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Performance Analysis of Anchor Nodes in WSNs for Estimation of Ranges Using ToA Method

Sudha H.Thimmaiah

Dept. of Electronics & Telecommunication Engineering,
Dr.Ambedkar Institute of Technology, Bengaluru-560056, Karnataka, India.

Abstract

Among the leading technologies of research interest in recent years, Wireless Sensor Networks (WSNs) has predominantly emerged as one area extensively applicable in monitoring, controlling and surveillance. In all these areas of application, the need for performance analysis of parameters of the WSN is essential for the efficient performance of the WSN. The efficiency of the WSN depends on the localization of nodes in the network. While many factors influence the node position errors, the placement of anchor nodes can significantly impact the error. Hence it is of paramount importance to minimize localization errors. Localization errors computed by RMSE can be determined by estimating ranges and the number of sensor nodes. Also, considering the parameters that affect localization -Node density, Anchor Nodes and Communication Range, localization errors can be estimated and computed. In this research study, simulation analysis for determination of range estimates and RMSE using ToA method is computed using MATLAB.

Key words-Wireless Sensor Networks, Number of Nodes, Anchor Nodes, Communication Range, Time of Arrival, Root Mean Square Error.

1. Introduction

Wireless sensor network (WSNs) is a new class of wireless networks that are becoming very popular with a huge number of civilian and military Wireless applications. A wireless sensor network is a wireless network that contains distributed independent sensor devices or nodes that is used to monitor the system, physical or environmental conditions. Sensor nodes are equipped with the onboard processor that manages and monitors the environment in a particular area. They are connected to the Base Station which acts as a processing unit in the WSN System. Base Station in a WSN System is connected through the Internet to share data. (Cheng *et al*., 2012). Many localization algorithms have been proposed for WSNs. Among the classifications for determining the location of a sensor node, this paper concentrates on - Range-Free and Range-Based Algorithms. Range-free techniques (Ruz *et al*., 2019; He *et al*., 2003) use connectivity information between neighboring nodes to estimate the nodes position, also, do not require any additional hardware and use proximity information to estimate the location of the nodes in a WSN, and thus have limited precision. Range-based techniques (Bulusu *et al*., 2000; Bahl and Padmanabhan, 2000; Niculescu and nath, 2003; Priyantha *et al*., 2000) require ranging information that can be used to estimate the distance between two neighboring nodes. Therefore, range measurements such as time of arrival (ToA), angle of arrival (AoA), received signal strength indicator (RSSI), and time difference of arrival (TDoA) are used to measure the distances between the nodes in order to estimate the location of the sensors.

1.1. Stages in Localization

The location accuracy of a sensor node impacts the efficiency of the WSN. To estimate the exact position of sensor node, there are three different stages which include (i) distance/angle estimation between the nodes, (ii) position computation of a single node, (iii) a localization algorithm - used for localization of whole network (Amitangshu Pal, 2010). Here, at each stage, different techniques with varying accuracy and complexity exist.

(i) Distance/Angle Estimation

Distance/Angle estimation is the pre-requisite for remaining two phases of localization. This refers to the measurement of distance or angle between the transmitter and receiver node. The different techniques for distance/angle estimation include - Time of Arrival (ToA), Time Difference of Arrival (TDoA), Received Signal Strength Indicator (RSSI) and Angle of Arrival (AoA).

(ii) Position Calculation

GPS (Global Positioning System) cannot be used for the localization of wireless sensor nodes due to various constraints. Once the initial calculation of a nodes distance or angle is estimated, the nodes position can be computed using any one of the following methods - trilateration, multilateration, triangulation, probabilistic approaches etc. Depending upon the processors limitations and availability of data, a particular method is chosen (Boukerche *et al*., 2007).

(iii) Localization algorithm: The most important and last stage of localization is the choice of localization algorithm. The information collected in previous two stages is utilized to localize sensor nodes cooperatively. Mostly, accuracy of this stage is affected by the ranging method, deployed environment, and the relative geometry of unknown nodes to the anchor nodes.

In a broad sense, localization algorithms in WSNs are divided into two categories:

(*i*) *Centralized*, and (*ii*) *Distributed*.

Centralized localization requires the migration of internode ranging and connectivity data to a sufficiently powerful central base station. Centralization is much more complex than a distributed setting. On the basis of ranging method used, localization algorithms for WSNs are broadly categorized into two types: (*i*) R*ange based localization*, and (*ii*) R*ange free localization*. Range based localization algorithms use the range –

distance or angle information from the anchor node to estimate the location. Several ranging techniques exist to estimate an unknown node distance to three or more anchor nodes. Based on the range information, location of a node is determined. Some of the range based localization algorithm includes: Time of Arrival (ToA) (Li *et al*., 2004). Time difference of Arrival (TDoA). Received Signal Strength Indicator (RSSI), Angle of Arrival (AoA). Range-free localization algorithms use connectivity information between unknown node and landmarks, wherein, landmarks can obtain its location information using GPS (Global Positioning System). Some of the range-free localization algorithm includes: Centroid, Appropriate Point in Triangle (APIT) and DV-HOP (Wang *et al*., 2009).

