

An Enhanced-Time Difference of Arrival Technique for Estimating Mobile Station Position in Wireless Sensor Networks

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ABSTRACT

There have been continuous search several hundred years from now for techniques to track an object from a remote location given certain facts. One of such is locating a Mobile Station (MS) which is an object within a cellular network. Existing outdoor techniques to locate this MS require optimization both in terms of accuracy and latency. In this paper, an Enhanced Mobile Station Positioning (MSP) model for Wireless Sensor Networks was developed and its performance was appraised using accuracy and latency metrics in line with Time Difference of Arrival (TDOA) procedure. This model used the difference in arrival time of the signal received at four base stations (BS) positioned within the neighborhood of the Mobile Station (MS) to locate the MS. The TDOA forms a hyperbola on which the MS can be found. The mathematical model was derived by solving the hyperbolas with Taylor's series expansion formula. The estimated position of the MS was calculated using Linear Least Square (LLS) solution in a repetitive manner. The performance of the formulated model was evaluated using accuracy and latency metrics. The result showed that the model located the MS within error distances of 189m for 67% and 300m for 95% of the time it was deployed. This result outclassed the same technique using three BS which located the MS within 235m at 67% deployment and 349m at 95% of the time the model was used. This gave approximately 14% improvement in accuracy. Simulation results also revealed that the latency experienced when the BSs were increased from three to four increased by 42.86% (0.085 seconds). It can be concluded that increasing the number of BSs from three to four gave a significant better accuracy in locating a MS within the BSs.

General Terms

Mobile Station Positioning techniques, GSM localization

Keywords

Mobile Station, Base Station, Time Difference of Arrival.

1. INTRODUCTION

Digital communication has evolved pretty well within the last few decades due to the increasing deployment of Wireless Sensor Networks. No doubt it has been a radical pattern shift that enabled multimedia communications between people and devices from any position. Mobile wireless communication system as an example of Cellular communication is realized using Global System for Mobile communications (GSM) devices. This GSM as effective and efficient as it is challenged with high energy consumption, security, screen size, storage capacity among others. Another major challenge is getting the exact or estimated location of an MS within a

network (MSP).

For several hundred years now, methods to find the position of a remote object with respect to a known location have been required. In [1] it was reported that these methods were first applied in road surveying, target ranging for weaponry as well as map making. There has been a speedy boom in the number of MS users within the last decade, as a result, the number of applications that require location information is growing swiftly and MSP services has become a key research topic among researchers in the area [2].

Applications that render services based on the knowledge of the MS position are called Location Based Service (LBS). MSP techniques are therefore the backbone upon which LBS thrives. The original reason for the development of MSP techniques to support LBS in cellular networks was the need to trace the origin of emergency calls (E-911) [3]. At present, this initiative is now being applied in different areas, for example location sensitive billing, location based marketing, location of nodes in a distributed sensor network, intelligent traffic system, weather applications, military artillery, just to mention a few.

Many single techniques have been proposed to estimate location of MS. Examples include Global Positioning System (GPS), Angle of Arrival (AOA), Received Signal Strength (RSS), Time of Arrival (TOA), Time Difference of Arrival (TDOA), Signal Attenuation Difference of Arrival (SADOA), Cell Identification methods (Cell-ID). Other techniques which are hybrid include RSS/TDOA, TOA/AOA, AOA/TDOA, SADOA/TDOA among others. They combine their individual strengths to make up a hybrid which outperforms each constituent technique. Since this is the case, it follows that the quality of a hybrid technique depends on the quality of its constituent techniques. This has motivated the authors in this study to enhance the TDOA.

