Measurement-based Geolocation in LTE Cellular Networks

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Abstract— This paper proposes a new method to estimate location of active LTE cellular service users. The proposed method is based on Reference Signal Received Power (RSRP) measurements and the predicted cell serving area. It uses LTE measurements and cell information together with a simple prediction model for calculation and evaluation of the accuracy of the user equipment (UE) geo-location in two dimensions. The evaluation of the proposed work is compared in two cases depending on the number of sectors on the same site that UE simultaneously reports. The root mean square error (RMSE) is used for validation. The main result shows the location accuracy increases 20% when reporting two instead of one sector on the same site.

Keywords—Geolocation, LTE

I. INTRODUCTION

The number of LTE users increased between 2016 to 2017 from 1.7 to 2.5 billion and is anticipated to reach 3.5 billion in 2020 [1]. LTE has enabled true wireline-like broadband experience in mobile cellular communications, triggering worldwide explosion in the smartphone use. LTE network optimization activities greatly depend on UE geolocation to detect traffic hotspot and service-problematic areas, making an accurate and computationally fast geolocation method highly demanded in cellular industry.

In the United States, the FCC in 1996 mandated that all wireless communication operators provide highly accurate coordinates of cellular phones engaged in emergency calls (E911) to public safely answering points (PSAP). FCC requirement has been adapted to the final form in 1998 [2]. Many other countries have passed similar regulations for cellular geolocation. At the same time, many smartphone applications require activation of the internal GPS receiver, but such measurements are, in general, not available to network operators for optimization. Therefore, UE geolocation capability is still a challenge in fourth generation of cellular technologies, as it was in previous three generations [3].

Multiple techniques have been proposed in the past to estimate the UE location. They can be divided into two main categories: mobile-based and network-based techniques. Mobile-based techniques are identified by the use of GPS receiver built into every smartphone in the market today. GPS location is an accurate and straightforward technique, but is limited to outdoor users and requires explicit user's GPS receiver activation that rapidly drains UE batteries [4].

Therefore, the network-based techniques are still the default method. These techniques use network information and measurements to estimate the UE location. Several techniques have been proposed in the past, such as Enhanced CellID (E-CID), which depends on the cell of origin (COO), where the UE is located within the serving area of the reported cell [4,5]. The time-of-arrival (TOA) and time-difference-of-arrival (TDOA) techniques consider timing of the signal traveling from the UE to the base station to calculate the distance. Both TOA and TDOA methods obtain good geolocation accuracy [6-9]. However, these techniques are impacted by timing errors due to multipath.

The angle-of-arrival (AOA) technique estimates the angle of the RF signal arrival from the UE, as seen by the base stations. It could be measured by the difference of antenna array elements or by power spectral density through the antenna array (beamforming). However, this is a costly method requiring deployment and alignment of antenna arrays on the base stations [4,6,10]. Furthermore, RF fingerprint technique is proposed, also called database correlation method (DCM), which locates the UE by using the measurements made by the base stations. UE compares these measurements with already stored RF fingerprint in its library to estimate the location by matching with the stored references [4,5]. Researchers also proposed hybrid techniques to enhance the UE geolocation accuracy, such as the TDOA technique with round trip time (RTT) or the TDOA technique with received signal strength (RSS), along with AOA techniques [11-12].

The new method proposed here seeks to estimate LTE UE location within the two-dimensional latitude/longitude grid via algorithm based on received signal level measurements (RSRP). Measurements are paired with simple prediction model relying on antenna position and direction from known cell configuration. The algorithm is presented here for two simplest cases with varying number of sectors on the same site (one and two), simultaneously reported in measurements. GPS readings from the same measurement set are used to calculate the root mean square error between the actual GPS location and the algorithm-estimated location.

The rest of the paper is outlined into three additional sections. Methodology, including dataset, scenario and algorithm description, follows this introduction. Paper ends with result presentation, conclusion and a preview of future work.

II. METHODOLOGY

Drive and walk testing is a routine method for collecting RF received signal level measurements in all cellular technologies. These measurements are used for post-rollout verification, multi-operator benchmarking and network troubleshooting and optimization. Geolocation results presented in this paper have been obtained in an urban outdoor environment in Midtown Atlanta, GA, USA. The total length of the measurement route has been 20 miles. This area was chosen for drive-test LTE data collection using common drive testing measurement equipment and data collection software.

