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User equipment geolocation depended on long-term evolution signal-level measurements and timing advance

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ABSTRACT

A new approach is described for investigating the accuracy of positioning active long-term evolution (LTE) users. The explored approach is a network-based method and depends on signal level measurements as well as the coverage of the serving cell. In a two-dimensional coordinate system, the algorithm simultaneously applies LTE measured data with a combination of a basic prediction model to locate the mobile device's user. Furthermore, we introduce a unique method that combines timing advance (TA) and the measured signal level to narrow the search region and improve accuracy. The developed method is assessed by comparing the predicted results from the proposed algorithm with satellite measurements from the global positioning system (GPS) in various scenarios calculated via the number of cells that user equipment concurrently reports. This work separates seven different cases starting from a single reported cell to five reported cells from up to 3 sites. For analysis, the root mean square error (RMSE) is computed to obtain the validation for the proposed approach. The study case demonstrates location accuracy based on the numbers of registered cells with the mean RMSE improved using TA to approximately 70-191 m for the range of scenarios.

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1. INTRODUCTION

Wireless cellular communication has improved rapidly in recent years. Long-term evolution (LTE) 4G has a robust, reliable, flexible, and peak data rate and is anticipated to reach 77.5 exabytes by 2022 [1]–[5]. Therefore, wireless geolocation has become the main part of human life due to the highly demanded location-based services and applications. All these necessities make accurate geolocation highly required in recent decades [6]–[9]. The United States Federal Communication Commission (FCC) requires all wireless devices must provide an accurate location to support emergency calls (E-911). These requirements have been issued since 1996 and updated to final form in 1998. In addition, the same regulations have been used in Europe and other continents [10]–[13].

These services and applications mainly depend on the global positioning satellite (GPS), built inside the smartphone. However, the GPS has limited indoor area due to weak signal inside the building [7], [14]–[16]. In addition, it needs four active satellites to estimate mobile device position. Recently, the minimization of drive test (MDT) powerful feature has been designed by telecommunication vendors based on standard LTE positioning protocol, but user equipment (UE) types limit it and subscriber privacy concerns. All these limitations led the researchers to investigate the position of the mobile device by other methods [17]–[19].

Many techniques had been proposed in the past to localize the mobile device based on network measurements to avoid the usage of the GPS. The most popular techniques that have been used with the fourth generation and with previous generations are the time of arrival (TOA) and time difference of arrival (TDOA) or observed time difference of arrival (OTDOA). Both are considered the signal's arrival time to geolocate the mobile device. Despite both the techniques having accurate geolocation, they are affected by multipath [20]–[24]. Another technique for mobile device geolocating in LTE network is enhanced cell ID (E-CID) [25], [26], which determines the distance based on just the coordinates of the serving cell. Therefore, this technique would not be met the requirements of the FCC. The angle-of-arrival (AOA) technique calculates the direction of the arrival signal from the mobile device. It can be done by calculating the time difference of arrival from antenna elements. Though this technique has acceptable accuracy, it is a costly technique needing some work, including installment and antenna configuration on the cells [24], [25], [27]–[29].

Recently, with the coming of the LTE network, the enhanced measured parameter timing advance (TA) has been used to estimate the location of the mobile device. In the past, with global system for mobile communication (GSM), TA was used in the 1990s; it had poor accuracy around 550-2,200 m due to poor performance in the early technology [14], [30], [31]. Currently, with the improvement and widening used for LTE cellular networks, TA has again gained consideration because of the timing constraint that enhances the resolution of the TA [32]–[34].

In this work, a new proposed approach seeks to estimate the coordinates of UE, which is called for any device connected to the users inside the LTE network within the two-dimensional plane. The approach relies on signal level measurements combined with propagation model predictions. The method is further enhanced with TA reports from the UE measurements and predictions are merged into a cost function whose minimum indicates the suggested UE position. This paper introduces the approach for seven scenarios via the different numbers of cells that arrived simultaneously by the UE simultaneous GPS reporting is utilized to compute the root mean square error (RMSE) between the actual GPS location and the proposed approach. The rest of the paper is outlined into Four sections. Following sections describe the research method that introduced in this article, then results and discussion, and concluding remarks.