In the present research, simulation of range based method using Time of Arrival (ToA) is considered for sensor node localization. The measured range in the above mentioned methods are based on the establishment of mathematical models (Patwari *et al*., 2005). The localization algorithm, Adaptive Information Estimation Strategy (AIES) is proposed in which, the unknown sensors are localized by an estimator that includes pair-wise measurements between all the sensors in the network. The determination of range estimates is computed and plotted against the RMSE (Root Mean Square Error) (Ruz *et al*., 2019).

2. Methodology

In the current research, the proposed range based AIES-ToA Algorithm is implemented.

AIES-ToA Algorithm - In the Adaptive Information Estimation Strategy methodology, pairwise measurements between peer-to-peer sensors are computed by an estimator. Measurements between any pairs of sensors aids the location estimate and enhances the accuracy of the localization system. The pair-wise distance measurements are estimated by statistical models. The true pairwise distances added to the distance error is the basis of the statistical model AIES-ToA.

The AIES-ToA methodology is 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

For WSN deployment, the procedure is as follows. The number of anchor nodes and unknown nodes are specified. The coordinates of each node is generated randomly and the communication between one node to another is defined, to obtain the set of nodes within the communication range to form a subset of WSN.

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

ToA is the measured time at which a signal arrives at the receiver. Hence, the total measured ToA is the time of transmission plus a propagation-induced time delay as shown in fig 1.

$$d = (t_b - t_a) \times v \text{ ....(1)}$$

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 modeled as Gaussian given by [30],

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

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 – reciever seperation distance $d_{i,j}$ is given by,

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

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

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

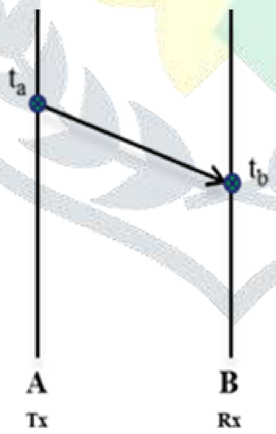


Fig 1: ToA

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. At present, considering AN is a parameter which affects localization - by varying the number of Anchor Nodes (AN) in the range 3 to 20, and keeping the Number of Nodes (NN) and Communication Range (C-R) as constants, a set of graphs - No. of Anchor Nodes Vs RMSE are plotted as shown below.

Table 1. AIES-ToA - Consolidated values for No. of Nodes=50

Sl.No.	NN=50				
	AN	C-R=5	C-R=25	C-R=35	C-R=50
		RMSE	RMSE	RMSE	RMSE
1.	3	4.054422	24.136975	33.331318	47.771204
2.	4	3.136345	19.620868	19.116893	30.378546
3.	5	2.712020	13.162436	20.798319	30.150958
4.	6	2.901487	10.103602	18.414694	18.163124
5.	7	2.842225	12.904617	16.467561	21.467614
6.	8	1.732781	9.5428894	16.203047	18.054949
7.	9	2.132702	9.1509768	13.069681	18.121165
8.	10	2.087409	8.7895630	12.951232	18.183257
9.	11	1.306389	7.1983229	12.331850	13.623579
10.	12	1.345545	8.3631051	9.9700780	14.442527
11.	13	1.434540	6.9328229	10.606332	12.734880
12.	14	1.243667	6.2415264	8.9287318	13.833318
13.	15	1.131209	6.0305447	8.2869832	11.812228
14.	16	1.331539	5.7622266	8.3837352	12.441609
15.	17	1.211081	5.7550911	8.6287876	11.276853
16.	18	1.183136	6.1206316	7.3234547	11.126592
17.	19	1.265220	5.9592741	7.5232890	12.397145
18.	20	1.068320	5.8647085	7.2679543	12.626275

