Minimizing Mobile Location Error Based on Hybrid ToA-CTA for Heterogeneous Network

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***Abstract*—In wireless localisation, time-based Location Determination Technology (LDT) with minimum error is one of the crucial techniques that can be used to improve resource management and quality of services. This study aims to improve the location accuracy of mobile user by using a hybrid time-based LDT. In this paper, minimising of the mobile estimation location error by using hybrid trilateration technology based on Time of Arrival (ToA) and Centroid Triangular Algorithm (CTA) has been discussed. It has been observed that this hybrid technique can be considered as an optimal solution for minimising the localisation error of mobile user which is located in a vicinity of the heterogeneous network environment. Based on simulations, the constructed model has resulted in a better location error distribution, and the localisation error can be minimised and satisfied the E911 requirements.**

***Index Terms*—Localization Error; ToA; Heterogeneous Network; Centroid Triangular Algorithm.**

I. INTRODUCTION

Wireless communication networks experienced a tremendous change in its technologies in the last few decades. Generally, the evolution of cellular wireless Generation (G) refers to the requirement of the improvement of the system based on frequency, technology, and speed. Due to the wide-ranging applications of wireless communication, recently, much interest in wireless localisation has been achieved. The primary drive behind the development of localisation techniques is to support location services (LCS) in cellular networks to locate any mobile station (MS) originating emergency calls[1]. The first regulation concerning the availability and accuracy of the localisation of such calls in the USA has been issued by the Federal Communications Commission (FCC) since 1996[2] for E911. Then, about six years later, a similar approach has been adopted by the European Union, but without defining minimum precision requirements for the estimated positions. LDT is a technique used in Location based-service (LBS) to estimate the position of a mobile user's location.

There are several ways have been identified that can be used to determine the position of a mobile user in a specific location. However, the accuracy of position estimation depends on the types of LDTs used. Choosing suitable LDT in determining the location of a mobile user becomes very crucial aspect especially when the user is located in the vicinity of a heterogeneous network environment. In this paper, a hybrid time-based LDT approach has been proposed in minimising mobile location error. It aims to improve the accuracy of the mobile user's location estimation by using ToA and CTA. The RMSE hybrid ToA-CTA localisation technique with worst-case scenario has also been presented in detailed to show the minimisation of mobile location error in a vicinity of the heterogeneous network.

The rest of this paper is organised as follows. In section II localisation technique and related work are discussed; these include distance related measurements. In section III, the types of localisation technique and scenario of heterogeneous network environment are explained. The explanation focusing on time-based and distance measurements included ToA without delay propagation and with delay propagation consideration. Hybrid Location Determination Technology (HLDT) by using TOA and CTA technologies are explained in Section IV whereas numerical experimental and simulation results are given in Section V. Finally, a summary is provided in Section VI.

II. LOCALIZATION TECHNIQUE

Currently, the landscape of wireless location estimating systems are filled with a variety of technologies[4]. Among the technologies, the Global Positioning System (GPS) is the most popular system. It is now being used for many other purposes and has proved to be a revolutionary technology in today's world[6] even though it has some limitations. GPS was created by the US Department of Defence for the navigation of the military in any part of the world under the circumstances. The localisation applied in GPS uses a precise time synchronisation, i.e. radio time-of-flight (RToF) lateration via satellites but has the limitations of only working outdoors and Line-of-sight (LOS)[5][6].

A. Modern-day Localisation Technique

Most of the modern-day wireless localisation technique is mostly based on traditional triangulation and trilateration principles. A combination of both is used in some cases, to determine the location of a mobile user[7][8][9]. Trilateration and triangulation techniques require at least three hearability of the signal from Base Stations (BS) to unknown location of Mobile Station (MS). The relation between receiving power, time and distance is very crucial in determining which base stations act as serving base station and another two will be the neighbouring base stations. The serving BS has been identified as the nearest distance from the MS with the highest power received signal. Since the focus of the study is trilateration localisation technique, triangulation technique is not being explained detail in this paper. In the trilateration technique, the location of an MS is estimated by measuring the distances from multiple reference points where the BSs are located. The distances can be obtained by measuring quantities like received signal strength (RSS) and time-of-flight, which are known to be distance dependent. Quite a number of time-based estimators or LDT can be used, including ToA, Time Difference of Arrival (TDoA) and Round-Trip Time of Flight (RToF), also known as two-way ranges[7].