2. METHOD

2.1. Dataset

The drive/walk test has been the classic technique to collect radio signal measurements in mobile network operators [18], [35], [36]. These measurements are used for coverage evaluation, operator benchmarking, and trouble shooting and optimizing cellular networks. The advantage of the driving test is the simultaneous recording of GPS coordinates, so every measurement is referenced to a precise location. In this paper, drive test measurements are used for validation of the proposed UE geolocation method. The environment selected for the driving test was an area in Atlanta, Georgia, USA. Radio frequency (RF) measurements are collected along the measurement route, approximately 20 kilometers long. The LTE measurement settings and cell configuration used in the algorithm are listed in Table 1.

Table 1. LTE measurement settings and cell configuration

Acronyms	Description
PCI	The cells are identified by Physical Cell Identity. It ranges between 0-503 unique identities with potential reuse over wider areas spanning more than 504 cells.
RSRP	Signal level measurement is gathered on reference sequence from serving and non-serving cells.
TA	The serving cell calculates and sends message by the MAC layer to the UE to ensure synchronized uplink reception.
Latitude/Longitude	Coordinates of the cells
Azimuth	The direction of antenna and calculated clockwise from north.
ERP	All cells have effective radiated power.

2.2. Algorithm description

In the proposed approach, UE coordinate estimation accuracy depends on the number of cells and sites reported simultaneously in a measurement report. This paper will cover seven scenarios, from a single cell to five cells from up to three sites. Regardless of the scenario, before algorithm deployment, the underlying region is divided into bins and each bin with 50 m. Multiple bins are grouped into cell coverage polygons determined by the predicted signal level according to the log-distance propagation models. The location polygon is a polygon that contains all the cells for which the mobiles will be located. The cell with the largest predicted signal level will claim a bin to the polygon:

$$\mathrm{SL} = \mathrm{EiRP\ (dBm)} + \mathbf{f}\,(\theta) - \mathrm{Pl(dB)} \quad (1)$$

where *Pl* is path loss according to log-distance propagation model, *f (θ)* is a function to calculate the antenna pattern to the appropriate gain, and the angle *(θ)* is the difference between the bin as viewed from the cell; the cell's azimuth as shown in Figure 1.

$$\theta = |\phi - \alpha)| \quad (2)$$

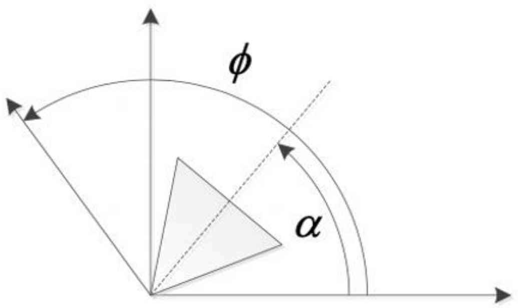

Figure 1. Geometry for calculation of Voronoi regions

Then, for each bin under consideration, the cost function is determined. The estimated location of UE will be the bin with a minimum cost function. The general form to calculate the cost function is (3),

$$G = \sum_{i=1}^{N} G_i^2 \quad (3)$$

where N is the number of cells reported simultaneously. Each individual cell cost is determined as (4),

$$G_i = \{[cos\emptyset_i - cos\alpha_i]^2 + [[sin\emptyset_i - sin\alpha_i]^2\}^{1/4} \quad (4)$$

where *R* is the distance between the evaluated bin and the cell, α_i is the azimuth for the i^{th} cell, and ϕ_i is the look angle from the i^{th} cell to the evaluated bin. The last part of the cost function is (5)

$$G_N = \sqrt{x^2 + y^2} - \hat{d} \quad (5)$$

where x_b, y_b are the coordinates for each bin under consideration,

$$\hat{d} = \min\,(d_0 10^{\left(\frac{RSLo - RSRP}{m}\right)}, 2d_0), \quad (6)$$

where $(\hat{d})$ is the estimated distance for UE location from the serving cell based on RSRP measurement from the dataset, m=40 dB/dec is the pathloss slope, and RSLo=-90 dBm is the reference for received signal level according to urban area [17]. Each Voronoi region has a centroid point, and the distance between this point and the cell is determined (d_0). A serving cell's radius should not exceed twice the distance between the centroid point and the cell 2 (d_0).