The Federal Communications Commission (FCC) of the United States of America issued out its accuracy standard in 2001 compelling all MSP service providers worldwide to work towards achieving it. The FCC accuracy requirement states that 67% of readings produced by any given (outdoor) MSP technique should be within 100 meters of the MS and 95% of the readings within 300 meters of the MS [4], [2]. The aim of every MSP technique therefore is to meet the FCC accuracy standard without necessarily consuming too much infrastructure or network resources in the process. The challenge lies in the fact that the accuracy of the existing (Network-based) outdoor positioning techniques is insufficient as they have not met the accuracy requirement of the FCC especially under the Non Line of Sight (NLOS) environments. Efforts are still being made in this regard. The

TDOA technique is the leading individual MSP technique and produces superior performance when the BS is increased [5]. This study therefore proposes an enhanced TDOA model to locate a MS within a Wireless Sensor Network by improving on the work done by [2] which used 3 BS. This study made use of measurements from four BSs to improve accuracy. Each TDOA measurement between any two BS produces a hyperbola on which the MS may be found. It is common knowledge that an increment in BSs would definitely add to complexity in the algorithm and increase latency. This paper therefore investigated the latency caused by the additional BS to see if the solution is sustainable. The rest of the paper is as follows. Section 2 discusses some key related works by other authors, in section 3, the TDOA mathematical model is derived, the methodology for the model is described in detail, and the Algorithm is shown. In section 4, the accuracy and latency results are presented and discussed. Based on these results, conclusions are made in 5. The paper closes by suggesting future works in section 6.

2. LITERATURE REVIEW

Due to the dramatic boom in MS usage within the last decade, MSP in cellular networks has become a hot topic among researchers. Some notable contributions by these authors are reviewed in this section.

Object location tracking started with the combination of the GPS technology with the internet. This made outdoor localization achieve good success in map navigation, people location, object tracking, etc. However, GPS technology meets its frustration in indoor applications because of the great weakening of the satellite signal and multipath effect caused by the obstruction from buildings and the complex indoor.

The two different approaches in position estimation techniques were presented in [6]: single estimation techniques and hybrid schemes. The single techniques include AOA, TDOA, TOA and RSS. The hybrid schemes for position estimation presented in the literature includes TOA/RSS, TDOA/RSS, TDOA/AOA and AOA/TOA. The literature showed that hybrid schemes tend to outperform single schemes. However, the more accurate a constituent technique of a hybrid is, the more accurate the hybrid will be. [7] In their works used Kalman Filters algorithm to locate a player within a football field. In the literature, TDOA and Kalfman Filters algorithm was combined to improve accuracy.

TDOA technique was studied in [8] and [5]. Specifically, the authors studied localization accuracy using Time Difference of Arrival (TDOA) measurements within a sensor network. Their results confirm high accuracy and show the superior performance of an additional BS. Attempts to grow accuracy led to the advent of many hybrid techniques which TDOA is a constituent part. [2] is an example of such a study. The authors proposed a RSS/TDOA location scheme using three BSs. According to their model the strength of the signal received at the BS, is used to find the distance between the MS and BSs. The time difference of arrival of signal exchanged between the MS and the BSs forms a hyperbola on which the MS lies. Solving the intersection of the hyperbolas gives the location of the MS. The accuracy of the TDOA meets its downfall due to obstacles or complex propagation mechanisms. Hence the need for more efforts to improve on TDOA. According to [2], and [6] increasing the number of BSs would be even more beneficial in terms of accuracy. This paper therefore studies the accuracy of the TDOA taking measurements from 4 BS (instead of the conventional 3 BS)

and further investigates the latency issues that arises due to additional BS.

3. TIME DIFFERENCE OF ARRIVAL

3.1 Mathematical Model

Suppose that each BS_i is capable of performing TOA observation, t_i then TDOA observation is defined as , T_i = t_i - t₁, i=1,...,N. Expressing TDOA observation as a function of station coordinates, the hyperbola produced is given by [2]

$$cT_i = \sqrt{(x-x_i)^2 + (y-y_i)^2} - \sqrt{(x-x_1)^2 + (y-y_1)^2} \quad (1)$$

is obtained. Where (x₁, y₁) and (x_i, y_i) are the coordinates of BS₁ and BS_i, respectively, and (x, y) is the unknown MS position. Consequently, the MS position is determined by solving the intersections of a set of N -1 hyperbola.