B. Related Works

Nowadays, with the advancement of wearable technology, Location Based Service (LBS) has been realised as a valued and potential service that should be offered by wireless operators to their customers conveniently and seamlessly without imposing any extra cost. New methods and techniques have been seeking continuously by the researchers who are aiming at improving the localisation accuracy[10][11]. Accuracy can be defined as the measure of the degree to which the measured quantity is the same as its actual value whereas precision is the measure of the degree to which the same measurement made repeatedly produces the same results[12][11]. The accuracy considers a constant error, systematic error, validity, and bias whereas precision can be related to random error, repeatability, reliability or reproducibility[11].

III. ToA Technology

ToA is a time-based trilateration positioning technique that directly relies on measurements of time taken to transmit a signal from MS device to BS or vice versa. It has been assumed that each BS generates circles with a radius area corresponding to each distance based on the measured times. According to [4][12], ToA is a technique that allows locating a Mobile Station by calculating the time of arrival of the signal from the MS to more than one BS. The location of MS can be estimated by identifying the intersection between all edges of network circles with different carrier frequency as illustrated in Figure 1.

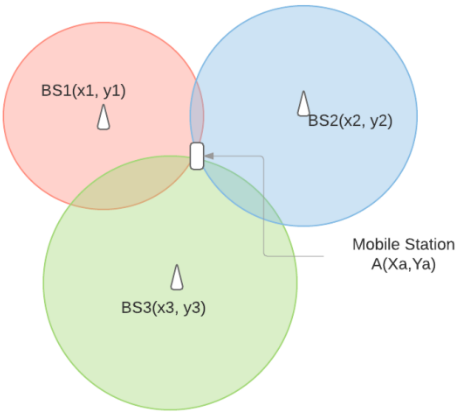

Figure 1: Mobile station location in a three hearability of heterogeneous network

In the ToA technique, the location of MS can be estimated either by measuring the phase of the received narrowband carrier signal or by direct measurement of the arrival time of a wideband narrows pulse. Basically, the propagation time of the signal can be directly translated into distance, based on the known signal propagation speed [4], i.e. the speed of light.

A. ToA Technique with Synchronization

In the ToA technique, the position of MS can be estimated based on the intersection of circles from at least three hearability of ToA measurements. The BS can easily get the time of arrival; hence get the time for travelling. However, in this technique, the time in BS and MS are assumed to be the same[14]. This method requires the network to be synchronised and exact time synchronisation is needed [12]. To satisfy this assumption, the BS and MS device should precisely synchronise their time.

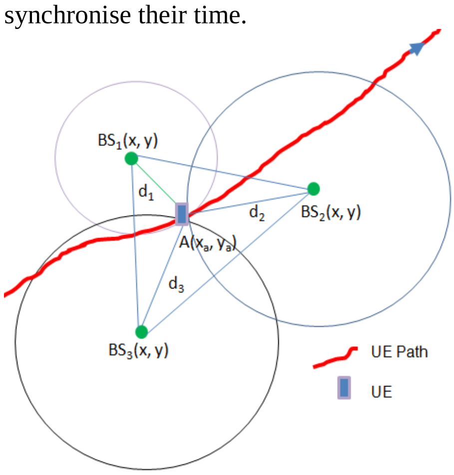

Figure 2: ToA based localisation with time synchronisation

Figure 2 shows the scenario of mobile user location determination in the availability of at least three signals from BSs with time synchronisation consideration. In a heterogeneous network, at a certain point of attachment, A(x_a, y_a), MS faces three hearability conditions in the availability of different networks with different carrier frequencies. From Figure 2, $BS_1(x_1, y_1)$ is observed as the nearest distance to MS, and it is assumed as a Serving Base Station whereas the others are called as neighbouring BSs. By assuming no delay propagation condition, the intersection between three circles with center of known Base Stations $BS_1(x_1, y_1)$, $BS_2(x_2, y_2)$ and $BS_3(x_3, y_3)$ which radius distance of d_1, d_2, and d_3 can be used to determine the true location of Mobile Station $A(x_a,y_a)$. The distance from MS, as a transmitter to BS, as a receiver can be defined according to the relation between the speeds of electromagnetic wave that propagates from a transmitter to receivers within a specific time and can be expressed as:

$$d_i = v_i \times (t_i - t_0) \qquad (1)$$

where: d_i = Distance from BS to MS in meter (m)
v_i = Speed of light, 3 x 10^8 ms^{-1}
$(t_i - t_0)$ = Time duration taken by the signal to travel (s)