A. Dataset

Dataset includes RSRP measurements from drive-tests and underlying cell configuration from a major US LTE cellular operator. Dataset does not include potentially useful timing advance (TA) measurements from the network Operation Support Subsystem (OSS). TA measurements estimate distance between a UE and the serving base station, but activating TA increases network signaling load, so a simpler method has been developed bypassing TA data. The collected data, relevant for this study, is summarized in Table1 and cell configuration parameters in Table2

Table 1: Relevant LTE measurements

LTE measurement	Comment
Serving Cell PCI	LTE does not support soft handover, so UEs are served by a single cell. The serving cell is identified by its Physical Cell Identity (PCI). PCI may range between 0 and 503 allowing allocation of 504 unique PCIs before reuse becomes necessary.
Serving cell frequency	LTE is deployed in several frequency bands with potentially multiple deployed carriers from the same band. This parameter indicates the carrier frequency of the serving cell.
Serving cell RSRP	Received power measurements collected on the reference sequence of the serving cell. It is not subject to power control or load control and is continuously transmitted by every cell. It is the principal measurement type, used via different LTE radio resource management including mobility management (handover and reselection) algorithms.
Non-serving cell PCI	LTE measurement reports RSRP measurements from non-serving cells simultaneously with the serving cell. Non-serving cells are associated by their PCIs.
Non-serving cell RSRP	RSRP measurements from non-serving cells. It comes in a pair with a corresponding PCI.

Table2: Cell Configuration

Cell Configuration	Comment
Lat and *long*	Latitude and longitude of each sector
Cell Azimuth	Antenna centerline pointing angle measured clockwise from the North
Cell ERP	Effective radiated power for each sector
Cell PCI	PCI allocated to the each cell

PCI reuse might present an issue requiring source cell ambiguity resolution mechanism. However, the considered cluster did not have any PCI reuse, so that issue was not imposed. Refrencing PCI detected in measurement reports with the PCI from the cell configuration allows identifying the source of a non-serving cell measurements. Therefore, it is important for cell configuration to be up to date to ensure accuracy.

B. Algorithm Description

Estimation of the UE location varies depending on the number of simultaneously reported sites and cells. Two cases described in Table 3 are covered in this study:

Table3: Geolocation Cases

Reported cells	Reported sites	Description
$NSector = 1$	$Nsite = 1$	UE reports single sector
$Nsector = 2$	$Nsite = 1$	Two sectors belonging to the same site are reported simultaneously

Prior to the UE location estimation, the simulation setup is initialized. The area is divided into geographical bins with 50m bin resolution. Serving location polygons are pre-calculated for each cell to speed up calculations and limit the UE search areas. Location polygons are variations of Voronoi polygons centered at each active LTE cell. Each of the bins within polygon will be assigned to one of the cells in accordance with a simple received signal level (*RSL*) prediction algorithms. The cell with the largest *RSL* in the bin captures the bin adding it to it's location polygon. Simple log-distance propagation model is applied to determine the RSL for each bin:

$$RSL = ERP[dBm] + f(\theta) - PL[dB] \tag{1}$$

$$PL = \overline{PL} + 10m\log(d / d_{ref}) \tag{2}$$

d: Distance between the cell and the geographical bin
d_{ref}: Reference distance
m: Path-loss exponent slope
$\overline{PL}$: Median pathloss predicted at reference distance
$f(\theta)$: Function describing realistic antenna pattern.

Function $f(\theta)$ Is defined differently for sector and omnidirectional antennas. For sector antenna, pattern is modeled as:

$$f(\theta)=\begin{cases}10\log_{10}(\cos\left(\frac{n\theta}{\pi}\right)^2), & |\theta|\le\frac{\pi}{3}\\ -20, & |\theta|>\frac{\pi}{3}\end{cases} \quad (3)$$

where n is the number of sectors on a site (typically 3). This function closely approximates common antenna patterns for multi-sector cellular sites. For an omnidirectional site the antenna model function is set at a constant value $f(\theta)=0dB$. The argument of the antenna pattern function θ is the difference between the azimuth of the sector and the direction to each bin under evaluation.

In the second step, the centroid point for each cell coverage polygon is determined and distance between the strongest server and the centroid point is calculated. Then, the distance to the UE is estimated using the RSRP measurement from the strongest server and by using the azimuth and incident angle to determine the direction to the UE. This calculation will be described in Section III. With the distance and direction, UE location has been estimated.

By extracting actual location (GPS reading) for each measured point, the root mean square error (RMSE) can be computed between the estimated and the actual location:

$$RMSE=\sqrt{\left(UE_{my}-UE_{ey}\right)^2+(UE_{mx}-UE_{ex})^2} \quad (4)$$

where UE_{my}, UE_{mx}: are actual UE coordinates in measured data and UE_{ey}, UE_{ex}: the estimated coordinates.

III. LTE ALGORITHM FOR GEOLOCATION CASES

Estimating UE location depends on the scenario determined by the number of sites and sectors detected simultaneously in a measurement. This study will present two simplest cases from Table 3.

