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OBSERVED TIME DIFFERENCE OF ARRIVAL BASED POSITION ESTIMATION FOR LTE SYSTEMS: SIMULATION FRAMEWORK AND PERFORMANCE EVALUATION

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Точне місцерозташування користувацького обладнання (КО) має першорядне значення для надійної роботи послуг визначення місцерозташування, що надаються операторами мобільного зв’язку та іншими додатками, що з’являються. У даній роботі розглядається ефективність визначення місцерозташування мережі LTE на основі методу спостережуваних відмінностей за часом прибуття (OTDoA) з використанням мобільних пристроїв. Вимірювання різниці в часі між прийнятими сигналами (RSTD) оцінюються КО з використанням виділеного опорного сигналу визначення положення (PRS), що передається в кадрі низхідної лінії зв’язку, де результати вимірювання часу використовуються мережею для визначення місцерозташування. Представлена структура моделювання для оцінки визначення місцерозташування в мережах LTE, де реалізована низхідна лінія зв’язку LTE. Для реалізації OTDoA використовується кореляційний метод вимірювання часу прибуття. Структура моделювання надає різні конфігурації і налаштування системних і мережевих параметрів для оцінки ефективності визначення місцерозташування LTE з використанням OTDoA по багатопроменевим каналам з завмираннями. Для визначення впливу різних параметрів системи LTE і налаштування процедури визначення місцерозташування на точність визначення місцерозташування виконуються різні сценарії моделювання. Результати моделювання показали, що на точність визначення місцерозташування сильно впливає стан завмирання каналу, коли точність вимірювань часу прибуття погіршується в умовах сильного завмирання. Однак точність визначення місцерозташування може бути значно поліпшена шляхом збільшення послідовностей визначення місцерозташування, що беруть участь в процесі оцінки, або в частотній області, або в часовій області

Ключові слова: LTE, визначення місцерозташування, оцінка, OTDoA, час прибуття, кореляція, моделювання за методом Монте-Карло, мультілатерація, канали з завмираннями, геолокація

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1. Introduction

Far back to two decades, the first regulations by the Federal Communications Commission (FCC) in the United States of America and by the European Union (EU) concerning the availability and requirements to support location services in mobile cellular networks, especially for emergency calls, were the main drive to the tremendous development in the field of mobile location estimation [1, 2]. Recently the commercial applications (such as billing, marketing and social networks) that utilize the mobile positioning services have been increased rapidly and new technologies have to be adopted to cope with the demanding requirements of accuracy, reliability and availability of current positioning and navigation systems [3]. Nowadays, the Global Navigation Satellite Systems (GNSS) receivers that are available even in small and portable devices are used to offer the emerged positioning and location-based services. However, GNSS positioning performance can be highly deteriorated in non-nominal operating conditions such as dense urban and indoor scenarios where severe shadowing is expected. With the recent advances in cellular random access networks and core networks, new terrestrial localization technologies are emerged to complement and enhance the satellite-based navigation to realize anywhere anytime positioning system [2, 4].

Due to the inherently desirable features of long-term evolution (LTE) signals such as abundance, large transmission bandwidth, high-received power, signal diversity, and geometric favourability of transmitter location, the positioning methods that are based on the LTE signals have recently received considerable attention by the research community [5]. The LTE positioning protocol was initially included in the LTE release 9 specifications as a mandate by the FCC to achieve the requirements of the emergency calls. The positioning schemes in LTE systems can be broadly classified into two categories depending on whether they are using the LTE signal or other signals (e. g. satellite signal) for positioning purposes [1, 2].

The positioning protocols specified in the LTE release 9 are the network Assisted Global Navigation Satellite System (A-GNSS), Enhanced Cell ID (E-CID) and Observed Time Difference of Arrival (OTDoA). The A-GNSS belongs to the category where the positioning mechanisms do not rely on the network radio access signalling. However, it still suffers from longer time to first fix and shorter battery life for the device when compared to other protocols. The other two positioning protocols (i. e. E-CID and OTDoA) are relying on the radio access signal. E-CID is a positioning scheme that cooperates the geographical location (cell ID information) for the serving evolved Node B (eNB) of the User Equipment (UE). However, the cell size influences the estimation accuracy of E-CID and the attained positioning accuracy does not fulfill the specified requirements. The last positioning protocol defined in the 3GPP LTE release 9 is OTDoA that can be described as self-sufficing mobile positioning scheme for LTE networks. It is a geolocation technique that exploits the multilateration (hyperbolic lateration) to estimate the mobile position where the lateration computation can be performed either in the UE or the location sever in the core network. The multilateration is performed after the measurement of the difference in arrival times from multiple eNBs by the UE using the downlink dedicated positioning reference signals (PRS) [1, 5, 6].

The estimation accuracy is considered as an important metric in most of the applications. Hence, each one of the LTE positioning schemes can be optimized to certain environments and conditions. It is worth mentioning that the uplink version of OTDoA (network-based) is defined in LTE release 11 [3, 7]. Although seamless mobile devices integration is feasible, location measurement units should be equipped in each base station, therefore accurate data may not be available to the public.

Therefore, studies are needed that are devoted to improving the OTDoA performance and to increasing the precise time delay measurements that's because OTDoA is considered as a potential positioning scheme for LTE systems and the most accurate positioning protocol universal to all mobile devices.