In the first approach, the UE search will be inside the coverage of the serving cell so that each bin belonging to the serving cell will be under evaluation. In the second approach, the TA parameters are used along with RSRP measurement to increase the accuracy of UE coordinate estimation. The TA unite in LTE 78.125 m. The distance between the serving cell and UE can be estimated by multiplying the TA index. TA parameter is used to calculate the mean distance d from the serving cell [32]:

$$\mathrm{d} = \mathrm{T.A} * 78.125\ \mathrm{m} \quad (7)$$

Using the TA parameter leads to a faster search limited to a TA ring instead of the entire area. Only the bins inside the TA ring width are a part of the search zone. The geometry for the scenarios considering the TA is depicted in Figure 2.

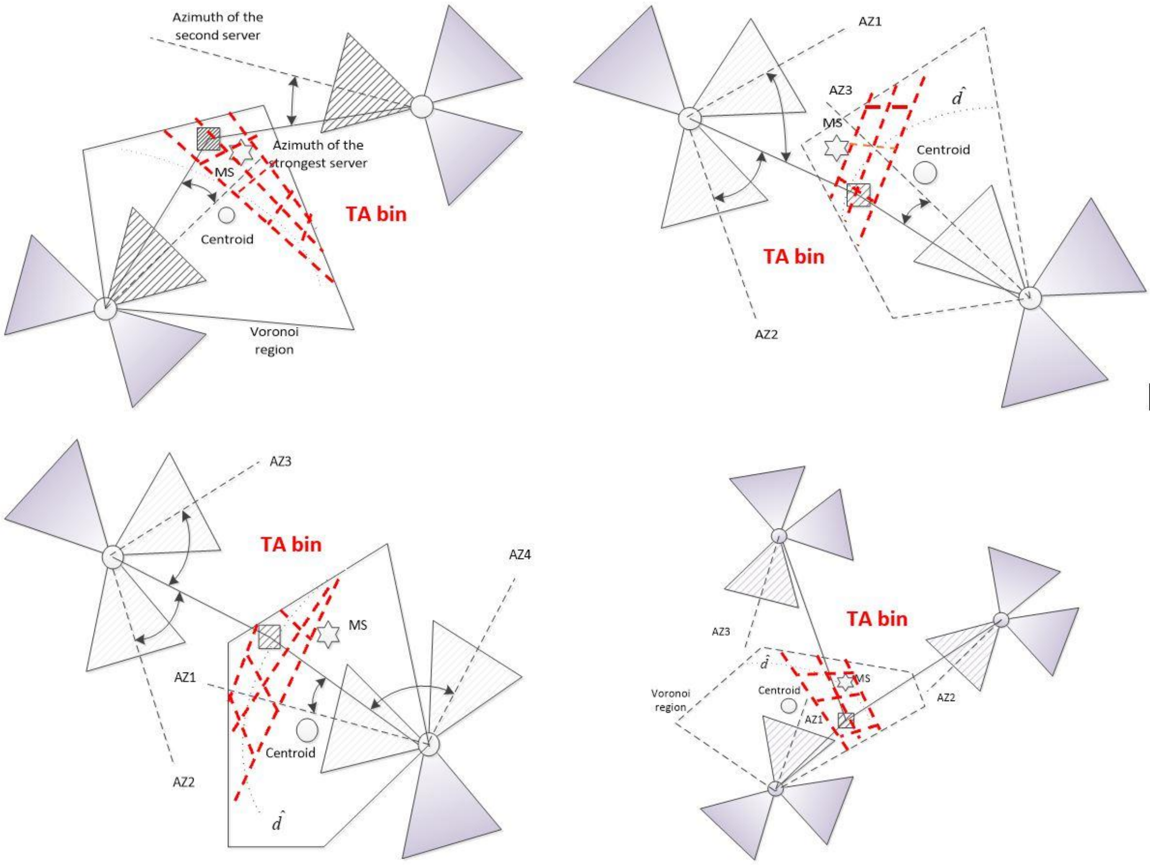

Figure 2. Geometry for case 3, 4, 5 and 6 with TA

In the last step, RMSE is determined between the estimated coordinates for the UE from the approach and the actual GPS measurement as:

