Preliminary Analysis of the Positioning Capabilities of the Positioning Reference Signal of 3GPP LTE

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ABSTRACT

Navigation and communications capabilities become necessary in current wireless transmission systems. The new mobile terminals demand higher requirements to satisfy high-data rate services, as well as new location-based applications. On one side, GNSS systems greatly succeed to provide precise positioning for new applications and services. On the other, multicarrier signals are widely used for high-capacity transmission, such as in xDSL, WiFi or WiMAX. Thus, the current commercial market proposes the combination of GNSS and communication systems to enhance performance. Nevertheless, the use of mobile terminals in harsh environments, such as urban or indoor areas, deteriorates the performance of GNSS receivers. Therefore, the application of multicarrier signals

also for ranging purposes is proposed to achieve the required NAV-COM system. Although multicarrier signals have been widely adopted in communications, little attention has been paid to their potential application to navigation systems. This trend, however, is changing, and LTE is the first wireless system that explicitly incorporates multicarrier signals with positioning capabilities, the so-called positioning reference signal (PRS). This paper presents authors' understanding of the characteristics of LTE multicarrier signal in terms of positioning capabilities, analysing preliminary performance in AWGN and multipath channel (e.g. by means of multipath error envelope).

1. INTRODUCTION

Wireless transmission systems have been traditionally designed to obtain a good performance on navigation or communications. However, there is a growing interest between users and service providers to design hybrid systems able to successfully combine navigation and communication capabilities, leading to NAV-COM systems. This growth is mainly produced by the potential revenue due to the introduction of location-based services (LBS) in mobile phones and portable devices, recently spread all over the world. In addition, the issue of legal mandates for the location identification of emergency calls (i.e. the E911 in the US, the E112 in Europe and 110 in China) has motivated the compliance of positioning accuracy requirements. In order to satisfy this interest, the multicarrier signal (MC) appears as a good candidate to play a prime role in NAV-COM systems.
Multicarrier signals are the preferred option for most wireless communication systems: wide area network (LTE, WiMAX), local area network (IEEE 802.11g), broadcast (DVB-T/H, DAB) and personal area networks. This signal waveform offers spectral efficiency, robustness against multipath and frequency-selective fading, higher data rates, and flexible resources allocation, with respect to single carrier. Nevertheless, the use of multicarrier signals has been basically focused on data transmission and no much attention has been paid on their positioning capabilities. In 2010, the 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) standard paved the way to change this trend by supporting LoCation Services (LCS) in its Release 9. Certainly, LTE uses as a primary positioning method the widely adopted Global Navigation Satellite Systems (GNSS), such as GPS, GALILEO or GLONASS. As it is well-known, GNSS systems achieve high accuracy and their time to first fix (TTFF) can be reduced with the assistance data provided by the LTE cellular network (i.e. assisted GNSS or A-GNSS). Nevertheless, these systems fail in harsh environments, such as indoors or urban canyons, where the visibility of satellites as well as the received signal power decreases due to the obstruction of the line of sight (LoS). Therefore, terrestrial signals with higher power and wider coverage are essential to obtain accurate locations. LTE specifies two complementary positioning methods: the enhanced Cell-ID (e-CID) and the Observed Time Difference on Arrival (OTDoA). The e-CID is based on the knowledge of the cell coverage to provide a rough position estimation. In contrast, OTDoA positioning is more accurate because of the use of a dedicated downlink signal for positioning, which is a multicarrier Orthogonal Frequency Division Multiplexing (OFDM) signal. Therefore, our interest is focused on the study of the positioning capabilities of this LTE multicarrier signal. Indeed, the literature does not provide any detailed analysis on the ranging performance of this signal. Thus, this paper aims at preliminary investigate LTE signal structure and its ranging capabilities. In particular this paper first describes the Long Term Evolution standard, especially its positioning specification. Secondly, the Crámer–Rao bound (CRB) for time delay estimation is introduced. Correlation-based estimation algorithms are also described and preliminary results on the timing estimation error are evaluated with the CRB in additive white Gaussian noise (AWGN) channel. Then, the LTE power signal level is computed with a software simulator to determine the signal-to-noise ratio (SNR) region of interest. Next, the multipath channel model is preliminary evaluated by means of the multipath error envelope (MPEE). Finally, some conclusions are drawn.

2. LONG TERM EVOLUTION (LTE)

Since 2004, the 3GPP consortium has been developing the Long Term Evolution (LTE) [1], a mobile communication system aimed to increase data rates, overall system capacity and user mobility, and to obtain low latency and high spectral efficiency with respect to its predecessor, the Universal Mobile Telecommunication System (UMTS). LTE mainly achieves this challenging performance by introducing a multicarrier OFDM signal for the downlink access with higher signal bandwidths (i.e. scalable from 1.4 MHz to 20 MHz). Another new feature to cellular networks is the Multiple Input Multiple Output (MIMO) data transmission, which exploits the spatial dimension. Because of its significant advantages, LTE becomes a promising technology for study, especially from the NAV-COM point of view.

