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Region of confidence measurement for the purpose of localization in wireless sensor networks

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ABSTRACT

Accuracy of localization of the sensor nodes is the key factor for the reliability and efficiency of wireless sensor networks (WSNs). Although a number of localization algorithms have been proposed for WSNs, the major challenge for most real-world applications is the uncertainty of measurements of the references. The proposed work describes a novel approach for estimating the localization accuracy with the help of the region of confidence (ROC), the common region formed from the intersections of the circular regions defined by the distances of numerous reference nodes in a 2D plane. The work investigates the feasibility of localization accuracy with the help of simulations performed for different scenarios with varying distances of the reference nodes. The proposed approach utilizes the ROC technique for providing a measurable significance for the evaluation of localization efficiency for a range of error conditions. This proposed work contributes towards the evolution of efficient localization techniques for real-world environments of WSNs.

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1. INTRODUCTION

Wireless sensor networks (WSNs) have attracted a lot of interest from researchers lately because of their many uses [1]. The utilization of various location-based services has surged in recent times, highlighting the need for more dependable localization services in future generations that are both precise and resource-efficient [2], [3]. WSN applications span various domains, including monitoring of traffic control, remote surveillance, underwater acoustic monitoring, acquisition and communication of the data and so on. Sensor node locations are very important to such applications and have led to the search for effective localization algorithms. There are several research challenges in WSNs affecting the performance in the network, and they include localization, middleware integration [4], network security, quality of service [5], deployment protocols [6], operating efficiency in the operating system [7], and synchronization in the timeline [8]. Development in the sensor grew with sensor technology becoming affordable and intelligent, and hence the sensor is adopted into wireless networks for various applications [9].

Localization plays an important role in determining the exact location of nodes in WSNs. Inaccurate locations of nodes cause incorrect information [10]. GPS is used for positioning nodes. However, using global positioning system (GPS) for positioning is expensive for large networks and sometimes GPS signals get interfered with [11]. To reduce costs and save energy, not all nodes use GPS. Only some nodes, known as beacon or anchor nodes, use GPS, and other nodes use localization algorithms [12]. However, existing localization algorithms cannot maintain accuracy for large-scale WSNs [13], [14].

WSNs operate in a distinct manner with sensor-based interaction with the external environment. Most applications require precise sensor node location in order to employ WSNs. The structure of a standard sensor node comprises several important components [15]. The transceiver provides data communication between sensor nodes in the form of radio frequency and operates in various modes such as sleep, idle, send, and receive mode [16], [17]. The microprocessor with memory (RAM and ROM) is tasked with the processing and storage of data in the form of input/output devices and memory circuits [18]. The analog/digital circuit interfaces with the sensor and deals with the handling and conversion of the continuous (analog) or discrete (digital) data into processor-readable format. The power supply is equally important for node operation. Nodes in the network may be categorized into dumb, settled, or beacon nodes based on the node's awareness regarding the node's position with the use of localization algorithms to identify the location geographically. The above categorization demonstrates the significance of the localization algorithms in the efficiency and reliability of the use of WSN in various applications [19].

In the context of sensor network localization, different techniques are used in robotics to find the position of the sensors using techniques such as angulation, lateration, trilateration, multilateration, and triangulation [20]. Angulation calculates the angles between the nodes, lateration calculates the distances between the known and unknown nodes [10], trilateration calculates the intersection of distances from three known nodes, and triangulation calculates the intersection of distances from at least two known nodes using trigonometric values [21].

For the majority of applications, knowing where sensors are located inside a network is convenient. Mao *et al.* [22] conducted a study that looked at different ways to measure the location of sensors in a network. They also talked about algorithms that can figure out the location of sensors in just one step. The authors explained the two types of algorithms in more detail: distance-based location algorithms and algorithms that rely on the connectivity of the sensors. They also explained the problems with distance-based algorithms that researchers are experiencing, as well as the solutions to these problems. In more recent research, the authors Iliev and Paprotny [23] conducted a comparison of various algorithms and techniques for determining sensor locations, evaluating their effectiveness and identifying the strengths and weaknesses of each method. They also discussed improving these techniques in terms of their accuracy, energy consumption, and coverage area. Langendoen and Reijers [24] investigated methods for locating sensor nodes in ad-hoc sensor networks by simulating the performance of three algorithms: N-hop multilateration, ad-hoc positioning, and robust positioning. They examined each step of these algorithms very closely to determine their performance in real-time scenarios. They concluded that there is no algorithm which is the best in all occasions. Each algorithm has its limitations depending on the location of the sensors. As illustrated in Figure 1, the region of confidence (ROC) is formed by the overlapping area of the communication ranges of multiple reference nodes and is used to estimate the possible location of an unknown node.