Denote the initial guess of the MS position as (x₀, y₀), the LLS solution is a common technique used to solve TDOA equations by using the first two terms of their Taylor series.

where:

$$M(x, y) = \sqrt{(x-x_i)^2 + (y-y_i)^2} - \sqrt{(x-x_1)^2 + (y-y_1)^2} - cT_i = 0 \quad (2)$$

The Taylor series expansion of M(x, y) around the point (x₀, y₀) is given by

$$M(x, y) = M(x_0, y_0) + \frac{\partial M(x,y)}{\partial x} \Big|_{x=x_0} (x-x_0) + \frac{\partial M(x,y)}{\partial y} \Big|_{y=y_0} (y-y_0) + \text{Higher Terms} \quad (3)$$

Therefore;

$$M(x_0, y_0) = \sqrt{(x_0-x_i)^2 + (y_0-y_i)^2} - \sqrt{(x_0-x_1)^2 + (y_0-y_1)^2} - cT_i$$

$$\frac{\partial M(x,y)}{\partial x} \Big|_{x=x_0} (x-x_0) =$$

$$\left[\frac{(x-x_i)}{\sqrt{(x_0-x_i)^2 + (y_0-y_i)^2}} - \frac{(x_0-x_1)}{\sqrt{(x_0-x_1)^2 + (y_0-y_1)^2}} \right]$$

$$(x-x_0) \frac{\partial M(x,y)}{\partial y} \Big|_{y=y_0} (y-y_0) =$$

$$\left[\frac{(y_0-y_i)}{\sqrt{(x_0-x_i)^2 + (y_0-y_i)^2}} - \frac{(y_0-y_1)}{\sqrt{(x_0-x_1)^2 + (y_0-y_1)^2}} \right] (y-y_0)$$

This gives;

$$M(x, y) =$$

$$\sqrt{(x-x_i)^2 + (y-y_i)^2} - \sqrt{(x_0-x_1)^2 + (y_0-y_1)^2} - cT_i$$

+

$$\left[\frac{(x-x_i)}{\sqrt{(x_0-x_i)^2+(y_0-y_i)^2}} - \frac{(x_0-x_1)}{\sqrt{(x_0-x_1)^2+(y_0-y_1)^2}} \right] (x-x_0) + \left[\frac{(y_0-y_i)}{\sqrt{(x_0-x_i)^2+(y_0-y_i)^2}} - \frac{(y_0-y_1)}{\sqrt{(x_0-x_1)^2+(y_0-y_1)^2}} \right] (y-y_0) = 0$$

where

$$m_{xi} = \frac{(x-x_i)}{\sqrt{(x_0-x_i)^2+(y_0-y_i)^2}} - \frac{(x_0-x_1)}{\sqrt{(x_0-x_1)^2+(y_0-y_1)^2}}$$

$$m_{yi} = \frac{(y_0-y_i)}{\sqrt{(x_0-x_i)^2+(y_0-y_i)^2}} - \frac{(y_0-y_1)}{\sqrt{(x_0-x_1)^2+(y_0-y_1)^2}}$$

$$f_i = \sqrt{(x_0-x_i)^2+(y_0-y_i)^2} - \sqrt{(x_0-x_1)^2+(y_0-y_1)^2}$$

After expanding (3) and substituting

$$m_{xi}x+m_{yi}y = cT_i - f_i + m_{xi}x_0 + m_{yi}y_0 \quad (4)$$

Expressing the set of linear equations in (4) in matrix form, it yields a solution of the form

$$A\hat{X}_{MS} = B \quad (5)$$

where

$$A = \begin{bmatrix} m_{x2} & m_{y2} \\ m_{x3} & m_{y3} \\ m_{x4} & m_{y4} \end{bmatrix}, \quad \hat{X}_{MS} = \begin{bmatrix} x \\ y \end{bmatrix},$$

$$B = \begin{bmatrix} cT_2 - f_2 + m_{x2}x_0 + m_{y2}y_0 \\ cT_3 - f_3 + m_{x3}x_0 + m_{y3}y_0 \\ cT_4 - f_4 + m_{x4}x_0 + m_{y4}y_0 \end{bmatrix}$$

The LLS solution is gotten from

$$\hat{X}_{MS} = (A^T A)^{-1} A^T B \quad (6)$$

After the LLS solution is performed repeatedly by solving hyperbolas about the point \hat{X}_{MS} . The current \hat{X}_{MS} estimate is fed back into the new estimate to be calculated until any further estimate would no longer yield a significant result but most likely waste time.

