



PERFORMANCE ANALYSIS OF NODE DENSITY AND ESTIMATION OF RANGES USING ToA METHOD FOR WSNs

Sudha H.Thimmaiah and Yamuna Devi, C.R.

Dept. of Electronics & Telecommunication Engineering,

Dr.Ambedkar Institute of Technology, Malhathahalli, Bengaluru-560056, Karnataka, India.

ABSTRACT

Wireless Sensor Networks (WSNs) facilitate the collection and transmission of data through spatially distributed sensor nodes that are generally deployed in a stationary manner. Wireless sensor-based communication systems have emerged as a rapidly growing research domain with extensive industrial applications. WSNs are widely employed in monitoring, control, and surveillance applications due to their capability for real-time data acquisition and communication. In such applications, the performance evaluation of WSN parameters is essential to ensure reliable and efficient network operation. Among the various performance aspects, localization, i.e., the estimation of the position of sensor nodes, plays a critical role in enhancing the quality and efficiency of services provided to end users. Therefore, minimizing localization error has become a significant research objective in WSNs. Localization error, commonly evaluated using the Root Mean Square Error (RMSE) metric, is influenced by factors such as range estimation accuracy, sensor node density, number of anchor nodes, and communication range. By analysing these parameters, the localization performance of the network can be effectively estimated and optimized. In the present study, a Time-of-Arrival (ToA)-based localization technique integrated with an adaptive information estimation model is proposed to reduce and approximate localization errors in WSNs. Simulation-based performance analysis for range estimation and RMSE evaluation using the proposed ToA method was carried out in the MATLAB environment.

Key words - WSNs-Wireless Sensor Networks, NN-Number of Nodes, AN-Anchor Nodes, CR-Communication Range, ToA-Time of Arrival, RMSE-Root Mean Square Error.

1. INTRODUCTION

A Wireless Sensor Network (WSN) is defined as a network of sensor node devices capable of communicating information collected from a specific field through wireless communication links. Accurate localization of sensor nodes is essential for the effective operation of WSN applications and for delivering reliable services to end users. In most practical scenarios, sensor nodes are deployed randomly over the monitoring region, resulting in unknown node positions that must be determined using suitable localization techniques. WSNs represent an emerging class of wireless communication systems that have gained significant importance in both civilian and military applications. These

networks consist of distributed and autonomous sensor nodes designed to monitor physical or environmental parameters such as temperature, pressure, humidity, and motion. Each sensor node is equipped with onboard processing capabilities to coordinate sensing, data collection, and environmental monitoring within the designated area. The sensor nodes communicate with a Base Station (BS), which functions as the central processing and data aggregation unit of the WSN system. Furthermore, the Base Station is typically connected to the Internet to facilitate data sharing and remote monitoring (Cheng et al., 2012).

Numerous localization algorithms and techniques have been proposed for Wireless Sensor Networks (WSNs) (Ewa Niewiadomska-Szynkiewicz, 2012). Among the different classifications of localization approaches, this study primarily focuses on Range-Free and Range-Based localization algorithms. Range-Free localization techniques (Bulusu et al., 2000; Cheng et al., 2012; Niculescu & Nath, 2003) estimate the position of sensor nodes using connectivity information among neighboring nodes. These approaches do not require additional hardware components, as they rely mainly on proximity and network connectivity information for position estimation within the WSN. Owing to the absence of explicit distance or angle measurements, Range-Free methods are generally characterized by lower localization accuracy and limited precision.

In contrast, Range-Based localization techniques (Alippi & Vanini, 2004; Bahl & Padmanabhan, 2000; Chen et al., 2006; Priyantha et al., 2000) utilize ranging information between neighboring sensor nodes to estimate inter-node distances. These methods employ measurement parameters such as Time of Arrival (ToA), Angle of Arrival (AoA), Received Signal Strength Indicator (RSSI), and Time Difference of Arrival (TDoA) to determine the relative distances among nodes, thereby enabling more accurate localization of sensor positions within the network.