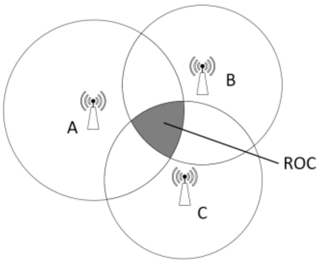


Figure 1. Overlapping area of ROC

To address localization challenges in WSNs, a region of confidence (ROC) is established to specify where unknown nodes can locate themselves. This system requires at least three satellites for two-dimensional localization and four for three-dimensional localization. The ROC is influenced by error variance in distance calculations between reference nodes and unknown nodes, resulting in an area referred to as the ROC area, which outlines the overlapping region for the ROC.

The purpose of our paper is to develop methods that can determine the ROC area under various environmental constraints, allowing for more precise location for nodes within a WSN. Furthermore, our paper will evaluate how well popular methods for location determination are capable of determining the location for unknown nodes within a WSN. The contribution of this work lies in the introduction of the framework based on the ROC with the formulation of overlap of geometric regions towards the localization reliability, the mathematical formulation of circle intersection geometry with Heron's formula for calculation of the ROC with mentions of the positive as well as the negative distance errors towards the localized ROC determinability.

2. PROPOSED METHOD

Our main purpose is to determine the overlapping area with the help of algorithms and various formulas and compare the percentage of error in distance in various situations. We also add here a new term to determine the ROC. This term shows in the flowchart.

2.1. Algorithm to determine ROC

In this work, a straightforward and efficient trilateration algorithm is employed. Trilateration is the method of using the signals received from a minimum of three base stations to compute the exact location of a sensor node. This method is illustrated in Figure 2.

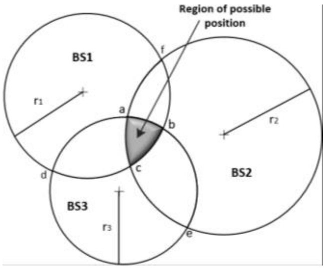


Figure 2. ROC in trilateration algorithm

Three signal strengths (r1, r2, and r3) received from three base stations (BS1, BS2, and BS3) are utilized in the algorithm. The signal strengths are utilized to form three circles with each center on the respective base station. The intersection points among the three circles are obtained, and they produce six possible points (a, b, c, d, e, and f). The intersection region formed with the intersection points is the possible region for the sensor node position. Surprisingly, the centroid of the triangle formed with the intersection region shared among the three points a, b, and c is the optimal position of the sensor node. It is an accurate and reliable technique for the sensor node position estimation in the network. The step-by-step procedure used to determine the ROC based on trilateration is summarized in Algorithm 1.

Algorithm 1. ROC determination using trilateration

```
Input:
Anchor node coordinates $A(x_a, y_a)$, $B(x_\beta, y_\beta)$, $C(x_C, y_C)$
Theoretical distances $D_a$, $D_\beta$, $D_C$
Experimental distances $R_a$, $R_\beta$, $R_C$
Output:
Region of Confidence (ROC) area and localization status
Begin
    Construct circle $C_a$ centered at A with radius $R_a$
    Construct circle $C_\beta$ centered at B with radius $R_\beta$
    Construct circle $C_C$ centered at C with radius $R_C$
    Compute intersection points between $C_a$ and $C_\beta$
    Compute intersection points between $C_\beta$ and $C_C$
    Compute intersection points between $C_C$ and $C_a$
    If any pair of circles has no intersection, then
      Return status = "ROC not determinable"
    End if
    Select three interior intersection points to form triangle T
    Compute side lengths a, b, and c of triangle T
    Compute semi-perimeter $s = (a + b + c) / 2$
    Compute area of triangle T using Heron's formula
    Compute circular segment areas corresponding to each circle
    Compute ROC area as the sum of segment areas and triangle area
    Return ROC area and status = "determinable"
End
```

The computational complexity of ROC computation is O(1) because the number of anchors is fixed (three), and the algorithm involves a constant number of geometric operations. For generalized N-node multilateration, complexity becomes $O(N^2)$ due to circle–pair intersection calculations.