As previously introduced, LTE positioning procedures are based on assisted GNSS, enhanced cell ID and OTDoA. The primary procedure is A-GNSS, but it may suffer difficulties in urban or indoor environments due to the loss of LoS. In these scenarios, e-CID may be a complementary procedure, however, its poor accuracy prevents its use for precise positioning. Thus, OTDoA appears either as an alternative procedure for stand-alone NAV-COM positioning or hybridization with GNSS.

2.1. Downlink positioning procedure or OTDoA

Specified as a downlink positioning procedure in the LTE standard [2], the OTDoA method is based on the user equipment (UE) estimates of the difference in the arrival times of downlink radio signals from multiple base stations (i.e. eNodeBs). Since the eNodeB locations are not provided to the user, the LTE Positioning Protocol (LLP) transfers the UE measurements to the location server, E-SMLC (Enhanced Serving Mobile Location Center). Based on the UE measurements, the E-SMLC estimates the UE position using a trilateration technique, and this position information is then sent back to the user. In addition, assistance data may be provided to the UE in order to obtain the timing measurements. Our interest is mainly focused on the assessment of the positioning capabilities of the LTE multicarrier waveform.

2.2. LTE pilot signals

The LTE standard [3] specifies a set of downlink signals based on an OFDM type modulation with different time-frequency distribution, whose basic structure is shown in Fig. 1. Some of these signals are synchronization signals (i.e. completely known, like the pilot signals in GNSS) suitable for ranging purposes, such as:

- the Primary Synchronization Signal (PSS) based on a Zadoff-Chu (ZC) sequence, and
- the Secondary Synchronization Signal (SSS) based on a length-31 m-sequence,

being defined along 62 subcarriers around the DC subcarrier. The synchronization signals (i.e. PSS and SSS) are used for cell search and acquisition of the signal without requiring any assistance data, then they can be used for Signals of Opportunity (SoO) applications. However, LTE follows the typical frequency reuse factor of a cellular network, which is equal to one. Thus, the received serving cell signal interferes with the received neighbour cell signals producing inter-cell interference, and resulting in the *near-far effect*. In order to obtain proper ranging measurements of the neighbour cells, the LTE standard in Release 9 specifies a ***positioning reference signal*** (PRS) that is especially dedicated for positioning purposes and mitigates the near-far effect, due to a higher frequency reuse factor (i.e. of six). This higher frequency reuse factor is achieved by shifting one subcarrier position the frequency pilot allocation transmitted by each base station. But this signal is not only allocated along the subcarriers of one OFDM symbol, the PRS pilot signal is scattered in time and frequency with pseudo-random sequences defined by a length-31 Gold sequence. In addition, the LTE system dedicates the so-called *positioning occasion* to this pilot signal allocating consecutive positioning subframes with a certain periodicity. The sophistication of this signal is even higher when the network mutes the PRS transmissions of certain base stations