2. Literature review and problem statement

In the literature, the OTDoA topic received considerable attention by the researcher in the field to analyze, optimize and quantify the positioning performance in different systems. The researchers in [6] considered linear least squares, nonlinear Gauss-Newton and Levenberg-Marquardt to solve the OTDoA position estimation problem. The performance is benchmarked using the Cramer-Rao lower bound (CRLB) analysis. The root mean square error (RMSE) is used as a metric to compare the considered solutions. However, the channel model used in [6] is trivial where the urban macro line of sight (LOS) path loss mode is used. The fusion of global positioning system (GPS) data with OTDoA has been investigated in [4] to achieve the necessary positioning accuracy for guidance and navigation applications. The OTDoA positioning error is characterized as a cumulative density function curve. However, the Gaussian distribution is used for modelling the accuracy of OTDoA. In addition, it was shown in [4] that relying on OTDoA is not yet a good sole of positioning for the considered application. While the joint ToA and DoA algorithm is presented in [5]. The performance of LTE positioning over typical multipath fading channels is considered in [8, 9] while the error analysis in the position estimation by resolving the first arrival path of the channel is presented in [10, 11]. It was shown that using the first path detection improves the positioning performance in multipath fading environment, however; the effect of LTE system and OTDoA parameters on the mitigation of performance deterioration due to channel selectivity is not identified. The baseline performance of position estimation for 3D MIMO system in indoor environment has been discussed in [12, 13]. The OTDoA positioning strategy has been investigated in [14–16] for employment in NB-IoT systems, however, several challenges have been identified such as the low sampling rate and poor PRS correlation characteristics that results in severe performance degradation [17]. In order to improve the performance, successive interference cancellation technique is used by estimating the channel taps. As discussed above, different aspects of OTDoA scheme have been investigated in the literature, however, the effect of channel severity on the positioning accuracy with performance evaluation with different LTE system parameters will be discussed in this paper.

3. The aim and objectives of the study

The aim of this paper is to identify the influence of various parameters on the positioning accuracy and the strategies that can be used to improve the performance over different channel models. To achieve that, simulation framework for OTDoA based position estimation in LTE networks is implemented using Matlab such that different configurations for the system and estimation algorithm parameters can be investigated and the following objectives are accomplished:

– study the maximum likelihood ToA estimation mechanism based on the correlation of reference signals;

– comprehensive simulation tests are conducted to study the effect of various parameters on the positioning accuracy with different selectivity levels;

– the parameters that have the most effect on the positioning performance are identified.

4. Multilateration based OTDoA positioning method

The basic principle of multilateration (trilateration) exploited by OTDoA scheme that is standardized in LTE as a downlink positioning method to determine the mobile location is depicted in Fig. 1. The OTDoA positioning depends on the measurements of the time differences between at least three hearability (hearability is defined as the capability of UE to hear or receive the downlink reference signals from multiple distinct locations, i. e., base stations even in the presence of close and strong interfering cells). The reference signal time difference (RSTD) is measured by the mobile device which refers to the timing difference in receiving two subframes from different cells, one is the reference cell and the other is the measured cell [2, 4].

The method of trilateration (also called the hyperbolic technique where at least three OTDoA measurements are required from an adequately scattered and geographically apart hearable base stations) for two-dimensional position estimation of the mobile device converts the time differences measurements to a set of points with the same time difference for a pair of cells. Hence, the estimation problem can be formulated as hyperbolic equation. The mobile device measures the time of arrival (ToA) in receiving the reference signal transmitted in the downlink frame from multiple base stations as shown in Fig. 1. The OTDoA is formulated by subtracting the ToA from several neighbour base stations. At least three base stations are involved in the OTDoA positioning method and two of the three RSTD measurements denoted as $\tau_{1,2}=\tau_1-\tau_2$, $\tau_{1,3}=\tau_1-\tau_3$ and $\tau_{2,3}=\tau_2-\tau_3$ can formulate two intersecting hyperbolic functions. The multilateration approach by which the intersection of two hyperbolic equations (corresponds to two of the three RSTD measurements) is the estimated location of the mobile device [1, 4, 6].

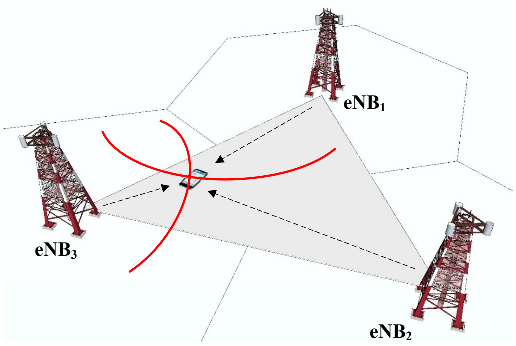

Fig. 1. Multilateration based Position Estimation

Assuming that the mobile device located at (x,y) has a priori knowledge of the positions of all surrounding base stations in the operating areas located at (x_1,y_1), (x_2,y_2) and (x_3,y_3), all the base stations are synchronized with each other. The least square solution of the system of equations given below in (1) represents the 2-dimensional coordinate estimation of the mobile position.