A. Case1

In this simplest case, the UE reports one single serving cell, as shown in Fig1. To locate the UE, the centroid point for the serving cell's Voronoi coverage region is computed. Distance $\hat{d}$ between the serving cell and UE is estimated using measured *RSRP* and by inverting equation for *RSL* as a function of distance and solving for distance:

$$\hat{d}=\min(d_0 10^{\left(\frac{RSL0-RSRP}{m}\right)}, 2d_0) \quad (5)$$

Where $\hat{d}$ is the estimated distance from the strongest server to the UE and d_0 is the centroid point for the pre-calculated serving area Voronoi region of the cell. RSL_o is the estimated received signal level at the reference distance d_o assumed at -90dBm. Pathloss slope was assumed at $10m = 40$dB/dec.

The estimated distance is limited to double Voronoi centroid point distance. Thus, if the calculated distance exceeded the predicted serving cell radius, the estimated distance will be limited to double distance from the strongest serving cell to the centroid point. Algorithm assumes serving cells is always the strongest.

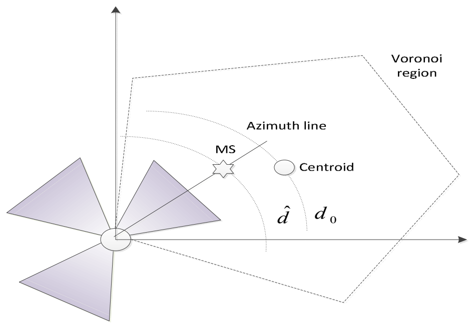

Figure1: case1

Estimated Cartesian UE coordinates become:

$$x_{mo}=\hat{d}\sin(\alpha) \quad (6)$$
$$y_{mo}=\hat{d}\cos(\alpha) \quad (7)$$

where α is the cell azimuth.

Relative shift in latitude and longitude degrees between the estimated UE location and the serving cell can be calculated as:

$$\Delta lon=\frac{x_{mo}}{R_E}\cos(Lat_{cell}) \quad (8)$$
$$\Delta lat=\frac{y_{mo}}{R_E} \quad (9)$$

where R_E =6378.14km is the approximate median radius of the Earth.

Finally, the estimated UE location is given by:

$$lat_m=Lat_{cell}+\Delta lat \quad (10)$$
$$lon_m=Lon_{cell}+\Delta lon \quad (11)$$

where lat_m, lon_m is the estimated location of UE and Lat_{cell}, Lon_{cell} are the cell coordinates retrieved from cell configuration provided by the operator.

B. Case2

In this case, the UE reports RSRPs from two sectors belonging to the same site, as in Fig2. To estimate the UE location in this scenario, the algorithm calculates the distance from the strongest server cell using the equation (5). The estimated azimuth of two reported cells is:

$$\alpha=\left\{\begin{matrix}\frac{\alpha_1(RSRP_1+125)+\alpha_2(RSRP_2+125)}{RSRP_1+RSRP_2+250}, \alpha_1-\alpha_2<180^\circ\\ \frac{(\alpha_1+360)(RSRP_1+125)+\alpha_2(RSRP_2+125)}{RSRP_1+RSRP_2+250}, \alpha_1-\alpha_2\ge180^\circ\end{matrix}\right\} (12)$$

where α_1, α_2 are individual azimuths and $RSRP_1, RSRP_2$ are signal levels [dBm] of two sectors reported in measurements. Individual azimuths are weighted by the RSRPs to bias estimated location towards the stronger cell. Constant offset of 125dB is applied to RSRP measurements in (12) to make azimuth weights positive, since -125dBm is expected as the lowest RSRP measured value. If lower signals are recorded, the offset should be increased.

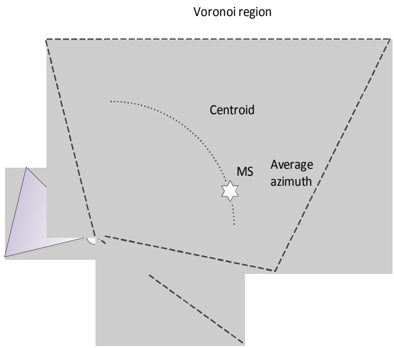

Figure2: Case2

Following the azimuth estimation, equations (6) and (7) are applied to determine coordinates x_{mo}, y_{mo} and equations (8) and (9) to compute Δlat and Δlon. Estimated UE location is finally given in equations (10) and (11), as in the case 1.

IV. RESULTS

Algorithm for LTE UE geolocation described in Section III has been implemented in MATLAB and evaluated using RSRP measurements and underlying cell configuration in an LTE network in Atlanta, focused on a cluster around Georgia Tech and Atlanta Botanical Gardens. In the single reported sector scenario (case 1), approximately 13500 applicable samples have been collected from a cluster of 21 sectors. Selected estimated geolocations are visualized in Fig3. GPS locations and algorithm estimations are shown together using different symbols.