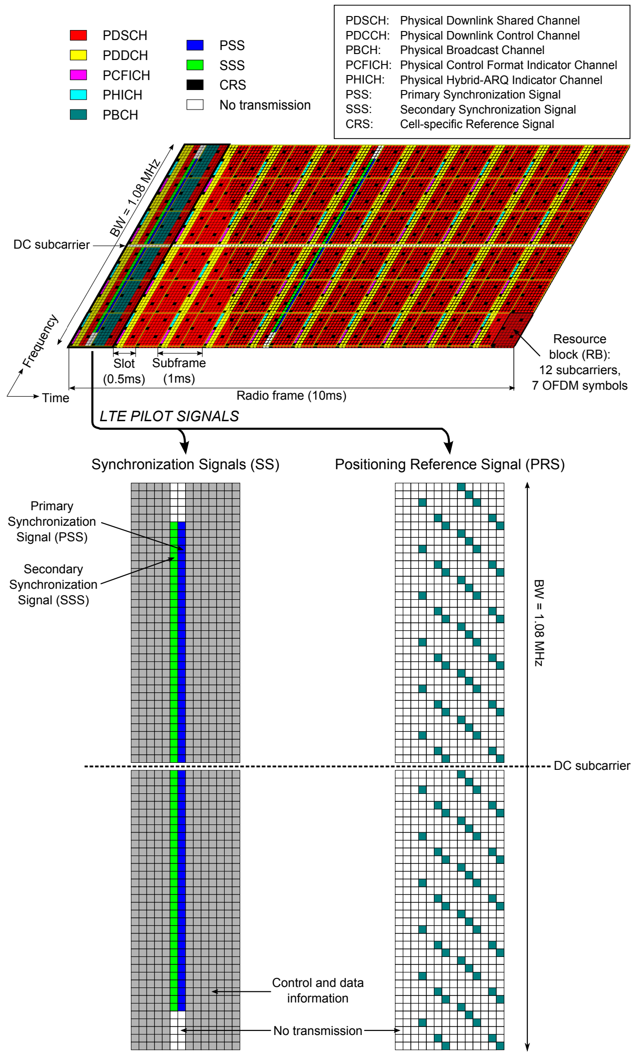

Fig. 1 Time-frequency grid of the LTE signals for 1.4 MHz bandwidth, FDD structure and normal cyclic prefix (CP).

(i.e. PRS muting), in order to further reduce the inter-cell interference. The main parameters for PRS configuration are shown in Table 1.

3. TIME DELAY ESTIMATION

The performance of the time delay estimation (TDE) can be assessed by establishing an accuracy limit. Thus, a lower bound on timing estimation help us to analyse the time synchronization algorithm implemented.

3.1. Crámer–Rao bound (CRB)

The Crámer–Rao bound (CRB) is the most common lower bound and describes the maximum achievable accuracy of any unbiased estimator in the moderate- to high-SNR region. Since the time delay is estimated with pilot sequences, the CRB can be analytically computed.

Table 1 Main parameters of the PRS signal.

PRS bandwidth	1.4, 3, 5, 10, 15 and 20 MHz
PRS periodicity	160, 320, 640 or 1280 ms
Consecutive subframes	1, 2, 4, or 6
PRS muting information[1]	2, 4, 8, 16 bits
PRS pattern	6-reuse in frequency
PRS sequence	Length-31 Gold sequence

[1] Number of positioning occasion configured for PRS muting (i.e. bit equal to 0 when PRS is muted).

Let us define the OFDM baseband signal format for one symbol used in the LTE downlink as

$$x\left[n\right]=\sqrt{\frac{2\cdot P_x}{N_c}}\sum_{k\in\mathcal{N}_a}p_k\cdot d_k\cdot\exp\left(j\frac{2\pi nk}{N_c}\right),\qquad(1)$$

where P_x is defined as the power of the band-pass signal, N_c is the number of subcarriers, $\mathcal{N}_a$ is the subset of active pilot subcarriers N_a, which must satisfy $N_a \leq N_c$, $d_{m,k}$ are the symbols, and p_k^2 is the relative power weight of subcarrier k, which is constrained by $\sum_k p_k^2 = N_c$ to give the nominal signal power P_x. This notation allows the flexible design of OFDM multicarrier signal optimizing the power and spectra distribution. It also has to be noticed that the OFDM symbol duration T_s is determined by the duration of the chip T_c and the number of subcarriers N_c, or the subcarrier spacing F_{sc}, i.e. $T_s = T_c \cdot N_c = 1/F_{sc}$. In addition, the OFDM signal generation can be efficiently implemented with the inverse fast Fourier transform (IFFT) of the pilot symbols vector $\mathbf{d}$.

Since the OFDM signal described in (1) is completely known, the Cramér-Rao Bound (CRB) expression for time delay estimation of $\hat{\tau}$ applied to the LTE signal formats can be derived from the general definition given by Kay [4],

$$\mathrm{var}\left(\hat{\tau}\right)\geq CRB(\tau)=\frac{1}{\dfrac{E_s}{N_0/2}\cdot\bar{F}^2},\qquad(2)$$

where $E_s = P_x \cdot T_s$ and $SNR = (C/N_0)/B$, being C/N_0 the carrier-to-noise-density ratio and B the bandwidth of the signal. The mean square bandwidth (MSB) or Gabor bandwidth of the OFDM signal, $\bar{F}^2$, defined by

$$\bar{F}^2\doteq\frac{\displaystyle\int_{-\infty}^{\infty}(2\pi f)^2\cdot\left|X(f)\right|^2df}{\displaystyle\int_{-\infty}^{\infty}\left|X(f)\right|^2df},\qquad(3)$$

can be approximated as follows,

$$\bar{F}^2\simeq\frac{\dfrac{1}{N_c}\displaystyle\sum_{k\in\mathcal{N}_a}(2\pi k\cdot F_{sc})^2\cdot\left|X(k\cdot F_{sc})\right|^2}{\dfrac{1}{N_c}\displaystyle\sum_{k\in\mathcal{N}_a}\left|X(k\cdot F_{sc})\right|^2}=\qquad(4)$$

$$=4\pi^2\frac{F_{sc}^2}{N_c}\sum_{k\in\mathcal{N}_a}p_k^2\cdot k^2,$$

by considering a rectangular power spectral density (PSD). Thus, the CRB for the LTE signal pilots, and in general any OFDM signal, is

$$CRB(\tau)=\frac{T_s^2}{8\pi^2\cdot SNR\cdot\displaystyle\sum_{k\in\mathcal{N}_a}p_k^2\cdot k^2}.\qquad(5)$$