3.2 Methodology

This section describes how the simulation was done. A

software package called Matlab was used for the simulation. Fig 2 shows that areas on the Cartesian plane were divided into hexagonal cells. Four arbitrary points $(x_1, y_1), (x_2, y_2), (x_3, y_3)$ and (x_4, y_4) were chosen to represent the various BS coordinates, BS_1, BS_2, BS_3 and BS_4 . The MS was placed in a known initial position (x_0, y_0) between the 4 BSs. The exact distances from the MS position to the various BS was also calculated and are represented as $D1, D2, D3$ and $D4$ respectively. A zero mean Gaussian random variable is generated as the noise (in decibel per metre) and subtracted from the value of the signal strength received at each BS. This noise value further varies the distance calculated between the MS and each BS coordinate. This would yield new distance values $D11, D22, D33$ and $D44$. If the time to travel from the MS to BS_1 and from the MS to BS_2 is t_1 and t_2 respectively, it follows that $t_1 - t_2$ is a constant. This means the difference between the corresponding distances $D11$ and $D22$ is also constant. Therefore the MS in-between the two BSs travels along a hyperbola and can be located on this hyperbola. See Fig 1. The TDOA using 4 BS produces three hyperbolas and the point of intersection between these hyperbolas produces the initial estimate for the MS position. The LLS solution is deployed to solve the matrices resulting from the linearization of the TDOA technique. The location performance was assessed in terms of the value of the distance error (Root Mean Square Error) defined by:

$$E_d = \sqrt{(x_{MS} - \hat{x}_{MS})^2 + (y_{MS} - \hat{y}_{MS})^2} \quad (7)$$

where (x_{MS}, y_{MS}) and $(\hat{x}_{MS}, \hat{y}_{MS})$ are the actual and estimated MS locations, respectively [2]. After several free runs of TDOA location estimation for random noise values between MS and BS, results are presented in section 4.