$$RMSE = \sqrt{(y_m - y_e)^2 + (x_m - x_e)^2} \tag{8}$$

where x_m, y_m are the coordinates for the UE in GPS measured data and x_e, y_e are coordinates estimated by the algorithm. The geometry of different scenarios is depicted in Figures 3-8.

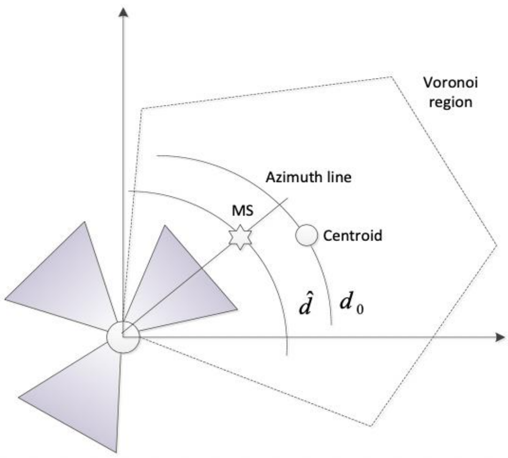

Figure 3. Geometry for case 1

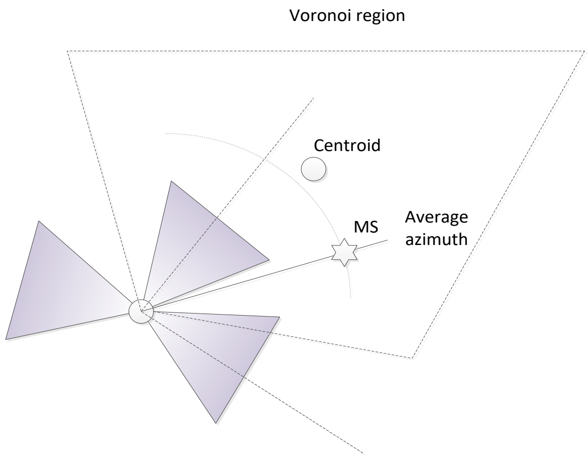

Figure 4. Geometry for case 2

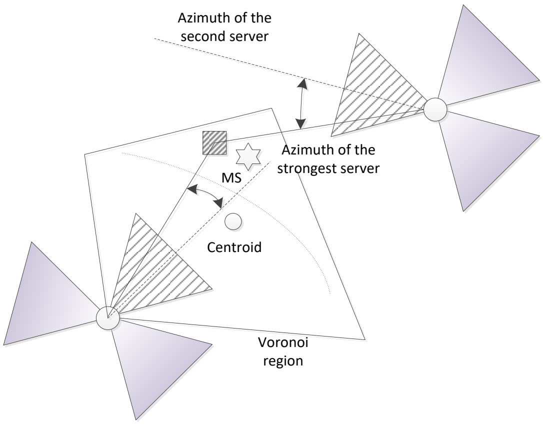

Figure 5. Geometry for case 3

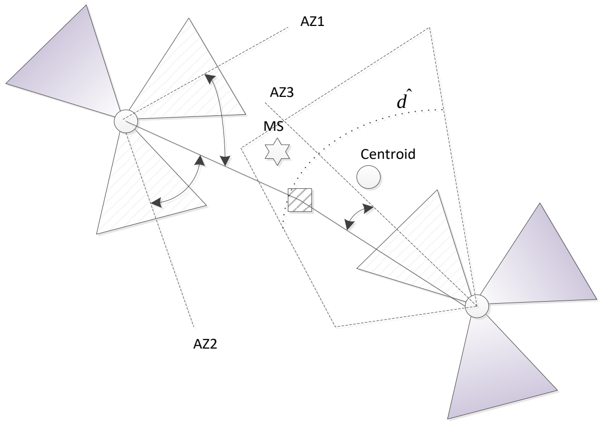

Figure 6. Geometry for case 4

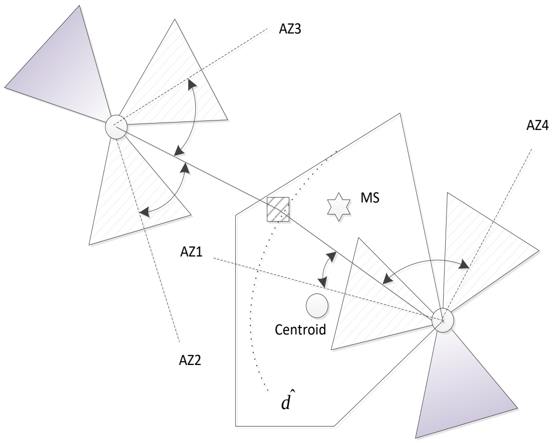

Figure 7. Geometry for case 5

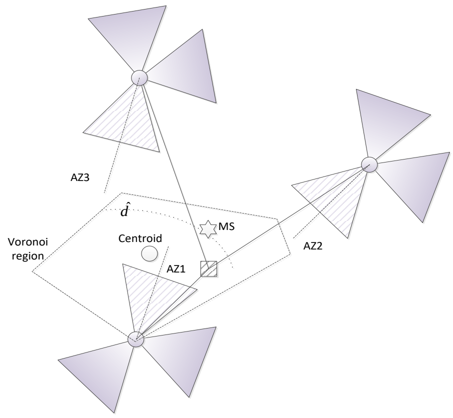

Figure 8. Geometry for case 6

3. RESULTS AND DISCUSSION

The geolocation algorithm explained in the previous sections has been implemented in MATLAB, with and without TA, both approaches used the same RSRP drive test measurements collected from an underlying operational LTE network in Atlanta, Georgia. This area is served by approximately 50 cells. The analysis results are summarized in Table 2. The primary metric has been the RMSE between the estimated and GPS UE coordinates. Both means and standard deviations are listed, along with relative improvement when TA is considered in the algorithm.

Table 2. RMSE errors for different scenarios

Cases	Mean (m) without TA	Mean (m) with TA	Improvement (%)	Std (m) without TA	Std (m) with TA	Improvement (%)