3.2. Maximum Likelihood Estimation

Once the lower bound for timing estimation in LTE has been evaluated, the maximum likelihood estimation (MLE) method is analysed, and preliminary ranging accuracy with LTE pilot signals is presented in additive white Gaussian noise (AWGN) channel, where the received signal $r\left[n\right]$ is defined by

$$r\left[n\right]=x\left[n;\tau\right]+w\left[n\right],\qquad(6)$$

being $w\left[n\right]$ the noise component.The MLE method is based on the correlation of the received signal $r\left[n\right]$ with a shifted and conjugated version of the reference signal $x\left[n\right]$, which is assumed periodical (i.e. circular correlation), in order to find the correlation peak. Thus, the correlation between the received and the transmitted signal is defined by

$$R_{rx}\left(\tau\right)\doteq\sum_{n=0}^{N_c-1}r\left[n\right]\cdot x^*\left[n+\tau\right],\qquad(7)$$

which results in the matched filter of the OFDM signal, and the estimated delay can be expressed as

$$\hat{\tau}=\frac{T_s}{N_c}\arg\max_{\tau}\left\{\left|R_{rx}\left(\tau\right)\right|^2\right\},\qquad(8)$$

where τ is the time delay. This method can be efficiently implemented by using the FFT operation as it is shown in Fig. 2. For instance, this FFT procedure is usually chosen for time and frequency ***acquisition*** in GNSS receivers.

The timing performance of the maximum likelihood method is evaluated by using the root mean square error (RMSE), which is defined by $\mathrm{RMSE}\left(\hat{\tau}\right)=c\cdot\sqrt{\mathrm{var}\left(\hat{\tau}\right)}$, being c the speed of light. The RMSE is computed for the LTE pilot signals considering the maximum transmission power and bandwidth specified in the standard. In Section 4.6 of the technical specification TR 36.942 [5], the maximum base station (BS) power is specified as follows:

- 43 dBm for bandwidth $\leq$ 5 MHz, and

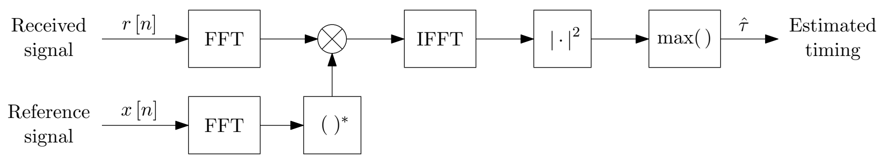

Fig. 2 FFT implementation of the correlation at the receiver.

- 46 dBm for 10, 15 and 20 MHz bandwidth.

Due to lack of information, we assume the power ***uniformly distributed*** among all the sub-carriers, the relative power weight of sub-carrier k is

$$p_k = \sqrt{\frac{N_c}{N_a}}, \quad \text{for } k \in \mathcal{N}_a. \tag{9}$$

In Fig. 3, the normalized power spectral density (PSD) of the LTE pilot signals for every bandwidth configuration shows how the power is spread over all the active subcarriers, assuming only pilot transmission. Then, the resulting RMSE, which is computed with 1000 Monte-carlo simulations, is compared with the corresponding CRB and plotted with respect to the C/N_0 in Fig. 4. As it can be seen, the LTE pilot signals attain the CRB bound and performance are improved as the occupied bandwidth of the PRS signal is increased.

4. LTE SIMULATOR

The preliminary results on the variance of the timing estimation with LTE pilot signals give a general idea of their maximum achievable accuracy. Nevertheless, a realistic C/N_0 working region has to be defined. For this purpose, a simulator of the LTE specification has been implemented in MATLAB. This LTE simulator generates a typical cell layout, as the one shown in Fig. 5, considering the parameters specified in the standard [5], which are summarized in Table 2. Thus, the received signal power from a BS i is computed using the expression given in [5, p.14],

$$P_{rx,i} = P_{tx,i} - \max\left(L_i - G_{tx,i} - G_{rx,i}, \text{MCL}\right), \tag{10}$$

where $P_{tx,i}$ is the transmitted signal power, L_i is the macroscopic pathloss, $G_{tx,i}$ is the transmitter antenna gain, $G_{rx,i}$ is the receiver antenna gain and MCL is the minimum coupling loss (MCL). The resulting power budget is used to compute the SNR and the signal-to-interference plus noise ratio (SINR) in an AWGN channel. The SINR is defined as the ratio of signal power to the combined interference and noise power, which is expressed as,

$$\text{SINR} = \frac{P_{rx,i}}{\sum_{j \neq i} P_{rx,j} + N_{rx}}, \tag{11}$$

where $P_{rx,j}$ is the received power from other antenna sectors, which causes the interference, and N_{rx} is the receiver