In this case, the time taken by the signal wave to travel from MS to each Base Stations (BS_i) is assumed to be synchronised from all Base Stations. Since ToA technique relies on the difference between the time of arrival and time of departure, all receivers and transmitters must be synchronised so that there is no error in the difference due to clock offsets. In GSM, this issue has been solved by additional hardware enhancements called Location Measurement Unit (LMU) in its network architecture. The LMU needs to be involved in performing time-based measurements and computation.

By using ToA method, the true location of mobile station, $A(x_a, y_a)$ can also be estimated by identifying the intersection of three line of distance between the MS location and each of Base Stations $BS_1(x_1, y_1)$, $BS_2(x_2, y_2)$ and $BS_3(x_3, y_3)$, i.e. d_1, d_2 and d_3 respectively. The true distances between MS to each base station can be denoted as d_1, d_2, and d_3[15].

$$d_1 = ToA_1 = \sqrt{(x_a - x_1)^2 + (y_a - y_1)^2} \quad (2)$$

$$d_2 = ToA_2 = \sqrt{(x_a - x_2)^2 + (y_a - y_2)^2} \quad (3)$$

$$d_3 = ToA_3 = \sqrt{(x_a - x_3)^2 + (y_a - y_3)^2} \quad (4)$$

These relations have been expressed based on Equation (1) where the distances, d_i (meter) is correlated to the Receive Signal Strength (RSSI in dB) that can be heard by the Mobile Station, $A(x_a,y_a)$ from each Base Stations (BS_i). The transmission of electromagnetic wave signal is subjected to multipath fading that has been discussed previously.

B. ToA Technique with Delay Propagation

In this research, the accuracy of localisation is considered based on the location error. Figure 3 shows a scenario of ToA based localisation with the delay of wave propagation consideration between BSs and MS. When considering the high frequency at which the signals travel from BS to MS, each circle shows delay propagations with a radius of d_{e1}, d_{e2} and d_{e3} respectively. The three circles are intersecting to each other. As shown in Figure 3, the location of MS can be estimated in the triangle area of $P(x_{23},y_{23})$, $Q(x_{13},y_{13})$, and $R(x_{12}, y_{12})$.

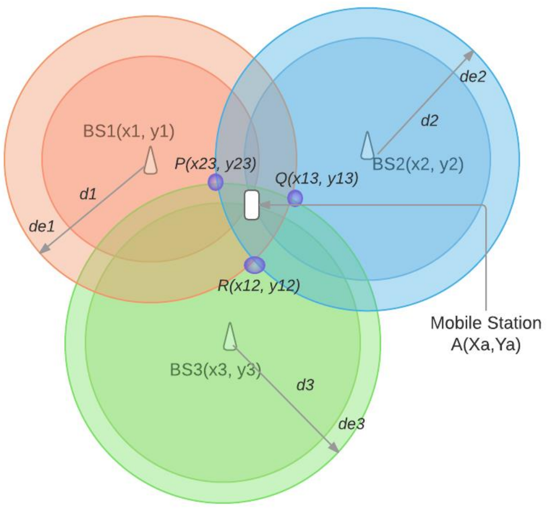

Figure 3: Scenario of ToA based localisation with delay propagation

Each BS transmits signal at a particular of a carrier frequency of the cellular network. The transmitted signal propagates at the speed of light, and it arrives at MS after a certain period known as a time delay [13]. Since this delay depends on the distance between BS and MS, it is the same as the time delay multiplied by the velocity of light, c. The number of delay samples, n_i in term of a particular carrier frequency, f_c can be expressed by:

$$n_i = ceil\left(\frac{d_i}{c} \times f_c\right) \quad (5)$$

where c = 3 x10^8 ms^{-1}, i.e. the speed of light in meter per second, and d_i is the distance between BS_i to Mobile Station in meter (m). The 'ceil' function is needed to round up the function since the number of delays is an integer. From Equation (5), the distance between BS_i to Mobile Station, $A(x_a, y_a)$ can be derived:

$$d_i = n_i \frac{c}{f_c} \quad (6)$$

By referring to Figure 3, the distances between a mobile station to each Base Stations with delay propagations can be denoted as D_1, D_2, and D_3.