Case 1	286	191	33	165	112	32
Case 2	233	176	24	137	112	18
Case 3	223	150	32	90	85	6
Case 4	198	120	40	102	79	22
Case 5	185	93	50	66	43	35
Case 6	163	78	52	63	32	50

In the first scenario, labeled as case 1, with a single reported cell, the mean, and the standard deviation (std) of the RMSE is approximately 286 and 165 m, respectively, without using TA, while 191 and 112 m, respectively when using TA. The maximum position estimation errors do not exceed 700 m without TA, whereas the peak at 530 m with TA, as shown in Figure 9. CDF presents the probability of exceeding errors. 75 percentile errors with TA are within 200 m, while within 400 m without TA.

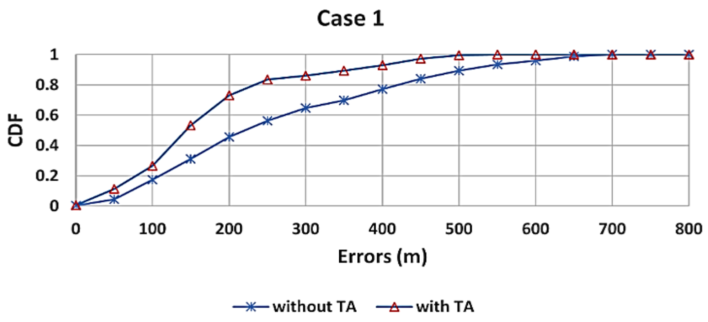

Figure 9. Case 1 probability of position errors with and without T.A

With two simultaneously reported cells from one site in the second scenario (case 2), the RMSE mean and the std is approximately 233 and 137 m, respectively, without TA, while 176 and 112 m, respectively, with using TA The maximum position errors without TA are 670 m, while T.A is 450 m, as shown in Figure 10. CDF in Figure 10 indicates a slight difference in errors; 40 percentiles are below 160 m without using the TA, while TA is below 100 m. In addition, 90 percentiles of the error are around 350 m with TA, which is better than 80 percentiles without TA for the same error.