$$\sqrt{(x_1-x)^2+(y_1-y)^2}-\sqrt{(x_2-x)^2+(y_2-y)^2}=d_{1,2},$$

$$\sqrt{(x_1-x)^2+(y_1-y)^2}-\sqrt{(x_3-x)^2+(y_3-y)^2}=d_{1,3},$$

$$\sqrt{(x_2-x)^2+(y_2-y)^2}-\sqrt{(x_3-x)^2+(y_3-y)^2}=d_{2,3}, \qquad (1)$$

where $d_{1,2}$, $d_{1,3}$, $d_{2,3}$ represent the equivalent ranges of the RSTD measurements $\tau_{1,2}$, $\tau_{1,3}$ and $\tau_{2,3}$, respectively. From the system of equations given in (1), it is obvious that the base stations location and the estimated time offsets are required to find the location of the mobile device. However, the OTDoA measurement should be acquired only from selected base stations so that the estimation problem results in a unique solution where only one intersection exists for two branches of the distinct hyperbolas. It is a common practice to use more than three measurements to ensure reliable and accurate estimation. In addition, the uncertainty in the mobile position estimation is due to the inaccuracies in the estimation of $\tau_{1,2}$, $\tau_{1,3}$ and $\tau_{2,3}$ as the timing offsets estimation is not a trivial task at the required level of accuracy [2, 4, 16].

An approximate maximum-likelihood closed-form and non-iterative solution to the multilateration OTDoA position estimation is given as [18],

$$\begin{bmatrix} x \\ y \end{bmatrix}=\begin{bmatrix} x_{2,1} & y_{2,1} \\ x_{3,1} & y_{3,1} \end{bmatrix}^{-1}\times\left\{\begin{bmatrix} d_{2,1} \\ d_{3,1} \end{bmatrix} r_1+\frac{1}{2}\begin{bmatrix} d_{2,1}^2-k_2+k_1 \\ d_{2,1}^2-k_3+k_1 \end{bmatrix}\right\}, \qquad (2)$$

where

$$k_1=x_1^2+y_1^2,$$

$$k_2=x_2^2+y_2^2,$$

$$k_3=x_3^2+y_3^2.$$

The above mathematical procedure given in (2) to solve the nonlinear equations given in (1) is capable of achieving optimum performance for arbitrarily placed sensors and valid for both distant and close sources.

5. Positioning Mechanism in LTE using OTDoA

The positioning scenario in LTE systems using OTDoA usually starts by checking the UE capability to perform the OTDoA multilateration based estimation. The location server shown in Fig. 2 provides assistant data to facilitate the positioning procedure.

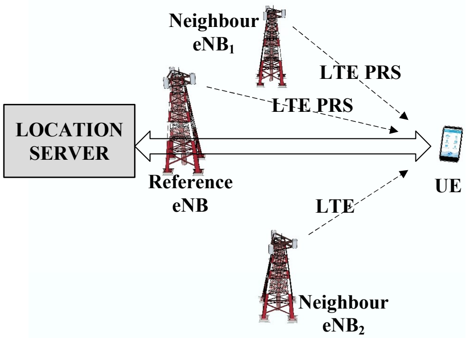

Fig. 2. OTDoA Position Estimation Mechanism in LTE

The information about the nearest base stations cell-ID, PRS information, slot number offset and PRS-subframe offset are provided to proceed with the positioning procedure. The eNBs transmit positioning reference signals (PRS) in the physical layer (no higher layer interpretation) to the UE in order to perform the required time difference measurements. The PRS are generated using orthogonal sequences so that the hearability of the UE will improve through isolating the PRS signals transmitted by other eNBs in the code domain. The BS responsibility is mapping the logical antenna port to the physical transmit antenna. The use of specially designed PRS signals enhances the precision and availably of the positioning. The RSTD is measured by the UE and reported back to the location server in order to find the geographical position using multilateration [1, 4].

5. 1. Positioning Reference Signals (PRS)

In LTE, the positioning reference signal is defined as pilot sequences specially designed for positioning requirements. The management of interference between the pilots and data is attained by avoiding the transmission of the data on the subframes allocated for positioning purposes, while the essential physical downlink control channels (PDCCH) and cell-specific reference signals (CRSs) are maintained similar to other subframes. In order to avoid the time-frequency collision, cell-specific frequency shift is utilized to prevent the interference up to six neighbouring cells [14, 19]. The positioning occasion is configured such that the PRS is transmitted periodically in the downlink subframes by setting the main parameters (PRS bandwidth, PRS periodicity, power allocation, consecutive subframes, PRS pattern, PRS sequence). The mapping of the PRS sequence (generated for a specific time slot and drawn from complex-valued QPSK constellation) on the resource elements of the radio frame over a time-frequency pattern is shown in Fig. 3 with shifts in the frequency domain and time domain to realize low interference structure. Defining $N_{\text{RB}}^{\max,\text{DL}}$ as the maximum number of downlink resource blocks (RBs) allocated for the PRS, the PRS sequence for the l^{th} orthogonal frequency division multiplexing (OFDM) symbol within the n_s^{th} time slot in the radio frame is given by:

$$r_{l,ns}(m)=\frac{1}{\sqrt{2}}\left(1-2c[2m]\right)+j\frac{1}{2}\left(1-2c[2m+1]\right), \tag{3}$$

where $m=0,1,\ldots,2N_{\text{RB}}^{\max,\text{ DL}}-1$ and $c[.]$ denotes length-31 Gold sequence pseudo-random number generator.