2.2. Formula to determine ROC

Here, we have used Heron's formula, which states that if the lengths of sides a, b, and c, then the area of triangle is:

$$A = \sqrt{s(s-a)(s-b)(s-c)} \tag{1}$$

Here, S is the semi-perimeter of the triangle; that is:

$$s = \frac{a+b+c}{2} \tag{2}$$

Therefore, Heron's formula can be written as:

$$A = \frac{1}{4}\sqrt{4a^2b^2 - (a^2+b^2-c^2)^2} \tag{3}$$

The sides 'a' of the inner triangle can be calculated as:

$$a = \sqrt{(x_{t1}-x_{t2})^2 + (y_{t1}-y_{t2})^2} \tag{4}$$

Similarly, the sides of b and c of the inner triangle (Figure 3) can be calculated like (4).

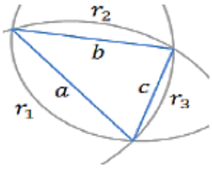


Figure 3. Inner triangle of overlapping area and their sides

In order to calculate the segment area:

$$A = r_1^2 \sin^{-1}\left(\frac{a}{2r_1}\right) - \frac{a}{4}\sqrt{4r_1^2 - a^2} \tag{5}$$

Now the combined overlapping area is,

$$A_{seg} = \sum_{n=1}^{3} r_n^2 \sin^{-1}\left(\frac{a}{2r_n}\right) - \sum_{n=1}^{3} \frac{a_n}{4}\sqrt{4r_n^2 - a_n^2} + \sqrt{s(s-a)(s-b)(s-c)} \tag{6}$$

2.3. ROC determination flowchart

Figure 4 shows the flowchart to determine ROC. This flowchart explains that if the experimental distances Ra, Rb, and Rc are greater than their theoretical distances (Da, Db, and Dc) from the sensor to the base station, then we can get the ROC.

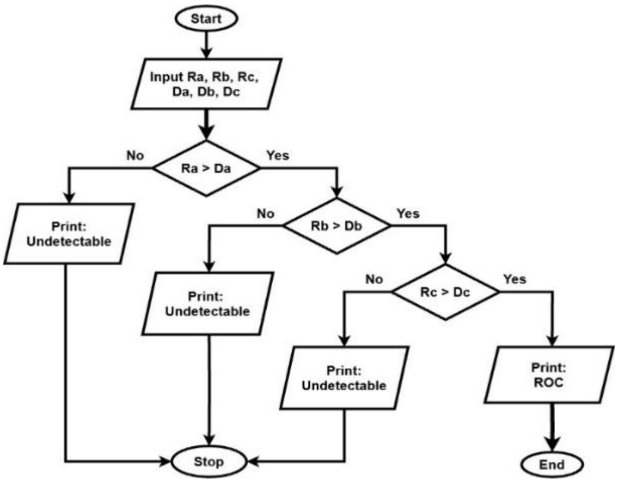


Figure 4. Flow chart of determining ROC

2.4. Experimental analysis

To determine ROC for the purpose of localization in WSN, two types of error can occur, including positive error and negative error. When the experimental value is greater than the theoretical value, we get positive error, and when the experimental value is less than the theoretical value, we get negative error. Positive error does not cause much problem to the location of sensor nodes because we can still get ROC. But when a negative error occurs, we cannot get any ROC. Figure 5 shows some scenarios of negative error.