$$D_1 = d_1 + de_1 = \sqrt{(x_a - x_1)^2 + (y_a - y_1)^2} + de_1 \quad (7)$$

$$D_2 = d_2 + de_2 = \sqrt{(x_a - x_2)^2 + (y_a - y_2)^2} + de_2 \quad (8)$$

$$D_3 = d_3 + de_3 = \sqrt{(x_a - x_3)^2 + (y_a - y_3)^2} + de_3 \quad (9)$$

where de_1, de_2 and de_3 are estimated distance error between each Base Station to Mobile Station and can be expressed respectively as in Equation (10)[16].

$$de_1 = n_1 \frac{c}{f_1}; de_2 = n_2 \frac{c}{f_2}; de_3 = n_3 \frac{c}{f_3}; \quad (10)$$

whereas f_1, f_2 and f_3 is carrier frequency of Base Stations, BS_1, BS_2 and BS_3 respectively. Besides, in determining the true distances, d_i between each BS to Mobile Station, $A(x_a, y_a)$ that using with time-sensitive systems, there is also the possibility of significant hardware delays must be accounted for. Figure 4 shows the worst-case scenario of ToA localisation with a delay of wave propagation consideration. In this situation, it is assumed that all BSs transmit the wireless signal to MS at $A(x_a,y_a)$ with delay propagation.

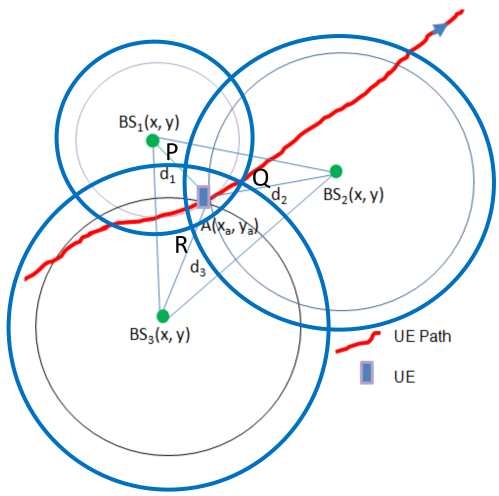

Figure 4: ToA based localisation with delay propagation

In this condition, the point of location of Mobile Station, $A(x_a, y_a)$ can also be localised in the area of PQR triangle based on the intersection of circles with the radius of D_1, D_2, and D_3 as stated in Equation (7), (8) and (9) respectively.

C. ToA -CTA Localization

ToA-CTA localisation is a hybrid localisation technique that combines the step of ToA LDT technique and centroid localisation technique. Based on Figure 3 the location of Mobile Station $A(x_a,y_a)$ can be estimated in an area of the heterogeneous network with delay propagation. The estimated location of Mobile Station, $A(x_a, y_a)$ can also be determined by calculating the centroid of the triangle PQR with distance error, i.e.:

$$A(x_a, y_a) = \left(\frac{x_{23} + x_{13} + x_{12}}{3}, \frac{y_{23} + y_{13} + y_{12}}{3} \right) \quad (11)$$

where (x_{23}, y_{23}), (x_{13}, y_{13}), and (x_{12}, y_{12}) is point coordinate of P, Q, and R respectively. In this situation, the location error of the Mobile Station, $A(x_a, y_a)$ can be identified by comparing all output data from MS location estimation by using ToA and estimation by using Centroid localisation Technique.

The location error between the true position of the Mobile Station, $A(x_a, y_a)$ and the estimated positions of MS (x_i, y_i) can be determined based on RMSE with mathematical expression below,

$$RMSE = \sqrt{\frac{\sum_{i}^{n}\left((x_a - x_i)^2 + (y_a - y_i)^2\right)}{N}} \quad (12)$$

where N is the number of observations.