1.1. Sensor Node Localization Stages

The efficiency and performance of a Wireless Sensor Network (WSN) are highly dependent on the localization accuracy of sensor nodes. Accurate estimation of sensor node positions generally involves three major stages: (i) estimation of distance or angle between neighbouring nodes, (ii) computation of the position of an individual sensor node, and (iii) implementation of a localization algorithm for determining the positions of nodes across the entire network (Amitangshu Pal, 2010). Various techniques have been developed for each of these stages, differing in terms of computational complexity, implementation requirements, and localization accuracy.

Stage-1. Distance/Angle Estimation: Distance and angle estimation constitute the fundamental prerequisite for the subsequent stages of localization in Wireless Sensor Networks (WSNs) (Paul and Sato, 2017). This stage involves measuring the distance or angular relationship between the transmitting and receiving sensor nodes. Several techniques have been developed for distance and angle estimation, including Time of Arrival (ToA), Time Difference of Arrival (TDoA), Received Signal Strength Indicator (RSSI), and Angle of Arrival (AoA). These techniques provide the essential ranging information required for accurate position estimation and overall network localization.

Stage-2. Position Calculation: Once the initial estimation of inter-node distance or angle has been completed, the position of a sensor node can be determined using localization methods such as trilateration, multilateration, triangulation, and probabilistic approaches (Panda and Priyadarshini, 2025). The selection of an appropriate localization method depends on factors such as the availability of measurement data, computational complexity, and the processing capabilities of the sensor nodes

(Boukerche et al., 2007). Although the Global Positioning System (GPS) is widely used for positioning and navigation applications, it is generally unsuitable for the localization of wireless sensor nodes because of several practical constraints, including high energy consumption, increased hardware cost, limited scalability, and poor performance in indoor or obstructed environments.

Stage-3. Localization Algorithm: The final and most critical stage of localization in Wireless Sensor Networks (WSNs) is the selection of an appropriate localization algorithm (Paul and Sato, 2017). In this stage, the information obtained from the previous phases, namely distance/angle estimation and position computation, is utilized collaboratively to determine the positions of sensor nodes within the network. The localization accuracy at this stage is influenced by several factors, including the ranging technique employed, the deployment environment, and the relative geometric arrangement between unknown sensor nodes and anchor nodes.

Broadly, localization algorithms in WSNs can be classified into two categories: (i) centralized localization and (ii) distributed localization. In centralized localization, inter-node ranging and connectivity information are transmitted to a computationally powerful central base station for processing and position estimation. Although centralized approaches generally provide higher computational capability and global optimization, they are often associated with increased communication overhead and computational complexity when compared with distributed localization techniques.

Based on the ranging methodology adopted, localization algorithms are further categorized into: (i) range-based localization and (ii) range-free localization. Range-based localization algorithms utilize distance or angular information obtained from anchor nodes to estimate the positions of unknown sensor nodes. Various ranging techniques, such as Time of Arrival (ToA), Time Difference of Arrival (TDoA), Received Signal Strength Indicator (RSSI), and Angle of Arrival (AoA), are commonly employed to estimate the distance between unknown nodes and multiple anchor nodes, thereby enabling accurate localization (Li et al., 2004). In contrast, range-free localization algorithms rely primarily on connectivity information between unknown nodes and landmark or anchor nodes, where the landmarks generally obtain their positional information through the Global Positioning System (GPS) (He et al., 2003). Commonly used range-free localization algorithms include Centroid, Approximate Point-In-Triangle (APIT), and DV-Hop algorithms (Wang et al., 2009).

In the present study, a range-based localization approach using the Time of Arrival (ToA) technique is considered for sensor node localization. The ranging measurements employed in these methods are derived through the formulation of mathematical models (Patwari et al., 2005). Furthermore, an Adaptive Information Estimation Strategy (AIES) localization algorithm is proposed, wherein the unknown sensor nodes are localized using an estimator that incorporates pairwise measurements among all sensor nodes within the network (Sudha H. Thimmaiah and Mahadevan, 2017). The computed range estimates are subsequently evaluated and analyzed using the Root Mean Square Error (RMSE) metric to assess localization performance (Ruz et al., 2019).