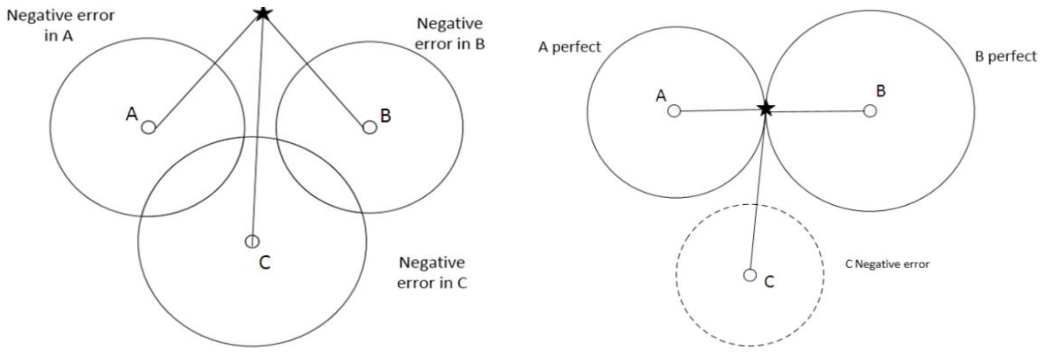


Figure 5. Undetectable ROC for negative errors

In this experiment, we use MATLAB to find out the overlapping area of sensor nodes. Based on the types of error, we have shown our experimental analysis in two scenarios. Scenario 1 is for determinable ROC, and scenario 2 is for indeterminable ROC.

Compared to classical trilateration, which outputs a single point estimate, the ROC-based approach reveals whether localization is geometrically feasible before position estimation is attempted. Existing methods treat all measurement errors uniformly, but ROC explicitly distinguishes between positive and negative errors, allowing early detection of failure cases. This reduces computational waste in systems where localization is repeatedly performed under noisy conditions.

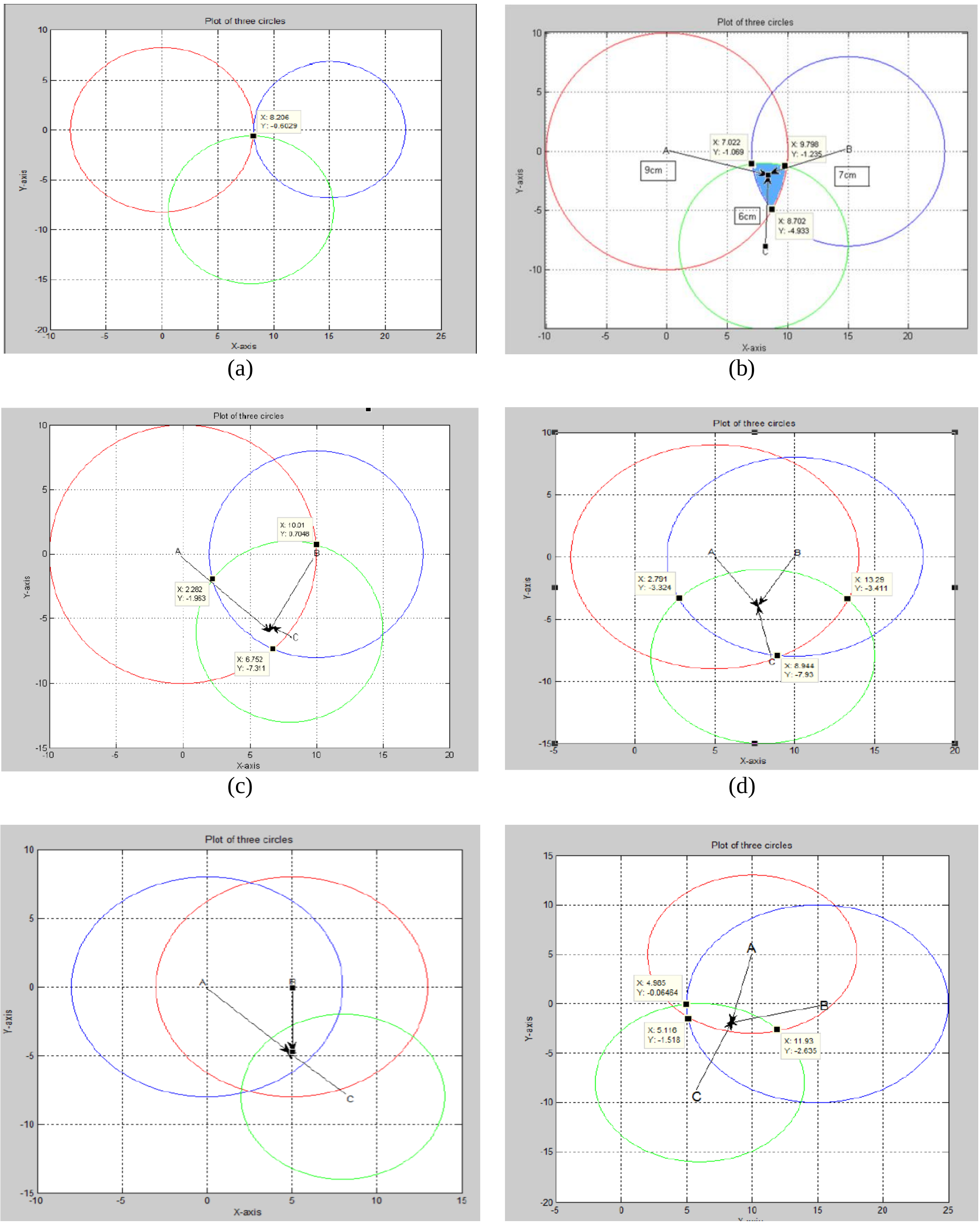
All simulations were run in MATLAB R2022a with a 2D coordinate system to ensure reproducibility. The configurations outlined in the experimental cases were used to manually initialize the anchor positions, theoretical distances, and experimental distances. ROC area was computed using custom functions that implemented in (1)–(6), while circle intersections were calculated using MATLAB-based geometric routines. In section 2 contains all of the coordinate values, radii, and mathematical formulas needed for replication, and section 3 goes into detail through the experimental cases.