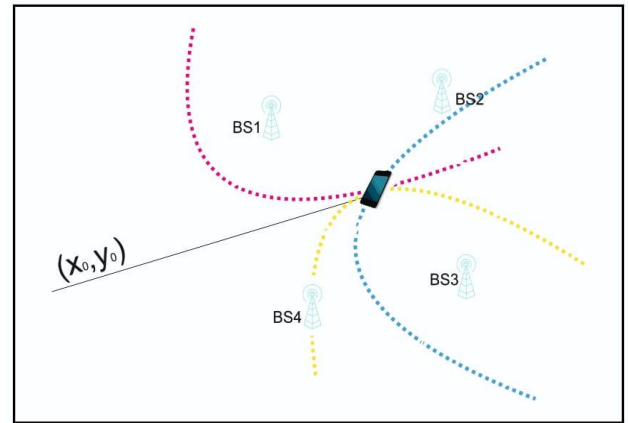


Fig 1: Time Difference of Arrival

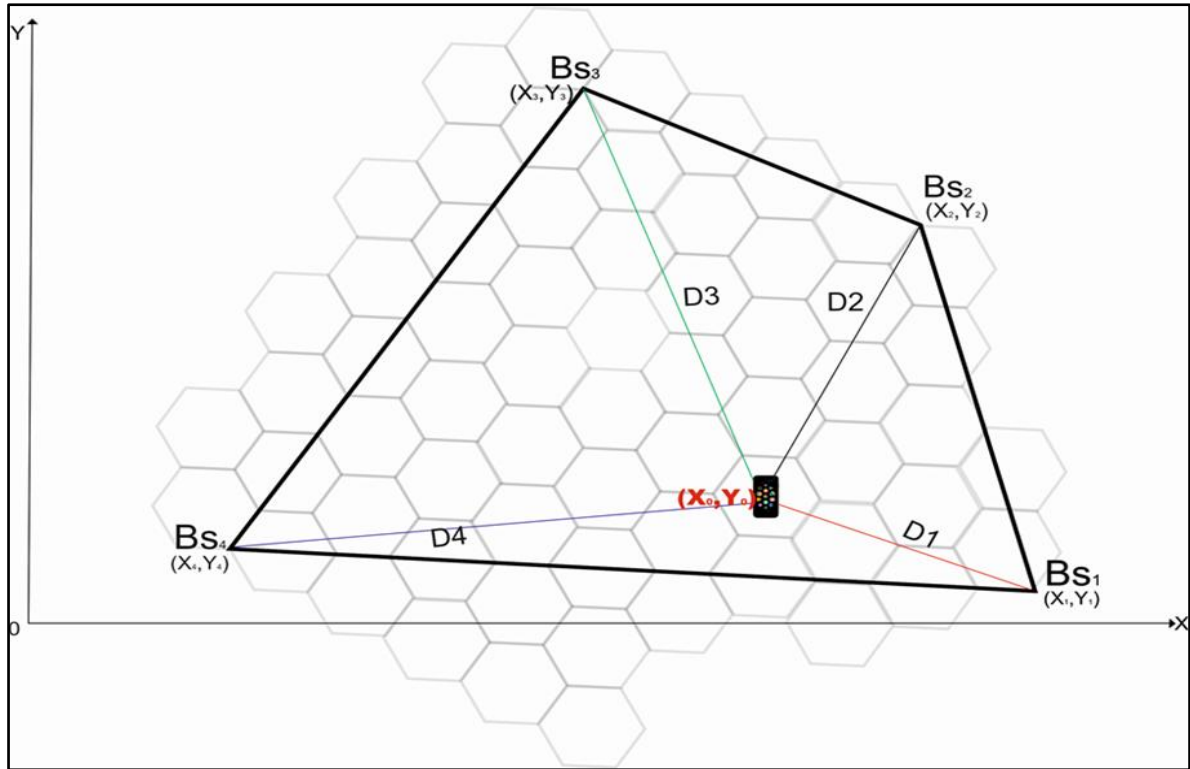


Fig 2: Simulation of the system

3.3 Algorithm of the System

The algorithm of the TDOA model is given in this section. Some assumptions were made as stated.

3.3.1 Overall Algorithm of the System

PRO: x_n, y_n are the coordinates of the n^{th} base station. The phone to be located is assumed to be a Mobile Phone object (MS) with the following properties. MS identity (imsi), Serving base station of the MS (sbs), a list of neighboring base stations ($nbs_{i,j}$) where $1 \leq i \leq 6$ and $1 \leq j \leq 2$, a list of neighboring sorted base stations ($nsbs_{i,j}$) where $1 \leq i \leq 4$ and $1 \leq j \leq 2$. The base stations have the following nested properties: signal strength, Base Station Code (cid), latitude (x), longitude (y).

POST: This algorithm calculates the location of a Mobile Station X_{ms} using the parameters in PRO and the formula in equation 12.

- Step 1: Identify the calling Mobile Station Object (MS)
- Step 2: Get MS.sbs
- Step 3: Set $i = 1$
- Step 4: Repeat step 5 to 7 while $i \leq 6$
- Step 5: set $nbs[i,1] = \text{getSignalStrengthDBM}(\text{MS.getNextnbs}());$
- Step 6: set $nbs[i,2] = \text{getCID}(\text{MS.getNextnbs}());$
- Step 7: set $i = i + 1$
- Step 8: sort nbs with the bubblesort algorithm (in descending order) as in 3.3.2
- Step 9: $nsbs[1,1] = \text{getSignalStrengthDBM}(\text{MS.sbs});$
- Step 10: $nsbs[1,2] = \text{getCID}(\text{MS.sbs});$
- Step 11: set i to 2
- Step 12: Repeat step 13 to 15 while $i < 4$
- Step 13: set $nsbs[i,1] = \text{get} \text{ nbs}[i-1,1]$
- Step 14: set $nsbs[i,2] = \text{get} \text{ nbs}[i-1,2]$
- Step 15: set $i = i + 1$
- Step 16: feed the content of nsbs into equation 6 to produce X_{ms}

Step 17: Exit

3.3.2 Bubble Sort Algorithm (Descending Order)

PRO: Assume list is an unsorted array of n elements.

POST: This algorithm returns the sorted version of list in descending order.

- Step 1: Start
- Step 2: for all elements of list Repeat step 3 to 6
- Step 3: if $\text{list}[i] < \text{list}[i+1]$ Repeat step 4 to 6
- Step 4: $\text{temp} = \text{list}[i];$
- Step 5: $\text{list}[i] = \text{list}[i+1];$
- Step 6: $\text{list}[i+1] = \text{temp};$
- Step 7: Exit

4. RESULT AND DISCUSSION

4.1 Simulation Data

The various E_d calculated for each iteration was expressed as a percentage of the Cumulative Distribution Function (CDF) and labelled as Location Distance. The result is presented in Table 1 and Table 2 below.