2. METHODOLOGY

In the present research work, a proposed Range-Based Time of Arrival (ToA) localization algorithm is implemented for Wireless Sensor Networks (WSNs) (Pandey and Varma, 2016). The proposed Adaptive Information Estimation Strategy based on Time of Arrival (AIES-ToA) utilizes pairwise measurements among peer-to-peer sensor nodes, which are estimated using an adaptive estimator (Sudha H. Thimmaiah and Mahadevan, 2018). The incorporation of measurements between multiple

pairs of sensor nodes significantly improves the localization accuracy and overall performance of the positioning system.

In the AIES-ToA approach, pairwise distance measurements are determined using statistical estimation models. The statistical framework of the AIES-ToA algorithm is developed by combining the true pairwise distances with the associated ranging errors. This methodology enables efficient estimation of sensor node positions while minimizing localization inaccuracies caused by measurement uncertainties (Sudha H. Thimmaiah, 2023).

The proposed AIES-ToA methodology is broadly divided into two modules:

2.1. Module 1: WSN Deployment

2.2. Module 2: AIES-ToA statistical model implementation.

2.1. MODULE 1: WSN DEPLOYMENT

The deployment procedure for the Wireless Sensor Network (WSN) is carried out as follows (Tossa et al., 2025). Initially, the number of anchor nodes and unknown sensor nodes is specified. Subsequently, the coordinates of all sensor nodes are generated randomly within the defined deployment area. Communication links between neighbouring nodes are then established based on the predefined communication range. Sensor nodes that fall within the communication range of one another are grouped to form subsets of the WSN, thereby enabling inter-node communication and localization processes.

Step 1: Specification of the number of anchor nodes and unknown nodes

Step 2: To generate randomly the coordinate values (x,y) for the defined number of nodes

Step 3: Define the communication range of peer-to-peer nodes

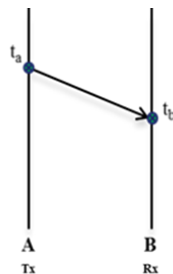
Step 4: Deployment of nodes in the WSN

Step 5: Select a subset of nodes in the WSN having the communication range defined.

Step 6: Connection of nodes in the WSN

2.2. MODULE 2: AIES-ToA STATISTICAL MODEL IMPLEMENTATION

Time of Arrival (ToA) refers to the measured time taken by a transmitted signal to arrive at the receiver node (Gireesh et al., 2025). Therefore, the total measured ToA consists of the signal transmission time combined with the propagation-induced delay encountered during signal travel between the transmitter and receiver, as illustrated in Figure 1.



$$d = (t_b - t_a) \times v$$

Fig 1: ToA

.....(1)

Where t_a - time at which the signal is transmitted, t_b - the time at which the signal is received at the receiver and v is the velocity of propagation of the signal. For example, in general, if there exists a transmission from sensor i to sensor j , the time delay is represented as -

$$T_{i,j} = d_{i,j} / v_p \text{(2)}$$

This implies that the time delay is modelled as Gaussian given by -

$$f(T_{i,j}=t \mid \Theta) = N(t; d_{i,j}/v_p + \mu_T, \sigma_T^2) \dots \dots (3)$$

where μ_T and σ_T^2 are the mean and variance of the time delay error and Θ is defined in equation (1). The variance of the time delay error is proportional to the square of the distance and is the location variance of the estimator. Finally, the localization performance of the algorithm is evaluated by calculating the RMSE. From the log-normal model the variance determined are proportional to the distances.

The actual transmitter – receiver separation distance $d_{i,j}$ is given by,

$$d_{i,j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \dots \dots \dots (4)$$

Lastly, the computation of the RMSE is achieved to determine the localization performance.

$$\dots \dots (5) \quad RMSE = \sqrt{\frac{\sum_{i=1}^n (Loc_{real}^i - Loc_{est}^i)^2}{n}}$$

Algorithm :

- Step 1: Deployment of Sensor nodes
- Step 2: Selection of subset
- Step 3: Representation of distance using ToA model
- Step 4: Estimation of Θ -variances are determined
- Step 5: Calculation of Fisher Information Submatrices
- Step 6: Merge Submatrices to form the FIM
- Step 7: Invert FIM to obtain variance of the estimators.
- Step 8: Compute RMSE

3. SIMULATION RESULTS

To determine the range estimates, simulation using MATLAB is considered by varying the network parameters that affect the localization error - RMSE.