2.4.1. Scenario 1: determinable ROC

In our study, we aim to determine the range of coverage (ROC) for localizing sensor nodes in a 2D space. To achieve this, we need a minimum of three satellites. When the actual distance measured between all satellites and the sensor node exceeds the expected (theoretical) distance, we can reliably determine the ROC. Figure 6 illustrates multiple scenarios related to calculable ROC, with nodes color-coded as follows: Red for node A, blue for node B, and green for node C. In Figure 6(a), a perfect overlap of three circles indicates that the experimental and theoretical distances align accurately, providing the correct localization point. Figure 6(b) depicts a situation where minor discrepancies exist between sensor-distanced nodes, with experimental distances of 10 cm, 8 cm, and 7 cm for nodes A, B, and C, contrasted against theoretical distances of 9 cm, 7 cm, and 6 cm, resulting in slight localization errors.

Figure 6(c) evidences a significant positive error for reference point C, with an experimental distance of 7 cm and a theoretical distance of 2 cm, leading to considerable localization accuracy issues. In Figure 6(d), all reference points exhibit substantial errors (e.g., experimental versus theoretical distances for A, B, and C are 9 cm vs. 5 cm, 8 cm vs. 4.5 cm, and 7 cm vs. 4.5 cm, respectively), causing an increase in the ROC curve area. Figure 6(e) features equal error differences for nodes A and B (1 cm), while point C displays a larger error difference of 2 cm. Finally, Figure 6(f) shows point B with a notably positive error, while nodes A and C have only slight positive errors.

These cases above clearly demonstrate the correctness and error margin for localizing the sensor nodes based on the distances from the reference satellites. Although simulations are done with artificial distances, these are based on real variations of the RSSI values from the IEEE 802.15.4 mesh motes, which could experience up to 5-40% variations due to noise.



(a) (b)

(c) (d)

(e) (f)