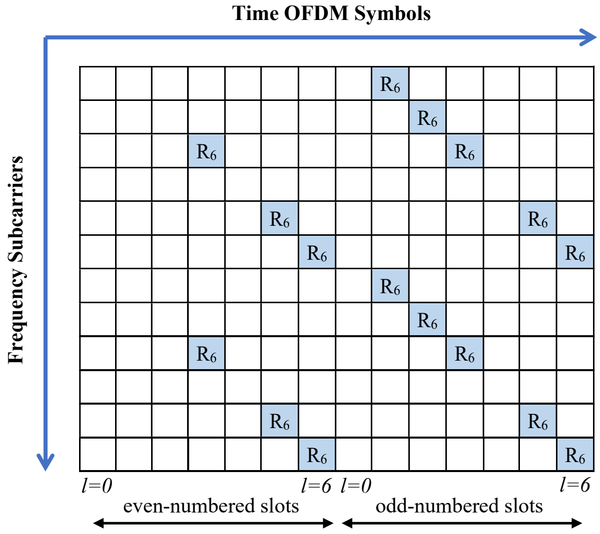

Fig. 3. Mapping of PRS (normal cyclic prefix) within physical resource block (PRB) in existing LTE networks [20]

The PRS is mapped to RBs to produce the transmitted signal sequence $R_{l,ns}$ in the frequency domain over the kth subcarrier.

$$R_{l,n_s}(k)=\begin{cases} r_{l,ns}(m) & \text{if there is } m \text{ mapped to } k,\\ 0 & \text{otherwise,}\end{cases} \tag{4}$$

where N denotes the number of subcarriers in the OFDM symbol.

5. 2. Signal Model

The frequency domain samples $R_{l,n_s}(k)$ where

$$k=0,1,2,\ldots N-1$$

are modulated over N subcarriers using OFDM modulation by employing Inverse Fast Fourier Transform (IFFT). After applying N-point IFFT, the n^{th} sample of the time-domain transmitted OFDM is given as:

$$x_{l,n_s}(n)=\frac{1}{\sqrt{N}}\sum_{k=0}^{N-1}R_{l,n_s}(k)e^{\left(j\frac{2\pi kn}{N}\right)}. \tag{5}$$

The cyclic prefix (CP) is formed by copying the last G samples (typically greater than the channel length L) of time domain OFDM symbol and appending them in front of the IFFT output in order to prevent the loss of subcarriers' orthogonality and to eliminate the inter-symbol interference (ISI) among the OFDM symbols. Hence, the complex baseband signalling of l^{th} OFDM symbol within the n_s^{th} time slot is given by:

$$x_{l,n_s}=\begin{bmatrix} x_{l,n_s}(N-G),x_{l,n_s}(N-G+1),\ldots\ldots,\\ x_{l,n_s}(N-1),x_{l,n_s}(0),x_{l,n_s}(1),\ldots\ldots,\\ x_{l,n_s}(N-1)\end{bmatrix}. \tag{6}$$

The baseband OFDM symbol of length $(N+G)$ samples is passed through a digital-to-analog converter (DAC) and up converted to a radio frequency centred at f_c then transmitted passing through multipath fading channel. Taped delay line model of the multipath channel is given as [2, 19]

$$h(t)=\sum_{l=0}^{L-1}h_l\delta(t-\tau_l), \tag{7}$$

where L is the length of the channel, h_l is the path gain, τ_l is the delay for each path which is related to the time of arrival (ToA) and $\delta(t)$ is the dirac-delta function. The received signal $y(t)$ is given as,

$$y(t)=x(t)*h(t)+w(t), \tag{8}$$

where $x(t)$ is the transmitted signal, $w(t)$ is the zero-mean complex additive white Gaussian noise (AWGN), and $*$ represents convolution. Channel samples representing the channel impulse response (CIR) of the multipath fading channel are collected into a vector of complex numbers denoted as

$$h_{l,ns}(n)=\left[h_{l,ns}(0),h_{l,ns}(1),\ldots,h_{l,ns}(N-1)\right],$$

where $h_{l,ns}(n)=0\ \forall n\geq L$ and $L<G$. The channel taps are zero-mean correlated circulaerly symmetric complex gaussian variables, i. e. $h_{l,ns}(n)\sim CN\left(0,\, p_{l,n_s}(n)\right)$, and $p_{l,n_s}(n)$ is the power of the n^{th} channel tap. At the receiver front-end, the received signal $y(t)$ is converted to discrete-time signal by an analogue-to-digital converter. The received sequence denoted as $y_{l,n_s}(n)$ after the matched filtering and sampling at F_s is given as [16, 19],

$$y_{l,n_s}(n)=\sum_{i=0}^{L-1}h_{l,n_s}(i)x_{l,n_s}(n-\tau_i)+w_{l,n_s}(n), \tag{9}$$

where $n=0,1,2,\ldots.$, τ_i is the time delay of the l^{th} tap of the channel impulse response, the parameter related to the ToA, and $w_{l,n_s}(n)$ denotes the system noise which is modelled as a white Gaussian process with zero mean and variance

$$\sigma_w^2=E\left[\left|w_{l,n_s}(n)\right|^2\right].$$

5. 3. Time of Arrival Estimation

In this section, reference signals aided maximum likelihood (ML) estimation for the starting point of the received signal to predict the ToA is discussed. Assuming flat fading channel, the maximum likelihood method for time of arrival estimation is optimum in the sense of the likelihood of the estimated parameters has asymptotic properties of being unbiased and achieving the Cramer-Rao Lower Bound (CRLB). Therefore, it will be considered in this paper. The reference signals such as PRS sequence are embedded in the transmitted frames during the positioning occasion and the received signal is passed through the channel with propagation model given as,

$$h_{l,n_s}(t)=h_0\delta(t-\tau_0), \tag{10}$$

where h_0 is the complex gain of the channel and τ_0 is the ToA.