IV. HYBRID LOCATION DETERMINATIONS TECHNOLOGY

Hybrid Location Determination technology is an LDT that consists of several steps of the algorithm in aiming to estimate the position of mobile users or user equipment location accurately.

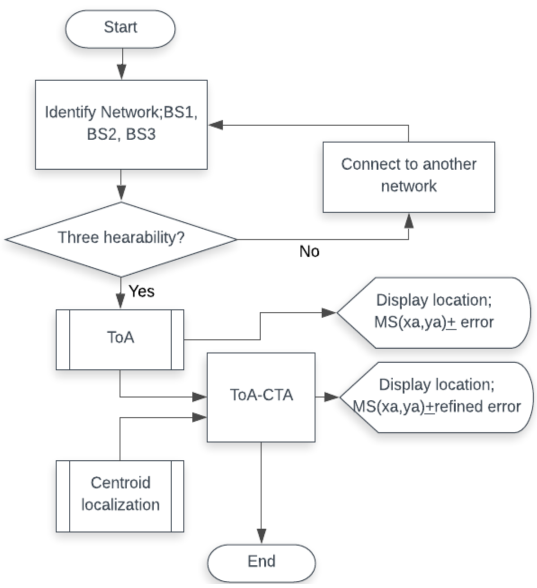

Figure 5: Flowchart of Hybrid ToA-CTA localisation

In ensuring the estimation of positioning with minimum location error, in this study, a combination of ToA and CTA have been simulated and analysed. In this research, hybrid ToA and centroid localisation has been used in minimising location error of mobile localisation. Figure 5 shows the flowchart of work in the development of the Hybrid LDT technique based on ToA and CTA technique. The calculation started by using ToA technique with ideal and worst-case consideration to identify the range of location error, d_e. Then this result has been compared with the ToA+CTA technique in purpose to refine and minimise the location error. The differences of location errors can be simulated by using Matlab programming with several iterations to get the minimum error of localisation estimation. In this case, the identified mobile station is assumed to be always located in at least three hearability of signal that comes from each base station, BS.

V. PERFORMANCE EVALUATION

The simulation and numerical experimental results have been used to evaluate the efficiency of the proposed Hybrid Localization Determination Technique based on ToA and CTA in minimising the location error of mobile user.

A. Simulation Result

In this research, the location error based on various carrier frequencies such as 800 MHz, 900 MHz, 1800 MHz, 2100 MHz, 2600 MHz, and 3.5 GHz is observed. Table 1 shows the distance error-based on each type of network available in wireless cellular communications.

Table 1
Distance Error Based on Carrier Frequency, f_c

Types of Network Available	Carrier Frequency, f_c (MHz)	Estimated Distance error, de_i (m)	Estimated Time delay, t_i (μs)
GSM800	800	0.37500	0.00125
GSM900	900	0.33333	0.00111
GSM1800	1800	0.16667	0.00055
UMTS/ 3G	2100	0.14286	0.00047
LTE/ 4G	2600	0.11538	0.00039
	3500	0.08571	0.00029

From Table 1, it has been observed that the higher the frequency carrier f_c, the shorter the estimated distance error. The time-based of the localisation estimation technique depends on the carrier frequency, f_c of the network involved in the heterogeneous network situation. The simulations to investigate the location of MS or user equipment (UE) when it is moving through the area of heterogeneous network firstly have been illustrated in Figure 6.

As shown in Figure 6, the Mobile Station, $A(x_a, y_a)$ is moving through its path in a scenario of a heterogeneous network, encompasses many different networks available such as GSM900, GSM1800, WCDMA, WiMAX and LTE. From the simulation scenario, it has been assumed that there are three fixed BSs, i.e. BS_1, BS_2 and BS_3 with coordinates of [10, 5], [5, 8], and [4, 3] respectively, and can be illustrated as in Figure 7.