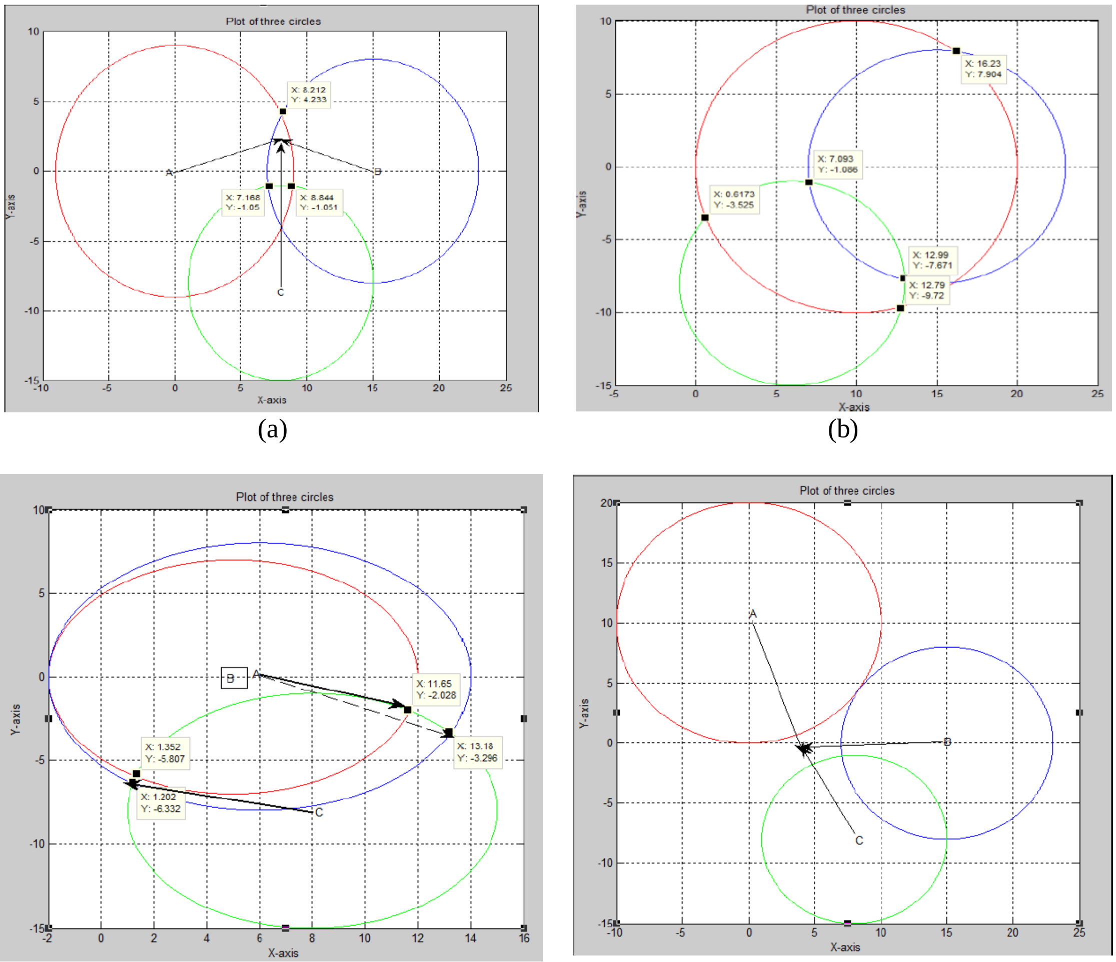
Figure 6. Possible scenarios for determinable ROC. (a) perfect overlap, accurate localization, (b) minor discrepancies, slight errors, (c) large positive error at node C, (d) substantial errors at all nodes, (e) equal errors at A and B, larger error at C, and (f) notably positive error at B, slight errors at A and C

2.4.2. Scenario 2: indeterminable ROC

When the actual distance measured between a sensor node and at least one reference node is shorter than the expected distance, determining the ROC becomes impossible. Figure 7 illustrates several instances where the ROC cannot be determined.

In Figure 7(a), the values of the sensor node distance to reference nodes A, B, and C are given as A= 9 cm, B=8 cm, and C=7 cm, respectively, while the theoretical values are A=8.8 cm, B=7.8 cm, and C=9 cm. Here, the negative error value belongs to reference node C. The sensor nodes' overlap does not generate an

ROC. In Figure 7(b), the sensor nodes' overlap does not have an accurate value to form an ROC. Figure 7(d) lacks any common overlapping area among the circles, leading to an undefined ROC as well. In Figure 7(c), while the measured distances match for nodes A and B, the expected distance for reference node C is double the measured distance. Despite some overlapping area, the ROC remains undefined in this scenario too. These instances illustrate situations where, due to discrepancies between measured and expected distances, determining the ROC becomes unfeasible.