Table 1. TDOA 3 BS data set

TDOA 3 BS	
Location Distance(m)	CDF (%)
20.45	0.008752
23.10	0.069536
24.50	0.157772
25.50	0.265615
26.20	0.387184
34.00	0.661693
39.40	1.042085
42.80	1.489144
45.50	1.989144

49.50	2.567576
54.60	3.246007
56.50	3.961693
61.40	4.773458
61.90	5.595027
65.70	6.491105
69.10	7.453850
73.90	8.510713
75.00	9.589144
86.70	10.89699
93.30	12.33424
94.50	13.79503
94.70	15.25973
95.20	16.73424
97.90	18.26169
105.30	19.93424
106.30	21.62640
107.30	23.33816
112.10	25.14405
120.20	27.10875
133.30	29.33032
136.10	31.60679
139.20	33.94405
139.90	36.29503
140.50	38.65777
153.80	41.28130
154.50	43.91856
169.90	46.85777
197.40	50.33620
203.50	53.93424
206.70	57.59503
225.70	61.62836
234.60	65.83620
234.80	70.04797
237.40	74.31071
244.80	78.71856
251.50	83.25777
274.90	88.25581
310.80	93.95777
353.50	100.49700
517.70	112.21660

Table 2. TDOA 4 BS data set

35.50	5.989144
39.50	8.567576
44.60	12.24601
46.50	12.96169
51.40	13.77346
51.90	13.59503
55.70	15.49111
59.10	17.45385
63.90	17.51071
65.00	19.58914
76.70	19.89699
83.30	21.33424
84.50	22.79503
84.70	23.25973
85.20	25.73424
87.90	26.26169
95.30	27.10875
96.30	29.33032
97.30	31.60679
102.10	33.94405
110.20	36.29503
123.30	38.65777
126.10	41.28130
129.20	43.91856
129.90	44.03990
130.50	44.29112
132.80	45.23543
135.10	46.09888
137.40	46.85777
139.70	50.33620
143.00	53.93424
158.00	57.59503
165.00	61.62836
172.00	65.83620
189.50	67.04797
206.70	74.31071
209.70	78.71856
219.50	83.25777
225.90	88.25581
259.00	93.45433
300.80	95.95777
343.50	100.49700
607.70	112.21660

TDOA 4 BS	
Location Distance(m)	CDF (%)
10.45	0.008752
13.10	0.069536
14.50	0.157772
15.50	0.265615
16.20	0.387184
17.00	0.661693
19.40	1.042085
22.80	1.489144

4.1.1 Accuracy Result

In this section, the dataset in Table 1 and Table 2 were plotted for easy analysis. The performance of each technique is analyzed based on the CDF of distance error (location distance) mainly at 67% and 95%. This result reveals by how much this solution approached the FCC accuracy requirement.