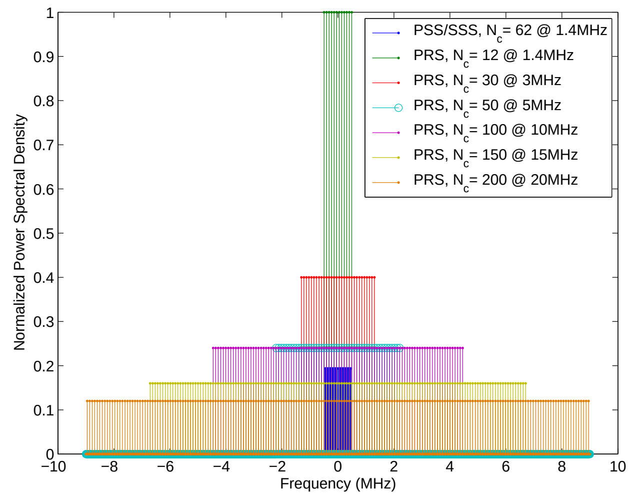

Fig. 3 Normalized Power Spectral Density (PSD) of the LTE pilot signals considering the maximum BS power specified in TR 36.942 [5].

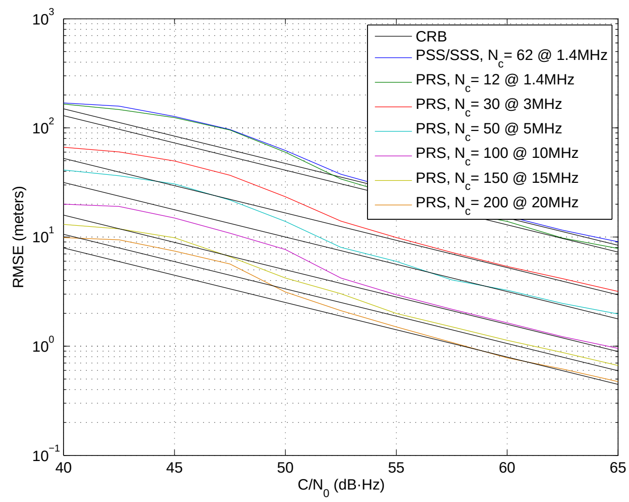

Fig. 4 RMSE of the MLE method for the LTE pilot signals (i.e. PSS, SSS and PRS) with respect to the C/N_0, considering only one OFDM symbol.

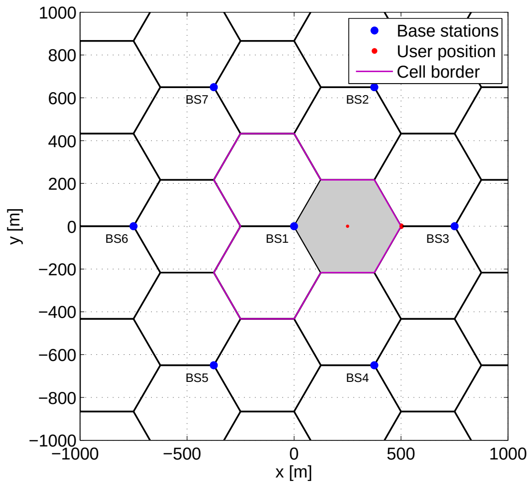

Fig. 5 LTE simulation cell layout.

noise floor. The values of the SNR and SINR for every possible position of the user in the cell layout are shown in Fig. 6 and 7. In order to characterize the C/N_0 region of interest, two critical user positions in a LTE scenario are considered, the center and edge of the cell, as it is pointed in Fig. 5. The SINR obtained with the LTE simulator for these two user positions are 12.96 and -6.13 dB, respectively. If the interference of the neighbour base stations is assumed to be Gaussian noise, these SINR values can be used in the CRB expression to obtain the pseudo-range from the user position to the base station. The results obtained for every LTE pilot signal are shown in Table 3. Therefore, the LTE signals work with C/N_0 between 45 and 75 dB·Hz, approximately, when interference is considered. Two main concerns about these preliminary results have to be finally remarked:

- The results have been achieved taking into account that the BS transmits only the pilot signals at the maximum power allowed. Validation of this assumption has not been done for lack of authors' information about real implementations.
- The SINR is computed assuming that every BS transmits the same LTE pilot signal, thus the frequency reuse is of one. As it has been discussed previously, the inter-cell interference can be reduced with frequency reuse of six specified for the PRS signal. Therefore, adequate analysis of the PRS interference is left as future work.