(a) (b)

(c) (d)

Figure 7. Possible scenarios for indeterminable ROC; (a) negative error at node C, no ROC, (b) no accurate overlap value, (c) expected distance at C is double measured, ROC undefined, and (d) no common overlapping area

3. RESULTS AND ANALYSIS

Here, we analyze different types of situations based on various reference nodes, their center's coordination, experimental distance, and theoretical distance of various sensor nodes. We also compute the percentage error in distance by the following formula. After that, we have discussed the results.

3.1. Result

We show the ROC status for each experimental analysis figure. Then we find the overlapping area of ROC. We have divided the various situations into different cases.

3.1.1. Case 1: reference node and theoretical distance constant and experimental distance change

When the positions of reference nodes and theoretical distance are constant and experimental distance is changing, the increases in the experimental distance also increase the percentage of error and overlapping area of ROC. Table 1 describes this situation.

Table 1. ROC status and overlapping area for case 1

Center's coordinate of reference nodes			Theoretical distance of sensor nodes			Experimental distance of sensor nodes			Percentage error in distance			ROC status	Overlapping area of ROC
A	B	C	Da	Db	Dc	Ra	Rb	Rc	Ea	Eb	Ec		
0,0	15,0	8, -8	8.1	6.8	7	9	7	8	11.1	2.9	14.3	Yes	1.83
0,0	15,0	8, -8	8.1	6.8	7	10	11	12	23.46	61.76	71.43	Yes	51.67
0,0	15,0	8, -8	8.1	6.8	7	13	10.5	14	60.49	54.41	100	Yes	96.81

In this table, we can see the reference node and theoretical distance are constant. When the experimental distance increases, it will also increase the percentage error in distance as well as the overlapping area of ROC.

3.1.2. Case 2: reference node constant but change in theoretical and experimental distance

When the positions of reference nodes (A, B, and C) are constant and experimental and theoretical distance is changing, if experimental distance is greater than theoretical distance, the percentage of error increases. Table 2 shows the overall situation result for case 2.

Table 2. ROC status and overlapping area for case 2

Center's coordinate of reference nodes			Theoretical distance of sensor nodes			Experimental distance of sensor nodes			Percentage error in distance			ROC status	Overlapping area of ROC
A	B	C	Da	Db	Dc	Ra	Rb	Rc	Ea	Eb	Ec		
0,0	15,0	8, -8	8.1	6.8	7	8.94	7.5	7.7	10.4	10.3	10	Yes	2.79
0,0	15,0	8, -8	10	7.2	4.1	12.5	9.1	5.3	25	26.4	29.3	Yes	15.18
0,0	15,0	8, -8	6.7	10	5.2	9.2	14.1	8.5	37.3	41	63.5	Yes	45.88

In this table, we can see the position of the reference node is constant. The percentage error in distance depends on its experimental distance and theoretical distance. Percentage error in distance will increase if experimental distance is greater than theoretical distance.

3.1.3. Case 3: theoretical distance constant but change in reference node and experimental distance

When theoretical distance is constant, changes in experimental distance and the positions of reference nodes also change the percentage error in distance. Table 3 shows the result analysis based on this situation for case 3. In this table, we can see theoretical distance is constant. If we observe, we can find out that the change in the position of the reference node and experimental distance changes the percentage error in distance.

Table 3. ROC status and overlapping area for case 3

Center's coordinate of reference nodes			Theoretical distance of sensor nodes			Experimental distance of sensor nodes			Percentage error in distance			ROC status	Overlapping area of ROC
A	B	C	Da	Db	Dc	Ra	Rb	Rc	Ea	Eb	Ec		
-10, -5	9,12	10,15	11	13	11.5	12.2	14.8	15	10.9	14.2	30.43	Yes	0
0,0	15,0	8, -8	11	13	11.5	15.4	17.8	14.2	40	36.9	23.4	Yes	281.87
15, -5	15,10	5,10	11	13	11.5	11.7	18.7	12.1	6.3	43.8	5.9	Yes	62.76

3.1.4. Case 4: change in reference node, theoretical distance, and experimental distance

When the positions of reference nodes, experimental distance, and theoretical distance all are changing, it will change the percentage of error and overlapping area of ROC. Table 4 shows the result analysis based on this situation for case 4. In this table, we can see the position of the reference node, theoretical distance, and experimental distance changing. When everything is changing, it also changes the percentage error in distance and the overlapping area of ROC.