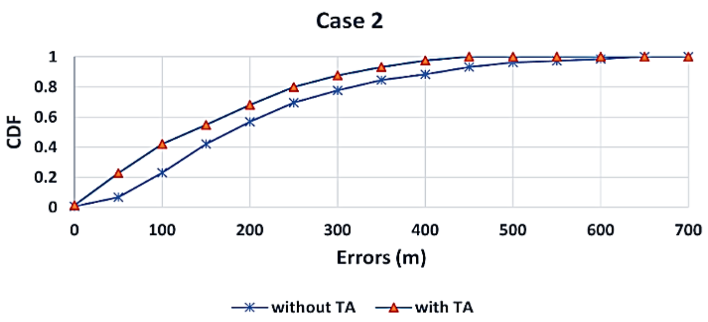

Figure 10. Case 2 probability of position errors with and without TA

In the third scenario (case 3), with two reported cells from different sites, the results show the mean and std are around 223 and 90 m, respectively, without using TA, while 150 and 85 m, respectively, with using TA Figure 11 shows the probability of position error less than 160 m is 60% with TA, when the same percentile of cumulative distribution function (CDF) belongs to 240 m without TA Also, the maximum position error without TA is less than 430 m, while with TA is below 330 m.

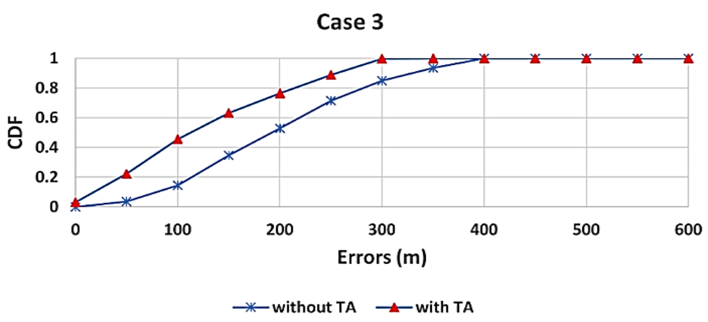

Figure 11. Case 3 probability of position errors with and without TA

In the fourth scenario (case 4), three reported cells simultaneously from two sites, the mean and std are around 198 and 102 m, respectively, without TA, whereas 120 and 79 m use TA CDF for this case presents 40 errors 150 m without TA, but 70 with TA is the same error shown in Figure 12. In addition, the maximum position errors are less than 400 and 290 without and with TA, respectively.

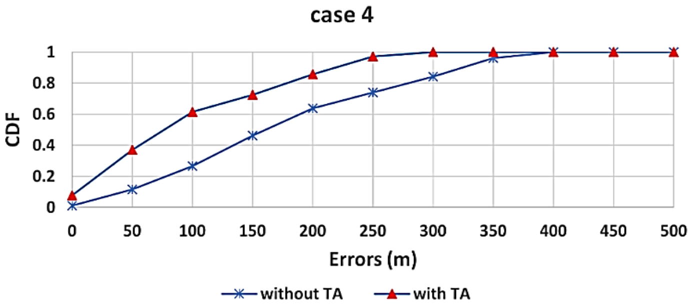

Figure 12. Case 4 probability of position errors with and without T.A

In the fifth scenario (case 5), with three reported cells from three sites, the results present that the mean and std is around 185 and 66 m respectively without using TA, while 93 and 43 m, respectively, using TA CDF in Figure 13 shows the significant difference in errors, 35% without TA is around 150 m when 90% corresponds to TA with the same error. Also, the highest position error is below 340 and 180 m without and with TA, respectively.

