted by $\mathcal{A}$, $|.|$ denotes fundamental parameters of a set as$(|\mathcal{T}| = T, |\mathcal{A}| = A)$. According to proposed model, location of nodes are denoted as $x_1, \dots, x_T, x_{T+1}, \dots, x_{T+A}$ where$x_i \in \mathbb{R}^q (q \geq 2)$. In other words, this network can be presented in the form of connected graphs which is given as $\mathcal{G}(\mathcal{V}, \mathcal{E})$ where $\mathcal{V}$ denotes vertices and $\mathcal{E}$ denotes edges of the network. In this network, every node is provided limited communication range (R) which helps to obtain improved network lifetime and energy efficient performance during communication. Using this assumption, exchange of information between node i and j is given as

$$\mathcal{E} = \{(i,j): \|x_i - x_j\| \leq R, i \neq j\} \quad (2)$$

Above equation (2) shows that the communication between nodes will happen if they are present in the defined communication range. For localization process, any of neighbor node are considered as anchoring node. Hence, target node set is given as$\Omega_i =$

$\{j: (i, j) \in \mathcal{E}$. Furthermore, to reduce the computational complexity, target node positions are defined as in the form of $q \times T$ assuming that$X = [x_1, x_2, \dots, x_T]$. In this work, it is assumed that positions of anchor nodes are known from theoretical deduction whereas target nodes (i) are given an initial position estimation as $\hat{x}_i^{(0)}, where\ i = 1, \dots, T$ hence it can be concluded that $(\hat{X}_i^{(0)})$ contains initial position estimation of all nodes.

Relationship between target node and neighboring node is established with the help of node's transmit power and received power which is given as

$$L_{ij} = 10\ log_{10} \frac{P_T}{P_{ij}} \tag{3}$$

Where P_T denotes transmit power of a node, received power from j^{th} node at i^{th} target node is denoted byP_{ij}. Based on this relationship, RSS localization problem is formulated according to the path loss model which is represented as

$$L_{ij} = L_0 + 10\,\gamma\ log_{10} \frac{\|x_i - x_j\|}{d_0} + n_{ij}, \forall (i, j) \in \mathcal{E} \tag{4}$$

Where L_0 denotes path loss for a short distance d_0, path loss exponent isγ, n_{ij} denotes log normal shadowing between node i and j node. This path loss model is modeled by considering zero-mean Gaussian random variable with varianceσ_{ij}^2. According to proposed approach, symmetric path loss measurement is assumed here i.e. $L_{ij} = L_{ji}$ for$i \neq j$.

With the help of path loss model presented in (4), we derive maximum likelihood estimator which is given as

$$\hat{X} = argmin_X \sum_{(i,j):(i,j)\in\mathcal{E}} \frac{1}{\sigma_{ij}^2} \left[L_{ij} - L_0 - 10\,\gamma\ log_{10} \frac{\|x_i - x_j\|}{d_0} \right]^2 \tag{5}$$

Eq. (5) is a non-convex and non-linear problem which is formulated to obtain optimal solution by applying Maximum Likelihood Estimator.

For further evaluation in this work, it is assumed that transmit power of all nodes are identical, path loss and range are equal for all nodes and $\sigma_{ij}^2 = \sigma^2\ \forall (i, j) \in \mathcal{E}$

4. Simulation Results and Analysis

The experimental study was carried out to localize wireless sensors using the proposed localization approach. Simulations were carried out using MATLAB tool and analysis were performed using higher configuration system. Present simulation study considers several crucial localization parameters, including the area where sensor nodes were deployed, the quantity of nodes to be deployed, the number of reference devices used, and the iterations or attempts made for localization. Received Signal Strength method was employed to assess the performance of localization error.

In the initial scenario, we maintained the number of reference devices at 4 and varied the number of nodes, including 4, 6, 8, and 10, while also adjusting the localization attempts. Figure 2 illustrates the performance of our model, RSSI-AML, in terms of root mean square error when employing adaptive maximum likelihood estimation, comparing it to the existing model, RSSI-ML. Figure 3 presents the average root mean square error of RSSI-ML for different numbers of sensor devices, while Figure 4 showcases the corresponding average root mean square error of RSSI-AML. The results of our proposed localization method are further detailed in Table 2, where they are compared to the performance of the established standard localization approach.