The target of ToA procedure is to estimate the time delay (τ_0) introduced by the channel using the maximum likelihood scheme. Using the flat fading channel model, the derivation of the ML estimator results in the correlation based estimator [19]. When the channel is multipath fading channel, the other paths affect the timing estimation of the first path by introducing interference that results into notable biased estimate. Therefore, the ML criterion can be considered as correlation profile based estimation criterion for detecting the first path arrival of the received signal that allows ToA estimation. The correlation profile based estimation can be implemented either in the time domain or in the frequency domain (by exploiting the FFT operation as depicted in Fig. 4).

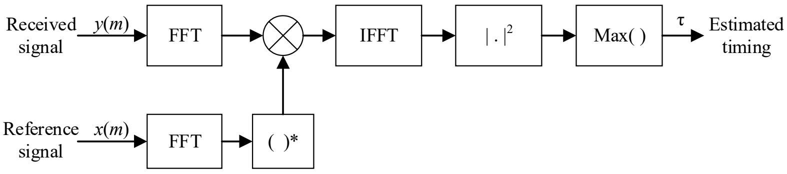

Fig. 4. Efficient implementation of the correlation based ToA estimation [19]

In the time domain, the ML timing estimation is based on computing the correlation between the received signal and locally generated template given as [2, 19]

$$R(t)=\sum_{l=0}^{N_{symb}-1}\sum_{n=0}^{N-1} y_{l,n_s}(n+t)\,x^{*}_{l,n_s}(n),\ t\in[0,W-1], \tag{11}$$

where $y_{l,n_s}(n)$ denotes the received signal, $x^{*}_{l,n_s}(n)$ is a copy of the transmitted signal locally generated by the UE, W is the search window size of 2G sample and N_{symb} is the number of OFDM symbols used to estimate τ_0. It is straightforward to write the correlation of the ToA estimation as [2, 19]

$$R(t)=P_s\sum_{l=0}^{N_{symb}-1} h_l\gamma(t-\tau_l)+w(t), \tag{12}$$

where P_s is the power of the transmitted signal x_{l,n_s}, $\gamma(t-\tau_l)$ is the normalized autocorrelation function of the reference signal and $w(t)$ is the noise term with variance σ^2. Assuming that the PRS sequence has ideal autocorrelation characteristics with unity transmission power then (12) can be written as

$$R(t)=\sum_{l=0}^{N_{symb}-1} h_l(t-\tau_l)+\varphi(t), \tag{13}$$

where $\varphi(t)$ is a term that captures the effect of noise and correlation interference.

In order to estimate the time delay of the first arrival path τ_0, non-coherent estimation is employed as the channel is unknown at the receiver with the assumption of constant channel over the observation interval. In LTE systems, the positioning occasions NPRS refer to several consecutive subframes embedded with PRS sequences. Hence, the correlation profile can be averaged over multiple subframes (i. e. NPRS position occasions) in order to reduce the noise effect on the estimation process [15, 16, 19]

$$\Lambda(t)=E\left\{\left|R(t)\right|^2\right\}. \tag{14}$$

The time index of the earliest detected peak in the correlation profile, which corresponds to ToA of the signal travelling through direct propagation path can be estimated by searching for the maximum of the correlation profile as [2, 9]

$$\tau_0=\arg\max_t \Lambda(t),\quad t\in[0,W-1]. \tag{15}$$

After estimating the ToA for the signal transmitted from different cells, OTDoAs are computed taking one of the cells as a reference. Then OTDoA is given by:

$$\Delta\tau_0^{iR}=\tau_0^{i}-\tau_0^{R}, \tag{16}$$

where τ_0^R and τ_0^i denote the estimated ToA for the reference cell and the i^{th} cell respectively.

It is worth mentioning that when the channel is flat fading (i. e. line of sight scenarios), the above ML correlation based estimator provides sufficient accuracy. However, the estimation accuracy may be affected when the channel is multipath especially when the first arriving path is not the strongest path. Therefore, in dense multipath environment, sophisticated processing for the correlation profile is required to mitigate the effect of late arriving paths. In addition, for an efficient implementation of the correlation, the frequency domain based approach using FFT can be efficiently realized as illustrated in Fig. 4.

6. Simulation Framework:
Positioning Parameters Exploration

The simulation framework for LTE positioning using OTDoA technique is depicted in Fig. 5. In this paper, the parameters affecting the performance of positioning methods are introduced in the simulation model, therefore parameters exploration can be simulated easily to provide the designer with an insight into the positioning errors for different parameters setting. The simulation framework starts with LTE network deployment where different topology models can be simulated. In Fig. 6, LTE network with 16 macro sites each having 3 cells, hexagonal grid with an inter-site distance of 500 meters. In addition, in order to evaluate the positioning performance and obtain reliable positioning estimation, the UE position is randomly distributed over the deployed network. In the simulation framework, after selecting the system bandwidth with the corresponding sampling rate and FFT size, the resource grid for each eNB is configured. The positioning reference signals are generated from length-31 Gold sequences and mapped on the specified resource grid with certain setting for PRS bandwidth, periodicity and positioning occasions as illustrated in Table 1.