Fig.4 quantifies the algorithm accuracy in the first scenario. The mean RMSE is approximately 406m with the standard deviation of 206m. The maximum position estimation errors are not exceeding 1km as shown in the top panel of the Fig4. The cumulative distribution function (CDF) in the bottom panel of the Fig 4 shows the probability of exceeding errors. Approximately 50% of errors exceed 350m (median) and 10% exceeds approximately 700m. This is a significant positional error, but scenario 1 is the most limited, with just a single sector reported. Therefore, in this scenario, algorithm is expected to just slightly improve accuracy from a simple UE location expected value, which is the center of the serving cell's Voronoi polygon.

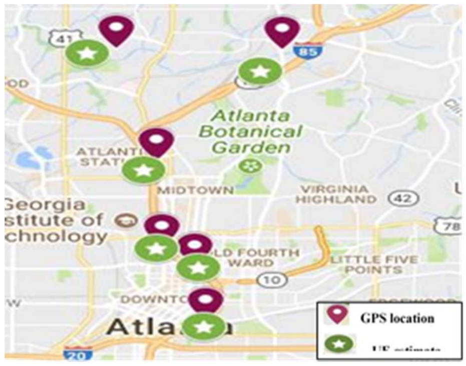

Figure3: Sample of selected estimated and GPS locations

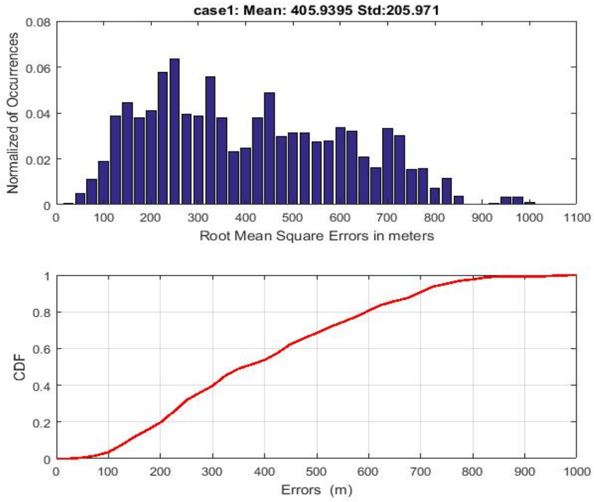

Figure4: Case1 error statistics

In the second scenario with two reported sectors on the same site, approximately 24000 applicable samples have been collected from 38 identified sectors. The error statistics is illustrated in Fig. 5. The mean RMSE has reduced to 324.6m and standard deviation remaining similar to the case 1 at 203m. The maximum position error is not exceeding 800m in this case. The CDF plotted in the bottom panel of Fig. 5 shows 50th percentile (median) at approximately 200m and 90th percentile below around 650m.

As expected, case 2 with two reported sectors from the same site, experiences lower measurement error that in case 1. Additional simultaneously-measured sector provides more information to the algorithm. Since in case 2 no additional cell positions are available from a co-site measured sectors, primary azimuthal accuracy is enhanced. Further enhancement is expected when additional sites are represented in measurements. These scenarios exceed the scope of this initial paper and will be reported in upcoming studies, including potentially extending the algorithm to include the timing advance reports.

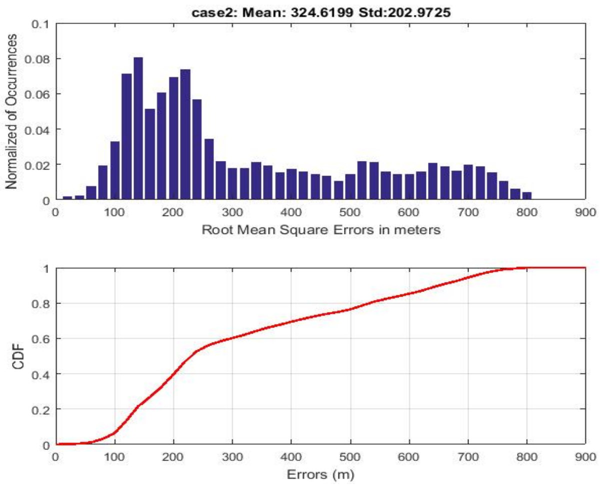

Figure5: Case2 error statistics

V. CONCLUSSION

In this paper, a simple algorithm has been proposed for estimating UE locations in LTE cellular networks. The algorithm uses LTE measurements and simple prediction model, together with basic cell configuration parameters, without relying on timing advance reports. Two scenarios are presented, with one and two simultaneously reported sectors on the same site. Measurement errors in these two most limiting scenarios do not significantly exceed reported measurement errors based on timing advance, indicating that combining timing advance with a simplest propagation modeling may further reduce geolocation error. In future work, algorithm will be extended to multi-site scenarios and potentially combined with timing advance in search of lowest UE geolocation error, as one of the important conditions for efficient cellular RF optimization.

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