Graph 1. AIES-ToA - Consolidated graph for No. of Nodes=50

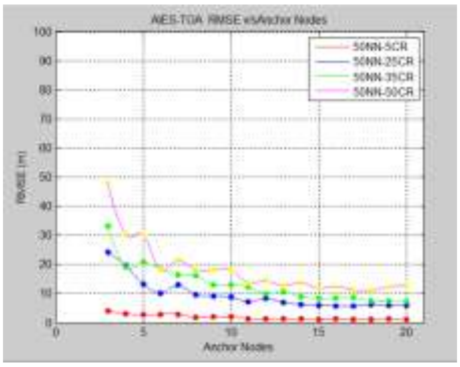


Table 2. AIES-ToA - Consolidated values for No. of Nodes=250

Sl.No.	AN	NN=250			
		C-R=5	C-R=25	C-R=35	C-R=50
		RMSE	RMSE	RMSE	RMSE
1.	3	4.247471	25.130599	28.642069	32.252835
2.	4	2.324099	17.209410	18.247844	28.870857
3.	5	3.365860	14.105267	19.171247	27.585671
4.	6	2.256246	12.279171	16.510172	31.091497
5.	7	2.427367	11.267206	14.142175	23.367817
6.	8	2.252558	9.510616	14.193277	18.985801
7.	9	1.998317	9.849501	12.486150	16.537885
8.	10	1.914547	8.876457	12.482637	17.659618
9.	11	1.490800	7.497434	10.020129	16.063054
10.	12	1.652108	8.961566	11.964930	16.339260
11.	13	1.276941	6.549358	9.686681	14.498194
12.	14	1.363087	6.672101	9.715490	14.371575
13.	15	1.280736	5.605368	8.631156	13.150532
14.	16	1.183463	6.093848	8.253531	12.256837
15.	17	1.255641	6.247329	8.460895	13.265301
16.	18	1.219022	5.573042	8.926088	11.943468
17.	19	1.244767	5.778787	7.695362	11.290771
18.	20	1.051800	5.987045	7.636148	12.328231

Graph 2. AIES-ToA - Consolidated graph for No. of Nodes=250

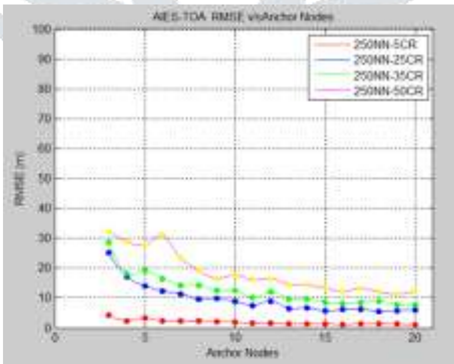


Table 3. AIES-ToA - Consolidated values for No. of Nodes=500

Sl.No.	NN=500				
	AN	C-R=5	C-R=25	C-R=35	C-Re=50
		RMSE	RMSE	RMSE	RMSE
1.	3	4.445482	22.227412	25.649392	57.643040
2.	4	2.838946	14.194732	21.049410	26.345983
3.	5	3.321022	16.605114	17.346809	25.797207
4.	6	2.870485	14.352426	18.279311	28.277653
5.	7	1.940930	9.704650	17.963931	21.644307
6.	8	1.919196	9.595984	12.666177	18.889179
7.	9	1.719381	8.596909	11.150980	20.218425
8.	10	1.922912	9.614562	11.996366	16.150168
9.	11	1.498165	7.490828	10.187498	16.511297
10.	12	1.532284	7.661424	10.396086	14.286584
11.	13	1.303565	6.517826	10.174724	14.501637
12.	14	1.284087	6.420436	9.342081	11.571135
13.	15	1.377300	6.886502	9.079393	11.533130
14.	16	1.150770	5.753851	8.356139	12.072497
15.	17	1.280988	6.404941	9.438416	11.997734
16.	18	1.111605	5.558026	7.896586	9.487682
17.	19	1.148847	5.744236	7.881751	11.466783
18.	20	1.194864	5.974324	7.285849	10.847623