5. PRELIMINARY ANALYSIS WITH MULTIPATH CHANNEL

The LTE cellular scenario where the OTDoA measurements are obtained suffers different timing errors. According to [6], the main sources of error are:

Table 2 Simulation parameters according to [5].

Parameter	Characteristic/value
System	
Carrier frequency	2 GHz
Bandwidth	$\leq$ 5 MHz
Cell layout	Hexagonal
Inter-site distance	750 m
Transmitter	
BS transmit power	43 dBm
BS antenna model	3 dB-beamwidth of 65-degree
BS antenna gain	15 dBi
Receiver	
UE antenna model	Omnidirectional, 0 dBi
UE noise figure	9 dB
Thermal noise density	-174 dBm/Hz
Channel	
Path loss model[1]	$128.1 + 37.6\log_{10}(R)$ dB

[1] R is the propagation distance.

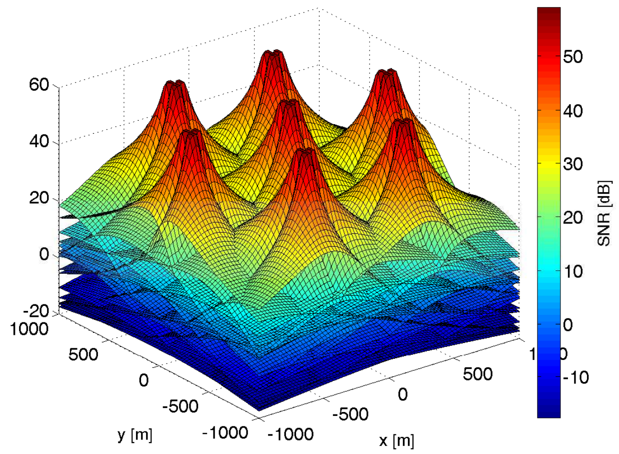

Fig. 6 SNR computed independently for every BS sector.

- eNodeB synchronization error,
- UE RSTD measurement quantization error,
- multipath propagation error,
- timing offset estimation error, and
- UE frequency instability.

Timing offset and multipath propagation errors have a higher impact on the estimation than other errors. Since the first one has already been studied in previous sections, the second one is taken into account now. The 3GPP standard specifies the multipath channel model for LTE in the Annex B of the specification TS 36.101 [7], according to

Table 3 Theoretical accuracy in meters of the **pseudo-range estimation of BS 1** at the center (RMSE_c) and edge (RMSE_e) of the cell (i.e. 250 and 500 from BS 1) considering interference and computed with the LTE simulator, which results in a SINR equal to 12.96 and -6.13 dB, respectively.

Signal format	BW [MHz]	# of pilots	Center		Edge	
			$(C/N_0)_c$ [dB·Hz]	RMSE_c [m]	$(C/N_0)_e$ [dB·Hz]	RMSE_e [m]
PSS or SSS	1.4	62	72.64	3.31	53.56	29.80
PRS	1.4	12	65.51	2.81	46.42	25.29
PRS	3	30	69.49	0.72	50.40	6.51
PRS	5	50	71.71	0.34	52.62	3.03
PRS	10	100	74.72	0.12	55.63	1.07
PRS	15	150	76.48	0.06	57.39	0.58
PRS	20	200	77.73	0.04	58.64	0.58

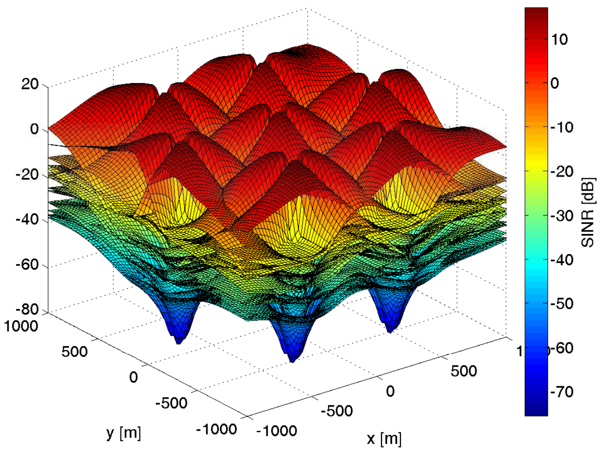

Fig. 7 SINR computed independently for every BS sector.