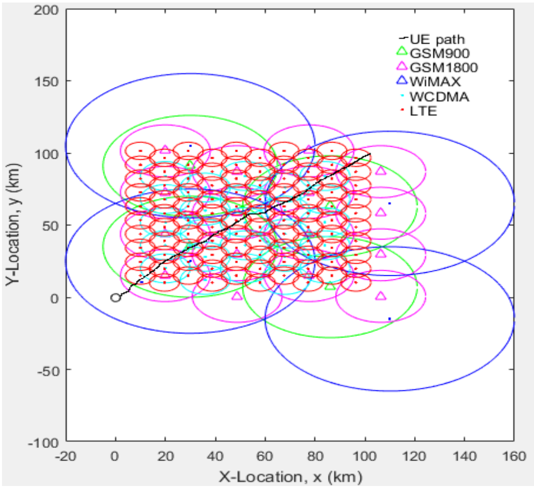

Figure 6: Simulation of mobile user moving in a heterogeneous network

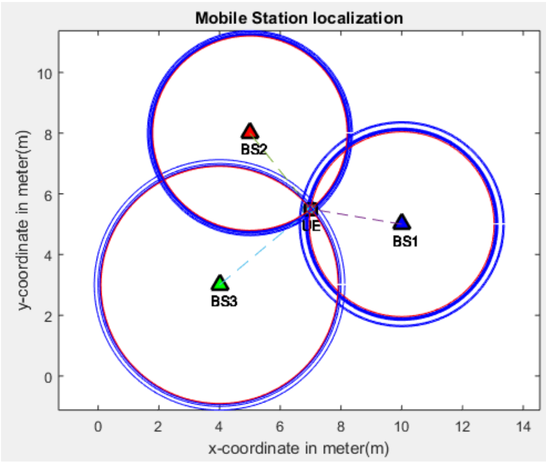

Figure 7: The PoA of mobile user in a heterogeneous network scenario

As mention previously, Point of Attachment (PoA) is a point where the location of a mobile user can be estimated. It is an intersection between received signals from all Base Stations that can be heard by the MS at a specific time of localisation. From Figure 7, the location of the Mobile Station, A(x_a, y_a) firstly can be determined by calculating the intersection point of three red circles i.e. d_1, d_2, and d_3. Based on the simulation result, the location of Mobile Station, A(x_a, y_a) is at PoA of [7, 5.5], without delay propagation consideration.

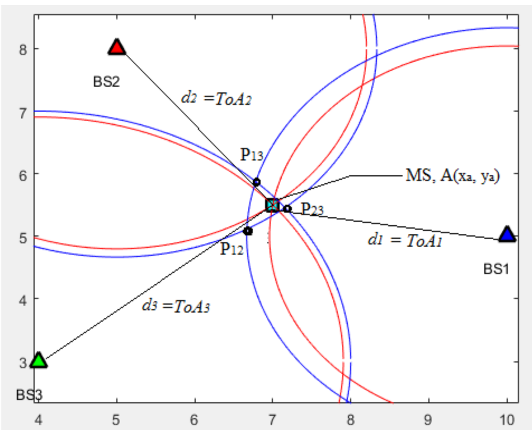

Figure 8: Simulation scenario of ToA with delay propagation

When considering location error caused by delay propagation, the distance between Base Stations to the Mobile Station follows equations (7), (8), and (9). Whereas the location of Mobile Station, A(x_a, y_a) can also be identified and located at any area of triangle P_{13}, P_{23}, and P_{12} in the situation of delay propagation consideration as shown in Figure 8.

B. Location Error

Figure 9 shows the probability of location of the mobile user with delay propagation based on different carrier frequencies. The location error of mobile localisation can be minimised by using ToA technique and CTA.

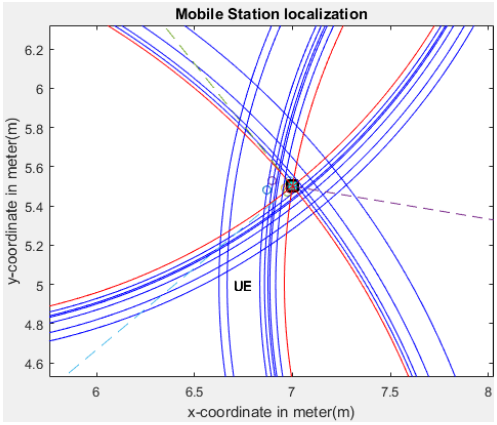

Figure 9: Scenario for estimation of mobile localisation by using CTA

The location estimation performance is evaluated by Root Mean Square Error (RMSE), and the simulation is performed more than 1,000 times for each carrier frequency in order to calculate the accurate result. The accuracy of mobile localisation can be evaluated based on the minimisation of location error. The RMSE is calculated for both ToA and ToA-CTA technique as listed in Table 2.