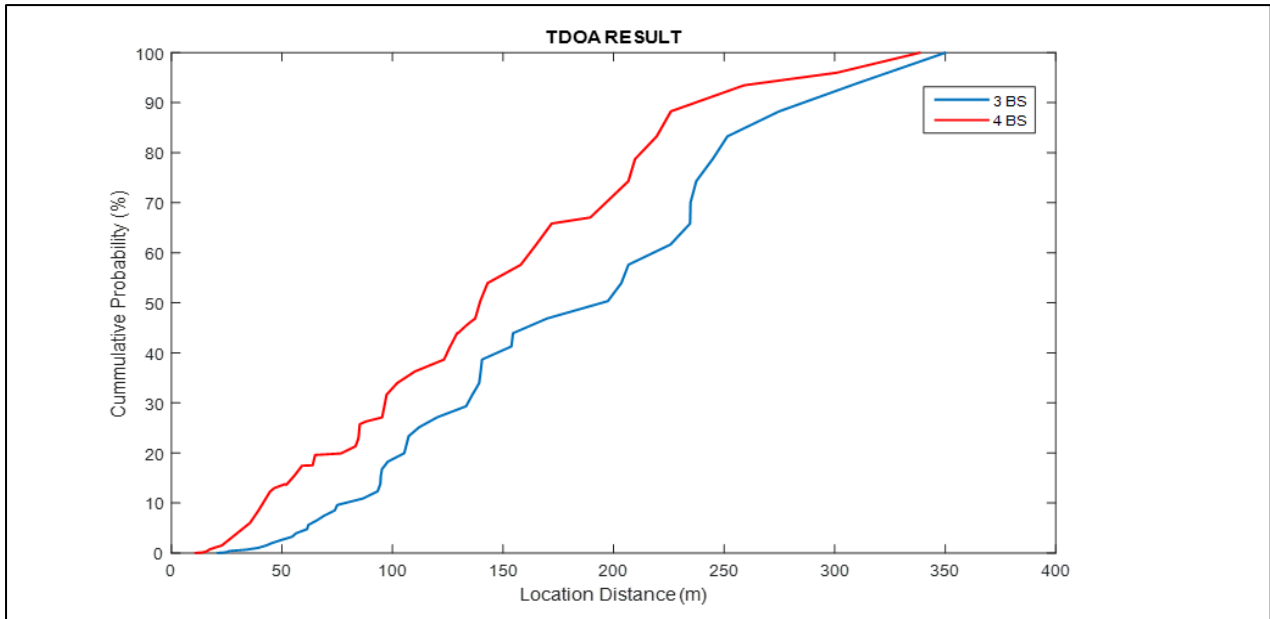


Fig 2: TDOA graph for 3 and 4 BSs

Fig 2 shows that with readings from 3 BS, at 67% the MS was located within a distance of approximately 235m. While at the confidence level of 95%, MS was found within 349m. In the case of 4 BS however, the MS location distance was 189m at 67% deployment, and 300m at 95% of use.

Table 3. Accuracy Result Summary

CDF (%)	TDOA METHOD	Location Distance(m)	Enhancement Level (%)
67	3 BS	235	19.6
	4 BS (Enhanced)	189	
95	3 BS	349	14.0
	4 BS (Enhanced)	300	

As shown in Table 3, the Enhanced technique improved on the 3 BS case by 19.6% and 14% at deployment levels of 67% and 95% respectively. This delivered an overall 16.8% improvement of the Enhanced TDOA over its 3 BS counterpart.

4.1.2 Latency Result

In this section, the average time it took to produce the location estimate for each technique is displayed. Latency is the delay experienced when producing a location estimate. In this case, the extra time delay experienced when the BS was increased from 3 to 4 gives the latency. A very high latency value could render a solution insignificant or totally unworkable notwithstanding a significant increase in accuracy. See Table 5 for comparison.

Table 5. Latency Result

TDOA METHOD	3 BS	4 BS (Enhanced)
Average Elapsed Time (Seconds)	0.113322	0.0198322
Latency Value	0.085	
Percentage Latency	42.86%	

As shown in Table 5, the latency value is 0.085 seconds which makes a 42.86% increment in time from 3 to 4 BS.

5. CONCLUSION

In this study, an enhanced TDOA technique was used to efficiently find the position of a MS in urban and suburban areas. The latency issues that accompanied the increase in number of BS from the conventional 3 to 4 was also investigated. This study showed that the developed technique with 4 BS outperformed the same technique using 3 BS given that no hardware adjustments were made to the currently available handsets. Simulation results showed that 67% of the readings were within 189 meters of the MS and 95% of the readings were within 300 meters. Hence, there is up to 16.8% improvement on the developed technique (using 4 BS) over the same technique using 3 BS.

Furthermore, the latency value was 0.085 seconds. Efforts could still be made to reduce this latency while sustaining the accuracy. The solution presented in this work is valuable to Communication Engineers, football league industry for goal line technology as well as any distress caller. The extra computation loading at the network end can be calmed by using modern powerful computation machines.

6. FUTURE WORKS

The following is recommended for future studies on this work:

- i. Efforts should be made to reduce latency without compromising accuracy.
- ii. Developed techniques should be stretched to locate more than one MS at a time. This would actually improve latency.
- iii. More than two techniques could be merged and their performance evaluated.
- iv. Other techniques could be employed to perhaps meet the FCC accuracy requirement.

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