extended ITU[1] channel models, which are based on a ***discrete tapped-delay-line*** with K taps:

$$h(\tau;t) = \sum_{k=1}^{K} a_k^t \delta(\tau - \tau_k), \qquad (12)$$

where the complex amplitude a_k^t follows a Rayleigh distribution. Two-ray multipath model with typical signal-to-multipath ratio (SMR) is considered for the preliminary analysis of the multipath channel. One of the ITU channel models is the extended typical urban (ETU) model [7], where SMR equal to 1, 3 and 6 dB can be seen as typical values. Thus, the assessment of the multipath impact on the time-delay estimation (TDE) can be addressed by means of the multipath error envelope (MPEE) with these SMR values. The MPEE describes the TDE error produced by the presence of a multipath ray, and in this case, it is computed with only one multipath ray using the correlation function of every LTE pilot signal. The results are shown in Fig. 8 for the synchronization signals and in Fig. 9 for the positioning reference signal, when the multipath ray is in-phase (solid line) and out-of-phase (dashed line). The tap delays of the ETU channel are also depicted to highlight the multipath ray error for those delays.

[1] ITU: International Telecommunications Union

The reduction on the multipath impact produced by the PRS signal with respect to the SS signals is mainly due to the slight higher bandwidth occupied that reduces the main lobe width of the correlation function. Thus, the multipath impact can be reduced with the PRS signal due to its bandwidth scalability up to 20 MHz. Other parameters, such as the higher number of symbols or the different spectra distribution, change the peak-to-sidelobe ratio (PSLR) of the correlation function, which also affects the resulting MPEE. Therefore, the results presented show the traditional three main factors that determine the multipath error envelope:

- **Bandwidth**: the bandwidth defines the main lobe width of the correlation function.
- **SMR**: the power of multipath rays with respect to the line-of-sight (LoS) ray.
- **Waveform**: the shape and form of the signal defines the correlation function.

According to the LTE downlink standard, only two kind of waveforms suitable for positioning have been presented: OFDM signal with contiguous pilot subcarriers (i.e. synchronization signals), and OFDM signal with distributed pilot subcarriers (i.e. positioning reference signals). For these cases, the power is uniformly allocated for all the subcarriers, but a different power allocation distribution could be considered. Thus, four different pilot distributions, which are shown in Fig. 10, are used to compute the MPEE. These distributions has been based on the pattern of the PRS signal and an advantageous power allocation for positioning. As it can be noticed in Fig. 12, the symmetry of the pilots slightly decreases the multipath impact. However, the power allocation modifies the PSLR of the correlation function, which can be seen in Figure 11, and directly increases the maximum delay estimation error. Further study should be conducted in order to evaluate the benefits of these power distributions on TDE performance. Thus, the flexibility of multicarrier signals may help in a future on designing an optimum signal waveform able to obtain a good TDE accuracy and multipath resistance.

6. CONCLUSION

A preliminary analysis of the Long Term Evolution (LTE) positioning capabilities is presented in this paper to evaluate its potential as NAV-COM system. First, the review of the 3GPP LTE standard has highlighted three positioning modalities: Assisted GNSS, Enhanced Cell-ID, and Observed TDoA (OTDoA). Focusing on the LTE multicarrier downlink signals used for OTDoA, especially the positioning reference signal (PRS), their assessment has been evaluated with the computation of the RMSE and the Crámer–Rao bound (CRB) in AWGN channel. In order to obtain the C/N_0 working region, a LTE software simulator has been implemented resulting on a range between 45 and 75 dB·Hz. Finally, an artificial two-ray multipath model has been preliminary analysed by means of the multipath error envelope (MPEE). Further research for validation of results, evaluation of 2D position performance and realistic multipath channel effects is left as future work.

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[7] 3GPP TS 36.101, *Technical Specification, User Equipment (UE) radio transmission and reception (Release 9)*, 3rd Generation Partnership Project Std., V9.8.0, (2011-06).

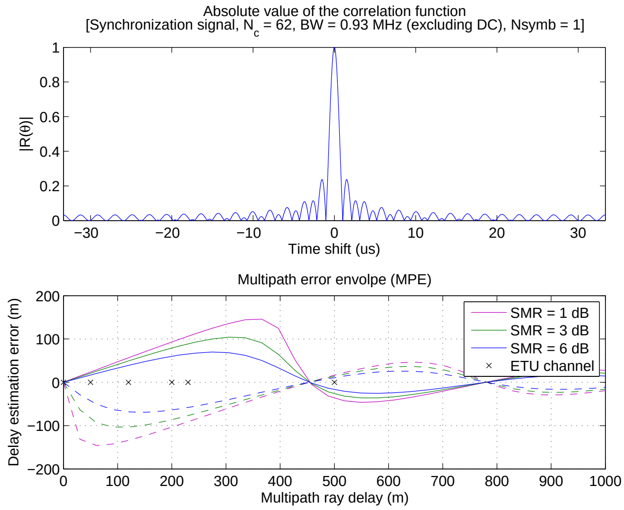

Fig. 8 Multipath Error Envelope (MPEE) of the SS signal (0.93 MHz).