The RSS measurement is generated by applying propagation model as presented in Eq. (4). For simulation study, a random deployment of nodes is considered where the network region is considered as $100\ m \times 100\ m$ with Monte Carlo iteration model. Initially, 500 Monte Carlo iterations are simulated to obtain the connectivity in network. Path loss exponent is considered as 3, reference distance is given as 1m and reference path loss is given as 40 dB and communication range is estimated as $R = Network\ Length\ (100\ m)/5\ m$

Table 1. Simulation parameters considered for present study

Parameter Name	Parameter Value Considered
Area	100 m × 100 m
Number of Sensors	4,6,8,10
Reference Devices	4
Localization Iteration	10,15,20,25,30
Localization measurement method	RSS
Path loss exponent γ	3
Reference Distance	1 m
Reference path loss	40 dB

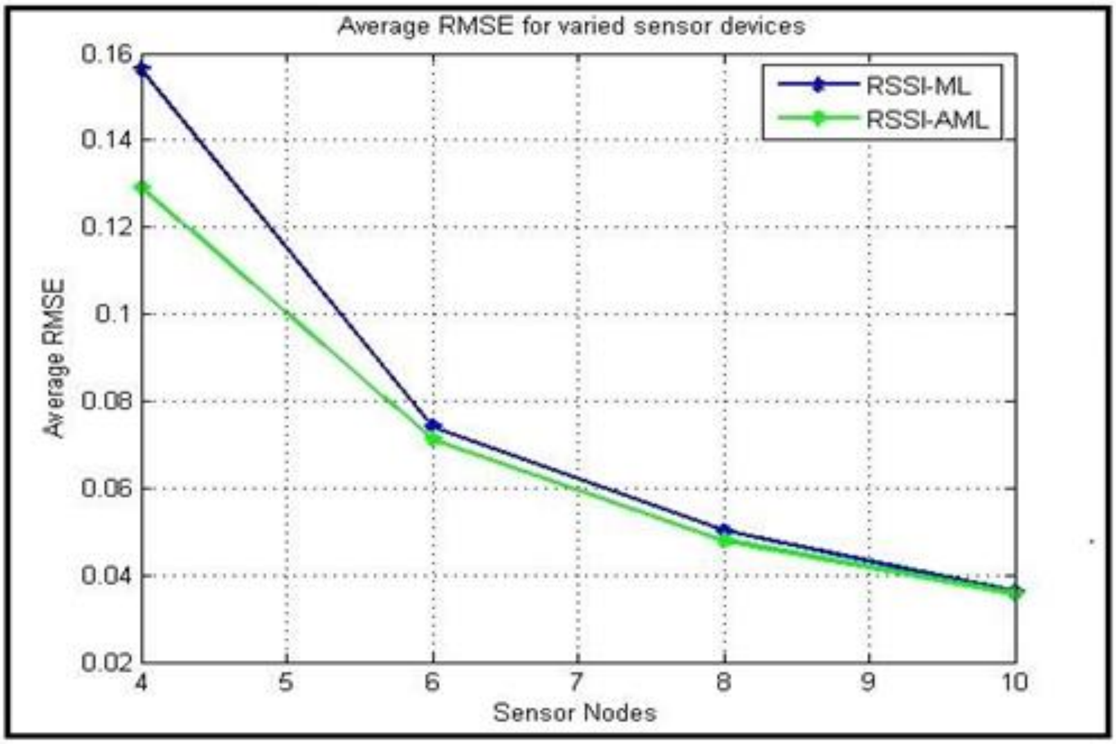

Figure 2. Varied localization attempt

In the second case, we conducted experiments in which we systematically altered the quantity of devices or nodes involved, while maintaining a consistent number of reference devices and localization attempts throughout the study. The outcomes of these experiments, which provide insights into the average performance under these specific conditions, are illustrated in both Figure 3 and Figure 4.