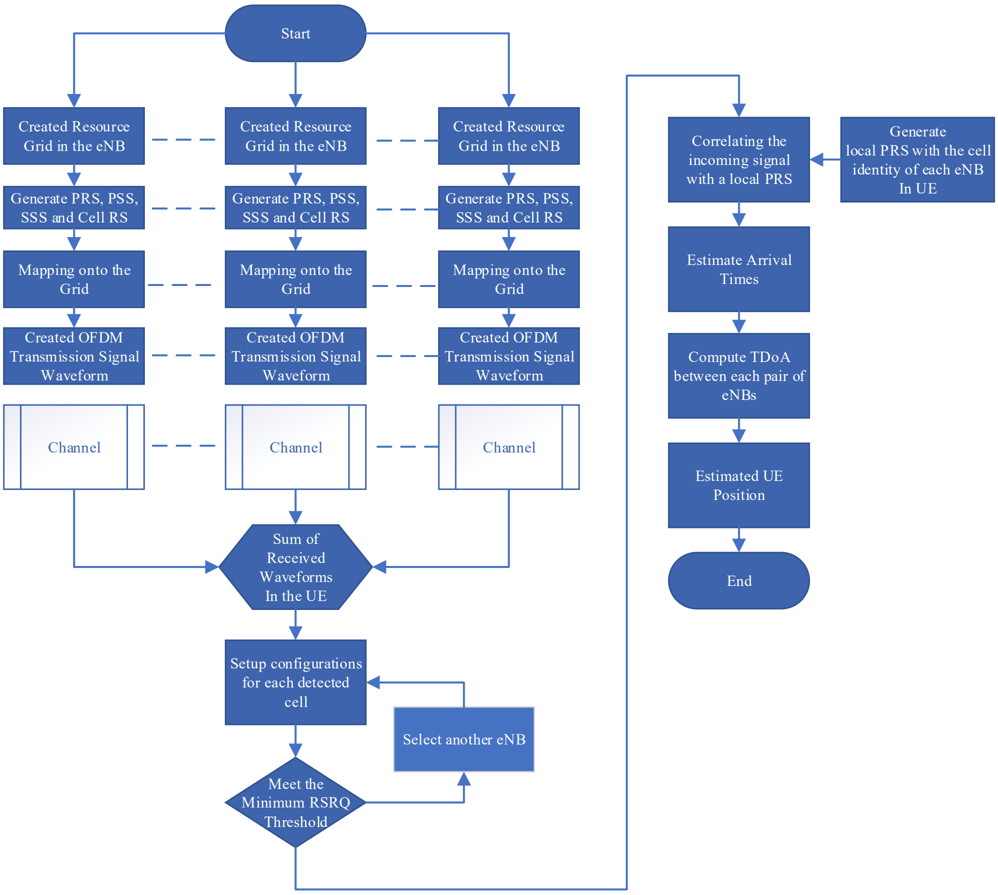

Fig. 5. Simulation Framework of OTDoA based LTE position estimation

Table 1

Simulation Framework Parameters Configuration

Parameter	Value
System bandwidth	10, 20 MHz
Sampling Rate	15.36, 30.72 MHz
FFT points	1,024, 2,048
Number of consecutive PRS subframes	1, 2, 4, or 6
PRS Resource Blocks	6, 15, 25, 50 or 100
PRS bandwidth	1.4, 3, 5, 10, 15 and 20 MHz
PRS periodicity	160, 320, 640 or 1,280 ms
Positioning occasions	1
PRS pattern	6-reuse in frequency
PRS sequence	Length-31 Gold sequence
Number of e-NodeBs	16
Inter-cite distance	500 m
Carrier frequency	2.1 GHz
Channel model	AWGN, EPA, EVA, ETU
Number of eNB and device antenna	1
PRS Muting	False
Normalized residual FO	Uniformly drawn in [−0.03, 0.03]
Duplex mode	FDD
Cyclic prefix	Normal
Channel bandwidth	10, 5 and 1.4 MHz
UE speed	3 km/h, 5 km/h
PRS power boosting	0 dB
PRS duration	1 ms

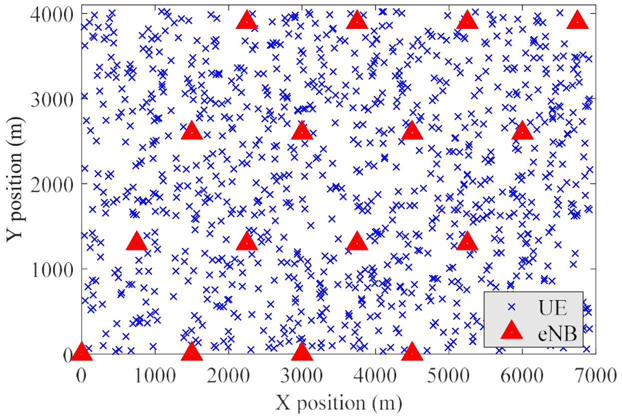

Fig. 6. Simulation framework deployment of UE and eNBs

The frequency domain reference sequences are transformed to time domain using OFDM modulation. The communication link between the eNB and UE is modelled as multipath fading channel. The UE receives the signal from the neighbouring cells, however, only cells with minimum reference signal received quality (RSRQ) are selected to be involved in the positioning process. The strong signals from a certain cell can increase the accuracy of the positioning performance as more ToA estimates are collected for OTDoA while weaker signals from faraway base station renders more errors in the estimation and hence degradation in the accuracy of the positioning. The locally generated PRS for each eNB is correlated with the received signal for ToA estimation from each eNB. The simulation model can be configured to perform the correlation over one or multiple OFDM symbols in addition the correlation profile can be averaged over several subframes for more accurate estimation of the time offsets. Finally, the OTDoA procedure described in section 4 is used to estimate the UE position. The system parameters for the simulation framework are summarized in Table 1.