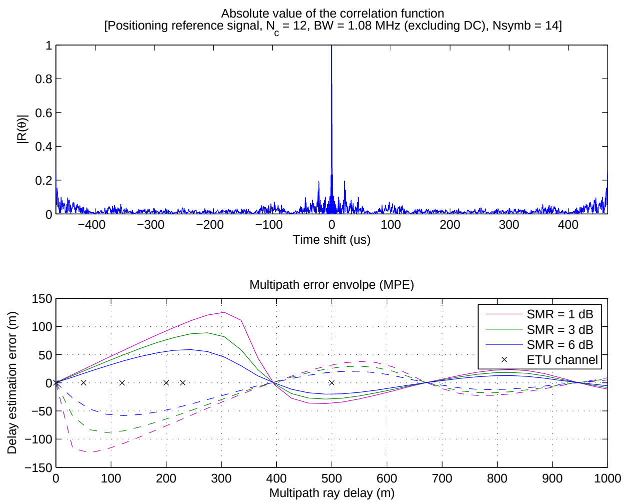

Fig. 9 Multipath Error Envelope (MPEE) of the PRS signal (1.08 MHz).

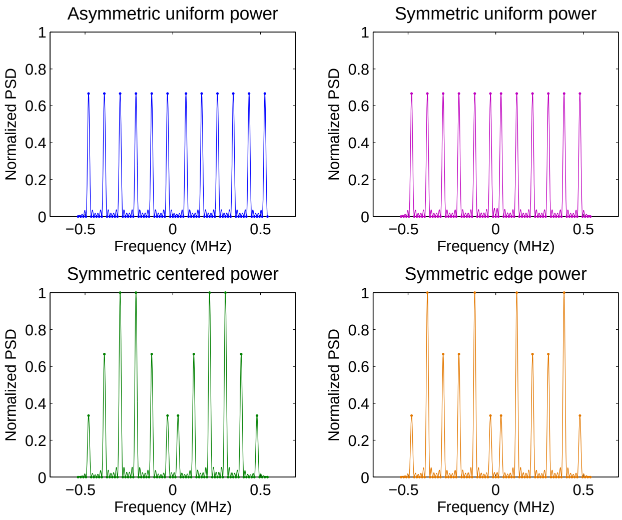

Fig. 10 Example of different MC distributions.

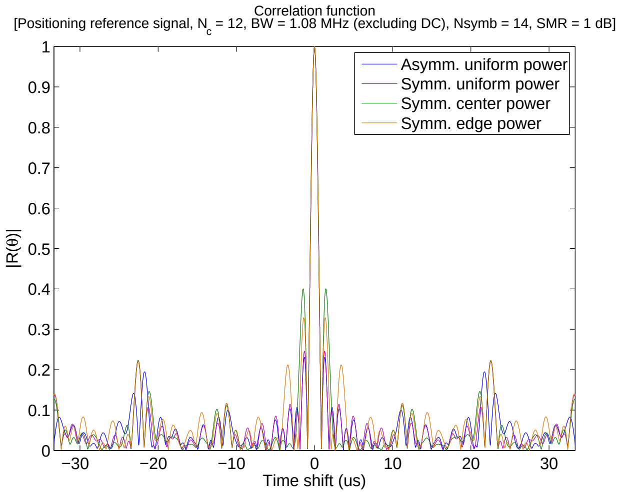

Fig. 11 Correlation function of the example distributions in the interval [-$T_s/2$,$T_s/2$].

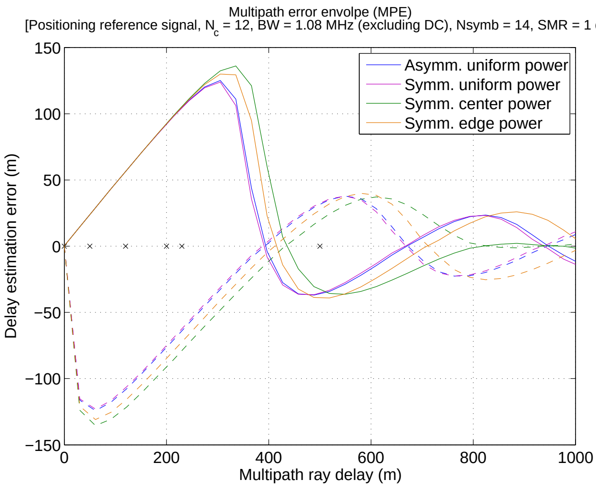

Fig. 12 Multipath Error Envelope (MPEE) of the example distributions.