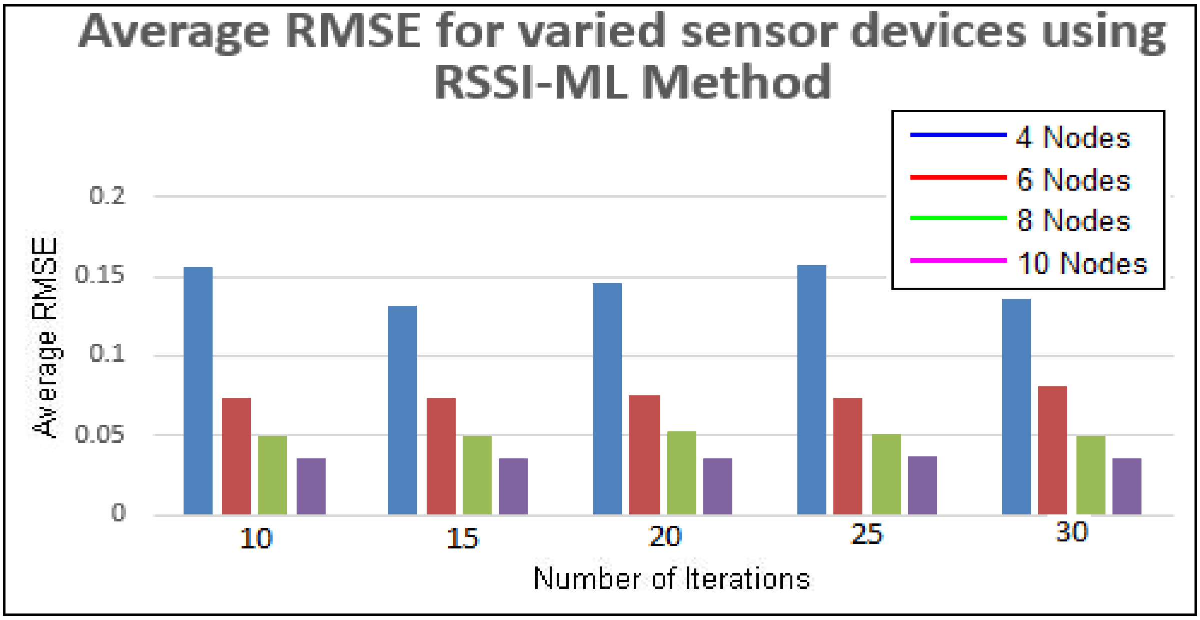

Figure 3. Average RMSE for varied sensor devices for RSSI-ML Method

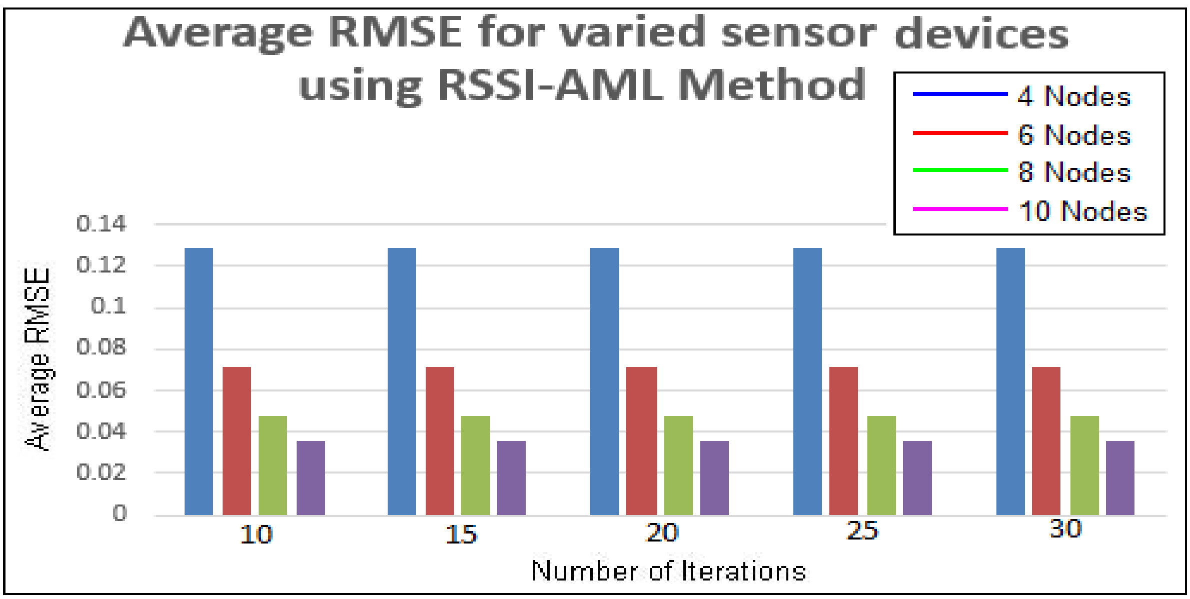

Figure 4. Average RMSE for varied sensor devices for RSSI-AML Method

In Table 2, the performance comparison of RSSI-AML with RSSI-ML is tabulated. Here we have considered varied number of sensor devices (4, 6, 8, and 10) and localization attempts (10, 15, 20, 25, and 30) by keeping the reference devices as constant (4).

Table 2: Performance comparison of RSSI-AML with RSSI-ML

Number of devices	Localization attempts	RSSI-ML	RSSI-AML
4	10	0.1564	0.1291
	15	0.1312	0.1291
	20	0.1455	0.1291
	25	0.1569	0.1291
	30	0.1357	0.1291
6	10	0.0742	0.0712
	15	0.074	0.0712
	20	0.0753	0.0712
	25	0.0736	0.0712
	30	0.0813	0.0712
8	10	0.0501	0.0479
	15	0.0495	0.0479
	20	0.0529	0.0479
	25	0.051	0.0479
	30	0.0496	0.0479
10	10	0.0361	0.0356
	15	0.0356	0.0356
	20	0.0351	0.0356
	25	0.0368	0.0356
	30	0.0357	0.0356

5. Conclusions

A wireless sensor network (WSN) comprise of hundreds or more sensor devices and a few information gathering devices. Localization algorithms provide fundamental support for many location aware applications. Localization of nodes in wireless sensor network has turned into an important criterion for providing better and effective service to the end users. The existing approach suffers from the problems like localization error and higher implimentation cost. To overcome these problems, the random deployment of nodes was made in a network region of $100\mathrm{m} \times 100\mathrm{m}$. Monte Carlo iteration model was used to obtain the connectivity in network and the simulation study was conducted by varynig the parameters like number of sensor devices, reference devices and localization attempts. The proposed model RSSI-AML uses Received Signal Strength based localization method and provides an adaptive maximum likelihood estimator to minimize or approximate the localization error in WSN. The result shows that our proposed localization scheme RSSI-AML surpasses the existing approach(RSSI-ML) in accuracy by minimizing the root mean square error .

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