7. Performance Evaluation and Simulation Results

The performance assessment of OTDoA based mobile positioning for LTE networks simulated using the framework presented in the previous section with the investigation of different parameters setting shown in Table 1 will be discussed in this section. The positioning accuracy is numerically evaluated in terms of cumulative distribution function (CDF) of the error measured using the distance between the actual and estimated position of the UE while the mean square error (MSE) metric is used to evaluate the performance of ToA estimation. The performance is evaluated over AWGN and the multipath frequency selective fading channels with various system parameters configuration. The channel models used in this paper are the following: extended pedestrian A model (EPA), extended vehicular A model (EVA) and extended typical urban model (ETU) [21]. In the simulation framework, the positioning results are generated by averaging the error over 10,000 Monte Carlo simulation trials.

The ToA estimation represents an essential task for multilateration based positioning methods. To assess the estimation accuracy and quantify its effect on the OTDoA positioning, the simulation framework is configured with the following parameters, LTE bandwidth, 10 MHz (50 Resource Blocks), PRS bandwidth, 1.4 MHz (NPRS=6) and number of subframes=2. The PRS correlation method is used to estimate the ToA as described in section (3.5). The correlation profile is presented in Fig. 7 where the maximum correlation exhibited when the time delay of the correlation leg is equal to the actual ToA. Therefore, the ToA can be estimated by searching for the peak of the correlation profile and the corresponding sample delay is converted to time delay based on the sampling rate of the system. The MSE of ToA estimation versus the single-to-noise ratio (SNR) over different channel models is presented in Fig. 8. For AWGN channel, the MSE of the ToA estimation decreases as the SNR increase as the correlation-based method corresponds to maximum-likelihood estimation. Hence, for AWGN channel, sufficient accuracy is provided where MSE is about 0.03 samples when SNR=10 dB. When the channel is multipath fading (EPA, EVA and ETU), the MSE starts to saturate as the SNR is increased achieving approximately MSE of 0.2, 1.9 and 4 samples for the three channel models, respectively. As the correlation method is based on searching for the peak of the correlation profile, biased estimation is resulted when the channel is multipath fading. The degree of channel selectivity severely affects the estimation accuracy as presented in Fig. 8 where the EPA shows less degradation in terms of MSE performance when compared with the EVA and ETU channels.

The positioning performance in terms of CDF of the positioning error for OTDoA is shown in Fig. 9. The simulation framework is configured with the same parameters used in Fig. 8 and the simulation results are generated for the considered channel models with SNR=0 dB and SNR=–5 dB. It is obvious that the positioning accuracy exhibited some degradation when the SNR is decreased to –5 dB. In addition, as the channel frequency selectivity is increased, the positioning error is increased where the ETU channel shows the worst performance among the considered channels due to the significant errors in the ToA estimation.

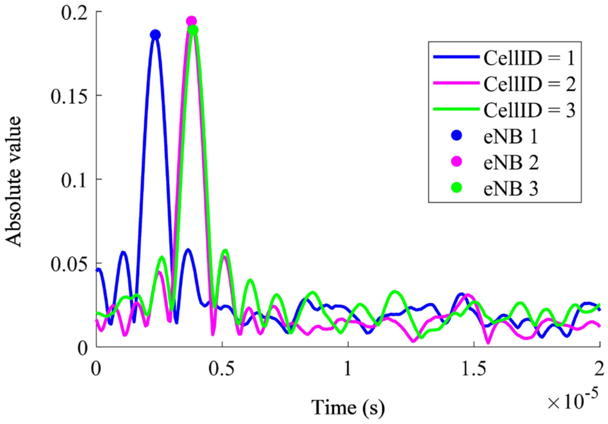

Fig. 7. Correlation profile for ToA estimation

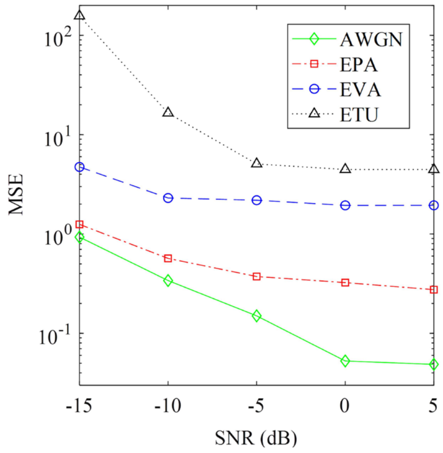

Fig. 8. MSE versus SNR for the ToA estimation

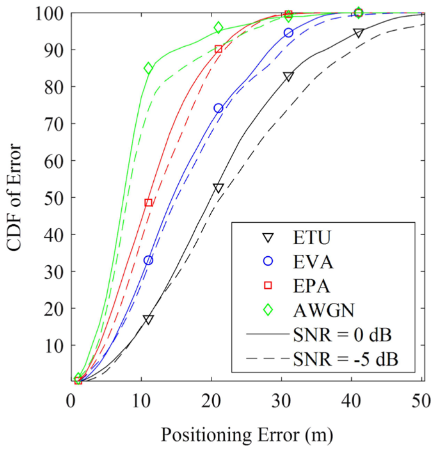

Fig. 9. Positioning performance for the AWGN, EPA, EVA and ETU channels, SNR=0, –5 dB

The influence of the number of PRS on the performance of the OTDoA estimation method is demonstrated in Fig. 10.