Table 4. ROC status and overlapping area for case 4

Center's coordinate of reference nodes			Theoretical distance of sensor nodes			Experimental distance of sensor nodes			Percentage error in distance			ROC status	Overlapp-ing area of ROC
A	B	C	Da	Db	Dc	Ra	Rb	Rc	Ea	Eb	Ec		
0,0	15,0	8, -8	8.2	6.8	7.2	10	8	7	21.9	17.6	-2.77	Yes	6.89
-10, -5	9,12	10,15	11	13	11.5	13	15	13.5	18.1	15.3	17.3	Yes	22.7
15, -5	15,10	5,10	10	9	8	11	12	14	10	33.3	75	Yes	56.94

Across all scenarios, ROC area increased monotonically with error magnitude. For example, in case 1, increasing the maximum error from 14.3% to 100% increased ROC area from 1.83 cm² to 96.81 cm². In case 3, repositioning reference nodes produced variations from 0 cm² (no effective overlap) to 281.87 cm² (large uncertainty region). These quantitative observations confirm that ROC area is a direct indicator of localization uncertainty.

3.2. Discussion

The significance of the work shown proves the value and efficacy of ROC in estimating the reliability of the localization process in WSNs in a quantitative manner. It has been demonstrated in the results that the determinable ROCs occur only when the values of the experimental distance are greater than the theoretical values, while negative and irregular values of the error give rise to undefined areas. This phenomenon has been vindicated in earlier works related to the instability of trilateration and proves that the value of ROC is an important precursor for the localization process to be feasible.

The experimental research in this paper informs us about the localization of a sensor node in a 2D region. In other scenarios, we determine the determinable and indeterminable ROC depending on the measured and theoretical distances between the sensor node of interest and the reference nodes. If the experimental distances are equal to the theoretical distances, we can have a determinable ROC and hence precise localization. Mismatched measured and anticipated distances lead to an indeterminable ROC, and hence localization is not possible in such a scenario. However, our study also reveals the effect of changes in the percentage error in distance measures and overlap area in the ROC with varying parameters, including location parameters of the reference nodes and experimental as well as theoretical distances. Evidently, with the changes in parameters, changes in the percentage error as well as the area of the ROC are also varying, thereby making it complex in terms of difficulties in the localization of the sensor nodes. The results reveal the importance of considering different aspects in the implementation of location algorithms in WSNs, still an area of scope for improvement in terms of accuracy in the location of sensor nodes.

4. CONCLUSION

This paper introduces a simulation-based assessment framework for optimizing sensor node placement, centered on the concept of the ROC. The ROC, defined as a jointly overlapped area among circles drawn from reference nodes to an unknown target node, serves as a metric to evaluate location determination accuracy under various error conditions. The research involved extensive simulations with varying reference node positions and distances to reflect realistic deviations in range estimations.

The findings emphasize measurable spatial confidence in localization, contrasting with existing trilateration-based methods that focus on point estimates. The proposed framework delivers region-based reliability measurements, enhancing the robustness and sensitivity of the localization process against disturbances from noise, sensor faults, or environmental variations. Results indicate that localization accuracy is highly dependent on the nature and scale of distance errors; scenarios with consistently overestimated distances yielded definable ROCs, while negative or asymmetric errors introduced significant limitations leading to undefined ROCs.Through numerical values like error percentage and ROC area, the study assesses localization stability, identifying thresholds for feasible localization. While this work is constrained to 2D stationary environments under optimal conditions, it opens avenues for future advancements, including extending the model to 3D spaces and incorporating machine learning to enhance its' feasibility in challenging conditions.

Further applications could entail adapting the framework for mobile sensor nodes, multi-hop localization systems, and integrating distance correction techniques to improve ROC predictions in real-world environments. Overall, this ROC framework promises to enhance scalability and accuracy for complex WSN localization applications.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Anisur Rahman	✓	✓	✓	✓	✓	✓	✓		✓		✓	✓	✓	✓
K. M. Safin Kamal		✓		✓	✓	✓			✓	✓	✓			✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis

I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting

Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable as no new data were created or analyzed in this study.

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