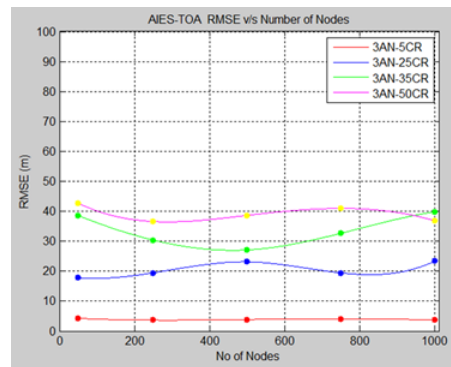
The parameters that affect localization are –

- 3.1. NODE DENSITY (NN)** These are the total number of nodes in a network, and in this simulation study they are varied from 10 to 1000 nodes.
- 3.2. ANCHOR NODES (AN)** These are the nodes whose location is known and are deployed grid-wise; they are varied from 3 to 20.
- 3.3. COMMUNICATION RANGE (C-R)** This is the range or the propagation distance to the rest of the nodes. It is varied from 5 to 50.

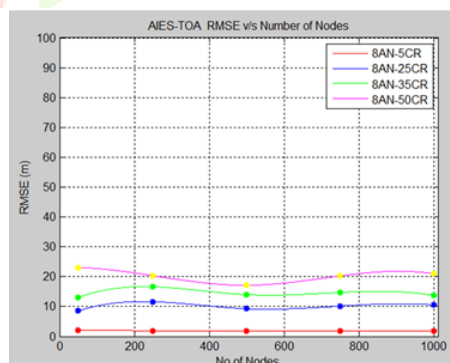
In this paper, considering NN which is a parameter which affects localization- By varying NN in the range 10 to 1000 and keeping the ANs and CRs as constants – a set of graphs - No. of Nodes Vs RMSE are plotted which are referred to as cases 1-4 with respective consolidated tables and corresponding graphs are herewith analyzed.

Case-1: AN=3 and C-R=5,25,35,50**Table 1.** AIES-ToA-Consolidated Values for Anchor Nodes=3

Sl.No.	AN=3	RMSE			
	NN	C-R=5	C-R=25	C-R=35	C-R=50
1.	50	4.276547	17.819315	38.615900	42.765471
2.	250	3.657326	19.456183	30.401786	36.573258
3.	500	3.863557	23.115664	27.095936	38.635566
4.	750	4.094792	19.432527	32.644189	40.947922
5.	1000	3.685142	23.360350	39.831872	36.851416

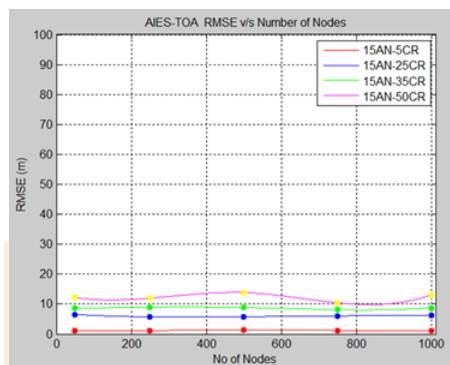
**Graph 1.** AIES-ToA-Consolidated Graph for Anchor Nodes=3**Case-2: AN=8 and C-R=5,25,35,50****Table 2.** AIES-ToA - Consolidated values for Anchor Nodes=8

Sl.No.	AN=8	RMSE			
	NN	C-R=5	C-R=25	C-R=35	C-R=50
1.	50	2.131280	8.520950	12.987429	23.101530
2.	250	1.899503	11.617086	16.633424	20.343172
3.	500	1.774678	9.258539	13.983001	17.113677
4.	750	1.724677	10.148907	14.726691	20.274871
5.	1000	1.874288	10.568798	13.734377	20.987122