Table 2
RMSE for ToA and ToA+CTA Approaches

Carrier Frequency, f_c (MHz)	RMSE value obtained by using ToA	RMSE value obtained by using ToA+CTA
800	0.37500	0.1076
900	0.33333	0.1321
1800	0.16667	0.0401
2100	0.14286	0.0212
2400	0.12500	0.0310
2600	0.11538	0.0393
3500	0.08571	0.0174

From Table 2, pertaining to 100 points of observed Mobile Stations, it is clear that the RMSE drastically reduces when ToA-CTA algorithm applied for estimating the location of mobile user compares to ToA for each carrier frequency. The observation shown in Table 2 has been displayed graphically in Figure 10 where the x-axis is the carrier frequency in MHz, and the y-axis indicates the corresponding value of RMSE.

Figure 10 shows the RMSE in localising of mobile user for each carrier frequency represented by GSM800, GSM900, GSM1800, UMTS/ WCDMA, and LTE/4G in a heterogeneous network, considering the worst-case scenario where all signals from each of three Base Stations facing delay propagations.

The relation between the RMSE of localisation for all frequencies has resulted where the higher the carrier frequencies, the lower the RMSE of the localisation estimation. From Figure 10, it is clearly noted that the RMSE value obtained using hybrid ToA-CTA algorithm reduces when compared to ToA technique.

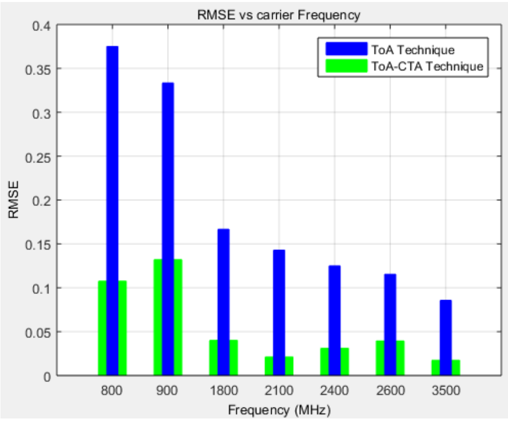

Figure 10: RMS Error values of ToA versus ToA-CTA in different carrier frequency

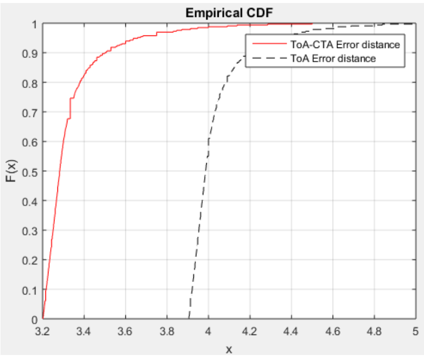

Figure 11: Comparison of CDF values of ToA versus ToA-CTA mobile localisation

Figure 11 shows the comparison of CDF plot between ToA technique and ToA-CTA in localising the mobile user. From Figure 11, the location error reduces from a radius of 4.40 m to 3.50 m at 95% of observations whereas at 67% of CDF the location error has been reduced from a radius of 4.00 m to 3.30 meters.

VI. CONCLUSION

In this paper, ToA-CTA algorithm has been applied over HLDT to reduce localisation error. From the simulation results, it can be noticed that HLDT with ToA+CTA algorithm significantly brings down the RMSE based localisation error by 71.08%. From the performance evaluation, it can be concluded that the location error of the mobile station can be minimised by using Hybrid time-based ToA-CTA technique. In other words, the accuracy of mobile user's location which is situated in the availability of heterogeneous network can be increased by using several steps of ToA-CTA technique, and this combination of techniques also known as hybrid LDT or HLDT. Based on the simulation result, it has been identified that this technique is satisfied the standard requirements of localisation that is introduced by FCC.

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