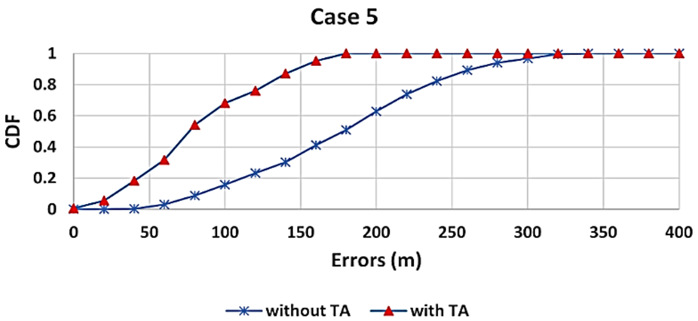

Figure 13. Case 5 probability of position errors with and without TA

In the sixth scenario (case 6), with four reported cells from two sites, the analysis result shows mean and std is around 163 and 63 m, respectively, without using TA, while 78 and 32 m, respectively, respectively, respectively, with using TA Figure 14 presents CDF for position errors, less than 100 m is approximately 80 % with TA, but 80 % without TA belongs to the errors around 220 m. Also, the highest errors were not more than 280 and 140 m without and with TA, respectively, in case 6.

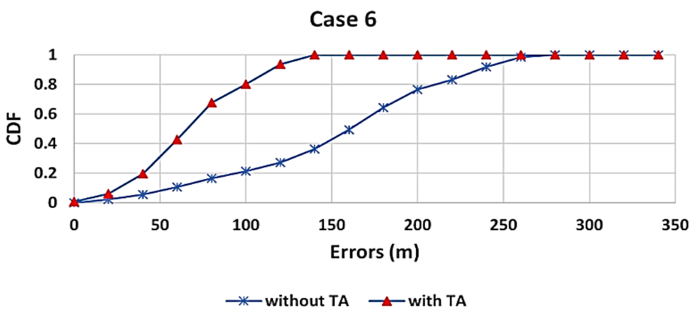

Figure 14. Case 6 probability of position errors with and without TA

In the seventh scenario (case 7), with five reported cells from up to three sites, the analysis results show mean and std is around 134 and 56 m, respectively, without using TA, while 70 and 33 m, respectively, with using TA The probability of errors, in this case, presents 95 % of errors around 200 m without TA, while 95% with TA is around 120 m, as shown in Figure 15. In addition, the highest position error is approximately 240 and 135 m without and with TA, respectively.

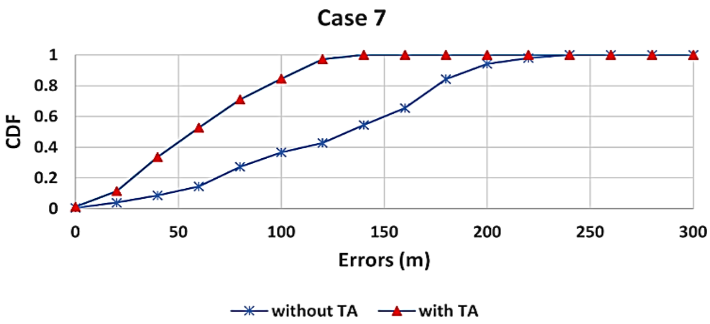

Figure 15. Case 7 probability of position errors with and without T.A

4. CONCLUSION

This paper intends to present an algorithm to estimate UE geographical coordinates without GPS. Instead, our algorithm is based on the drive test RSRP measurements paired with the received signal predicted by a simple propagation model. An algorithm is optionally enhanced with the timing advance for increased accuracy and convergence speed. The algorithm is evaluated via comparison with the GPS recorded during the same drive test that was used to collect RSRP measurements used in the algorithm. In practice, this geolocation algorithm can be deployed on UE measurement reports collected by cellular network OSS without needing the expensive and time-consuming drive test. The algorithm is investigated through seven scenarios, from one cell to five simultaneously reported cells on different sites. RMSE between the GPS and geolocated coordinates is calculated from the same measurement report used for geolocation to express the accuracy of estimation. As expected, accuracy increases with more cells reported simultaneously from more sites. Additional accuracy increase is achieved with the TA integrated into the algorithm to reduce search size and error with a TA ring.

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