The simulation framework is configured with the following parameters, LTE bandwidth 10 MHz (50 Resource Blocks), number of subframes=2 and SNR=0 dB. The positioning performance in terms of CDF of the error is evaluated when the PRS bandwidth is 1.4 MHz (NPRS=6) and 5MHz (NPRS=25) over AWGN, EPA, EVA and ETU channels. When the NPRS is equal to 6, the channel severity effect on the performance is significantly observed where best and worst performance is achieved when the channel is AWGN and ETU channels, respectively. As presented in Fig. 10, increasing the number of PRS to 25 demonstrates significant improvement in the positioning accuracy compared with its counterparts when the number of PRS was 6. The performance of OTDoA based positioning exhibits almost an identical performance for AWGN, EPA and EVA channels and very slight difference in CDF for ETU channel.

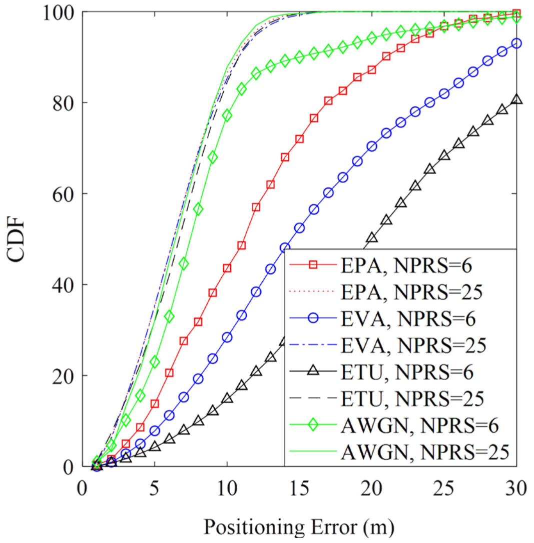

Fig. 10. Positioning performance over AWGN, EPA, EVA and ETU channels for different number of NPRS

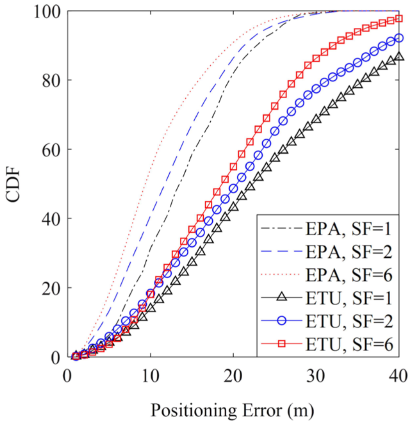

Fig. 11. Positioning performance over EPA, EVA and ETU channels for different number of subframes

The effect of increasing the number of subframes involved in the estimation of the positioning performance is highlighted in Fig. 11. The simulation framework is configured with the following parameters, LTE bandwidth 10 MHz (50 Resource Blocks), PRS bandwidth 1.4 MHz (NPRS=6) and SNR=0 dB. The positioning performance in terms of CDF of the error is evaluated when the number of subframes is equal to 1, 2 and 6 over EPA and ETU channels. It is obvious that averaging the correlation profile over several subframes (the number of subframes is 2 and 6) shows significant improvement in the positioning accuracy compared with their counterpart when the number of subframes equal to 1. In addition, the performance gap due to the channel severity is decreased when the number of subframes is increased. However, even when the number of subframes is increased to 6, the influence of the channel severity is still obviously noticed on the performance of OTDoA based positioning over the considered channels.

8. Discussion of the Results

The performance evaluation of OTDoA for LTE systems over different channel models clearly demonstrates that the accuracy of ToA estimation significantly affects the positioning performance for LTE systems. The reason for the performance degradation in estimating the correct time delay of the channel using correlation particularly in fading channels is due to the biased estimation when the strongest path is not the first path. Therefore, the first path detection of the channel should be used in order to adjust the estimation as searching for the correlation peak might not be appropriate in severe fading conditions. Nevertheless, it was observed that the performance degradation in OTDoA in severe fading conditions can be mitigated to a certain level by increasing the NPRS sequences. It is worth to mention that positioning schemes that rely on time measurements inherit the limitation of poor accuracy in systems with low sampling frequency. Therefore, enhancing the resolution of the estimation in such systems is crucial as the resulted correlation profile has a wide main loop.

Further researches can be directed to address several research gaps. It can be directed to employ more bandwidth of the LTE system to increase the accuracy of positioning measurements, or use deep learning to improve the performance of LTE positioning by detecting the first path arrival; also, a narrow band internet of things (NB-IoT) can be implemented to investigate opportunities for device tracking using OTDoA measurements. Furthermore, considering the first path detection to enhance the accuracy in addition to the parameters optimization of the estimation process can be studied in the future.

9. Conclusions

1. The accuracy of ToA estimation and OTDoA positioning method is evaluated over various channel models. The ToA estimation has shown a significant effect on the overall positioning accuracy. The worst performance is observed over ETU channel that corresponds to severe selectivity conditions. The positioning performance deteriorates in severe fading conditions due to the inaccurate estimation of ToA.

2. The performance degradation of OTDoA in severe fading channels can be mitigated through increasing the number of PRS either in time or frequency directions.

3. Improved accuracy is observed when the NPRS is increased and a comparable performance is noticed over different channel models. Increasing the number of subframes improves the performance as well, however, the accuracy enhancement is marginal and the channel severity effect will still exist.

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