Graph 3. AIES-ToA - Consolidated graph for No. of Nodes=500

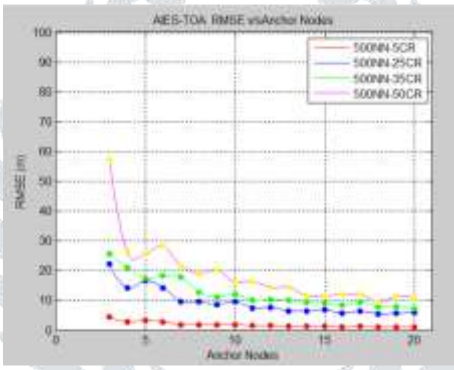


Table 4. AIES-ToA - Consolidated values for No. of Nodes=750

Sl.No.	NN=750				
	AN	C-R=5	C-R=25	C-R=35	C-R=50
		RMSE	RMSE	RMSE	RMSE
1.	3	4.737680	19.876079	35.767976	44.553057
2.	4	2.768841	13.241652	20.579846	36.261781
3.	5	3.062244	12.323780	16.280627	27.037708
4.	6	1.999223	12.054717	15.637420	21.565269
5.	7	2.224130	12.265550	15.031654	24.876872
6.	8	2.474558	10.622379	12.860501	17.987219
7.	9	1.848310	10.415123	13.600460	17.904428
8.	10	1.777321	9.355967	12.206285	15.966932
9.	11	1.426962	7.881786	12.680251	14.805801
10.	12	1.574093	8.095219	11.235612	15.499038
11.	13	1.434272	6.868664	10.939839	15.904563
12.	14	1.095129	6.723996	7.928428	12.877792
13.	15	1.231919	5.753588	7.705170	12.600083
14.	16	1.260391	5.774832	8.829843	12.535825
15.	17	1.193346	5.687559	8.145592	11.094155
16.	18	1.117765	6.255759	7.359979	10.401428
17.	19	1.110439	6.040721	9.343724	10.851009
18.	20	0.991498	5.513707	7.889016	9.664769

Graph 4. AIES-ToA - Consolidated graph for No. of Nodes=750

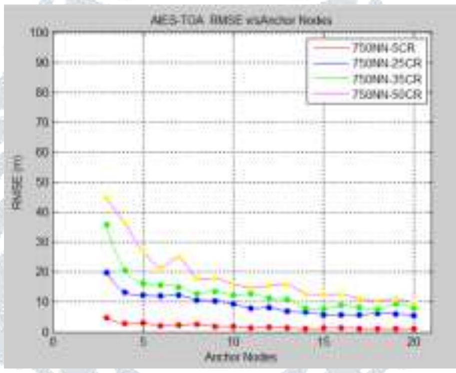
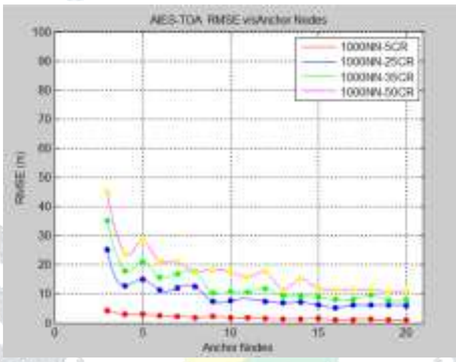


Table 5. AIES-ToA - Consolidated values for No. of Nodes=1000

Sl.No.	AN	NN=1000			
		C-R=5	C-R=25	C-R=35	C-R=50
		RMSE	RMSE	RMSE	RMSE
1.	3	4.363974	25.180146	35.252204	45.044118
2.	4	2.962452	12.796153	17.914615	23.851331
3.	5	2.951283	15.042193	21.059070	28.276657
4.	6	2.508173	11.235305	15.729428	21.216289
5.	7	2.397991	12.104558	16.946382	20.992538
6.	8	1.872670	12.557344	17.580281	17.511078
7.	9	2.200504	7.324124	10.253774	18.486757
8.	10	1.767879	7.766368	10.872915	17.580771
9.	11	1.707883	7.695823	10.563215	15.741426
10.	12	1.513327	7.541549	11.860757	17.562936
11.	13	1.305410	6.874502	9.352867	11.426213
12.	14	1.363500	7.077343	9.119908	15.238079
13.	15	1.519011	6.166453	8.854485	11.846075
14.	16	1.084892	5.302641	8.068935	11.592892
15.	17	1.212077	6.181402	8.053811	11.611026
16.	18	1.226482	6.161911	9.630530	11.515129
17.	19	1.059896	6.280373	7.686299	10.731944
18.	20	1.122155	5.952434	8.003872	11.190879

Graph 5. AIES-ToA - Consolidated graph for No. of Nodes=1000



From the above graphs, it is observed that as the number of anchor nodes increase for different communication ranges, the RMSE values decreases, which is the desired result. Also, as the communication range increases, the corresponding RMSE values increase due to the random deployment of both Anchor Nodes and Number of Nodes.

4. Conclusion

The evaluation of localization errors for the range based technique ToA was considered to estimate positions of sensor nodes. MATLAB was used as the simulation tool , the localization parameters which were considered are-sensor nodes deployment area, number of nodes to be deployed, number of anchor nodes and the communication range. The metric RMSE was computed, which is the deviation of the estimated node location from the actual node location, and hence represents the localization error.Using the statistical ToA model based on the pairwise measurements, distances are estimated. Case studies- for different values of NNs and C-Rs, graphs for ANs versus RMSE are plotted.The simulation results using MATLAB indicate an optimization of ANs to maintain an average RMSE error for different scenarios, to determine range estimates using ToA. This implies minimization in localization errors of the sensor nodes used in the wireless sensor network.

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