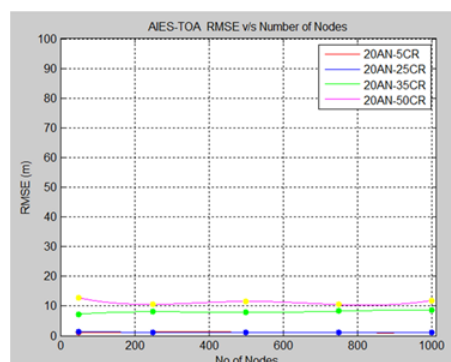
**Graph 2.** AIES-ToA - Consolidated graph for Anchor Nodes=8

Case-3: AN=15 and C-R=5,25,35,50**Table 3.** AIES-ToA - Consolidated values for Anchor Nodes=15

Sl.No.	AN=15	RMSE			
	NN	C-R=5	C-R=25	C-R=35	C-R=50
1.	50	1.117248	6.512711	8.524966	12.196672
2.	250	1.174891	5.724804	8.956520	11.981409
3.	500	1.330662	5.770801	8.845317	13.842426
4.	750	1.201554	6.058872	8.092668	10.425976
5.	1000	1.110085	6.118266	8.718849	13.122416

**Graph 3.** AIES-ToA - Consolidated graph for Anchor Nodes=15**Case-4: AN=20 and C-R=5,25,35,50****Table 4.** AIES-ToA - Consolidated values for Anchor Nodes=20

Sl.No.	AN=20	RMSE			
	NN	C-R=5	C-R=25	C-R=35	C-R=50
1.	50	1.078315	1.300056	7.268812	12.810017
2.	250	1.213976	1.176176	8.071946	10.560680
3.	500	1.198925	1.153090	7.825910	11.571158
4.	750	1.015663	1.190628	8.274555	10.490158
5.	1000	1.034166	1.076626	8.734046	11.899057

**Graph 4.** AIES-ToA - Consolidated graph for Anchor Nodes=20

The above set of graphs demonstrates that, with an increase in the number of sensor nodes, the RMSE values exhibit only marginal variations across different communication ranges while maintaining an approximately stable average trend. Furthermore, an increase in the number of anchor nodes results in a reduction in RMSE values for the corresponding communication ranges, thereby indicating

improved localization accuracy. In contrast, the RMSE values tend to increase with an increase in communication range. This behaviour can be attributed to the random deployment of both anchor and unknown sensor nodes within the Wireless Sensor Network (WSN), which affects the ranging precision and consequently influences the overall localization performance. Additionally, the observed decrease in Root Mean Square Error (RMSE) with a higher number of anchor nodes across varying communication ranges confirms the enhancement in localization accuracy, which is consistent with the expected theoretical outcome.

4. CONCLUSION

The evaluation of localization errors for the range-based Time of Arrival (ToA) technique was carried out to estimate the positions of sensor nodes in the Wireless Sensor Network (WSN). MATLAB was employed as the simulation platform for implementing and analyzing the proposed localization model. The key localization parameters considered in the simulation included the sensor node deployment area, the total number of deployed nodes, the number of anchor nodes, and the communication range. The localization performance was assessed using the Root Mean Square Error (RMSE) metric, which represents the deviation between the estimated sensor node position and the actual node position, thereby quantifying the localization error. Based on the statistical ToA model, pairwise measurements among sensor nodes were utilized to estimate inter-node distances.

Further, several case studies were conducted for different values of unknown nodes (NNs) and communication ranges (C-Rs), and corresponding graphs illustrating the relationship between anchor nodes (ANs) and RMSE were plotted. The MATLAB simulation results demonstrated that optimization of the number of anchor nodes can effectively maintain an acceptable average RMSE under varying network scenarios while determining range estimates using the ToA technique. These findings indicate a significant reduction in localization errors, thereby improving the overall localization accuracy of sensor nodes in the wireless sensor network.

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