# Downlink Synchronization of LTE Base Stations for Opportunistic ToA Positioning

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***Abstract*—Long Term Evolution (LTE) signals are a very good complement to Global Navigation Satellite Systems (GNSS) in urban environments, due to their attractive positioning capabilities. However, the network-based positioning methods defined in the LTE standard hinder the use of these signals for ranging in an opportunistic way. This is mainly due to the lack of synchronization between LTE base stations (BSs) in most of current network deployments. To circumvent this limitation, this paper proposes a method to synchronize LTE BSs using time-delay and frequency tracking loops and *a-priori* known receiver position. The main considerations on the use of this method for opportunistic time-of-arrival (ToA) positioning are discussed. Using real LTE signals emulated in the laboratory, positioning results are obtained with a software receiver under a dynamic trajectory, validating the use of the proposed synchronization for opportunistic ToA positioning.**

## I. INTRODUCTION

There is an increasing use of positioning technologies complementing Global Navigation Satellite Systems (GNSS), mainly in urban and indoor environments. This is due to the stringent requirements demanded by location-based services (LBS), in addition to legal mandates for emergency calls [1], such as E911 or E112. In this context, Long Term Evolution (LTE) systems offer appropriate capabilities for positioning, even though these systems were primarily designed for wireless communications purposes. In addition to assisted GNSS (A-GNSS), LTE specifies in [2] a downlink positioning method based on the observed time-difference of arrival (OTDoA) of wideband and dedicated signals [3], i.e. positioning reference signal (PRS). However, the application of OTDoA-based location services in LTE commercial networks is not mature yet.

Positioning methods specified in the LTE standard [2] are centralized on the network, who coordinates, assists and manages the position determination of the user equipment (UE). The evolved serving mobile location centre (E-SMLC) is the network entity aimed to support UE positioning and to deliver assistance data. In the OTDoA method, the E-SMLC calculates the UE position, by using the ranging measurements (done by the UE with assisted PRS data), the location of the base stations (BSs) and their timing information, which can be referred to an absolute GNSS time. The positioning accuracy is ultimately constrained by the network application that is being provided. Thus, the deployment of LTE positioning services is practically restricted to or conditioned by network operators.

An alternative to network-based localization in LTE is the use of cell-specific reference signals (CRSs) as signals of opportunity for positioning, as proposed in [4] and [5]. First, time-of-arrival (ToA) estimates from neighbour BSs are obtained with the CRS, and then the UE calculates its position with those estimates and the known location of the BSs, which is generally of public access. However, the transmission time or frame timing of the BSs is not available, being a major problem for opportunistic localization. Indeed, clock synchronization between BSs is a major requirement for accurate and reliable positioning using either PRS- or CRS-based ranging estimates, being much tighter than the timing requirements for communications purposes, such as in coordinated multipoint (CoMP) transmission [6] or in small cells deployments [7]. These clock offsets between BSs avoid the use of ranging estimates for standalone LTE positioning. Thus, downlink synchronization of LTE BSs has to be tackled for opportunistic positioning.

Network synchronization for ranging-based positioning has been of special interest in wireless sensor networks (WSNs). Round trip time (RTT) or two-way ranging measurements are proposed for synchronization protocols of sensors and anchor nodes, such as in [8]. Geometrical localization in the presence of clock offsets is described in [9]. The displacement of the receiver is used for localization and tracking of asynchronous sensors in [10]. However, to the best of the authors' knowledge, the implementation and validation of the concept of downlink synchronization using LTE signals of opportunity has not been presented. Therefore, the authors propose a synchronization technique able to compensate the timing offsets between BSs and receiver. This is achieved by time-delay and frequency tracking loops, and considering known the position of the receiver during the synchronization process. This allows opportunistic localization with ToA algorithms. The paper discusses the application of this method for standalone positioning, and provides results with real LTE signals emulated in the laboratory. This opportunistic use of LTE signals allows positioning in many scenarios that are not foreseen in the standard yet, such as the use of signals from different network operators.

This paper is structured as follows. The signal model, tracking architecture and the proposed downlink synchronization is presented in Section II. The applications of this method to opportunistic ToA positioning are discussed in Section III. Results in an example scenario are provided in Section IV, before drawing the conclusions in Section V.

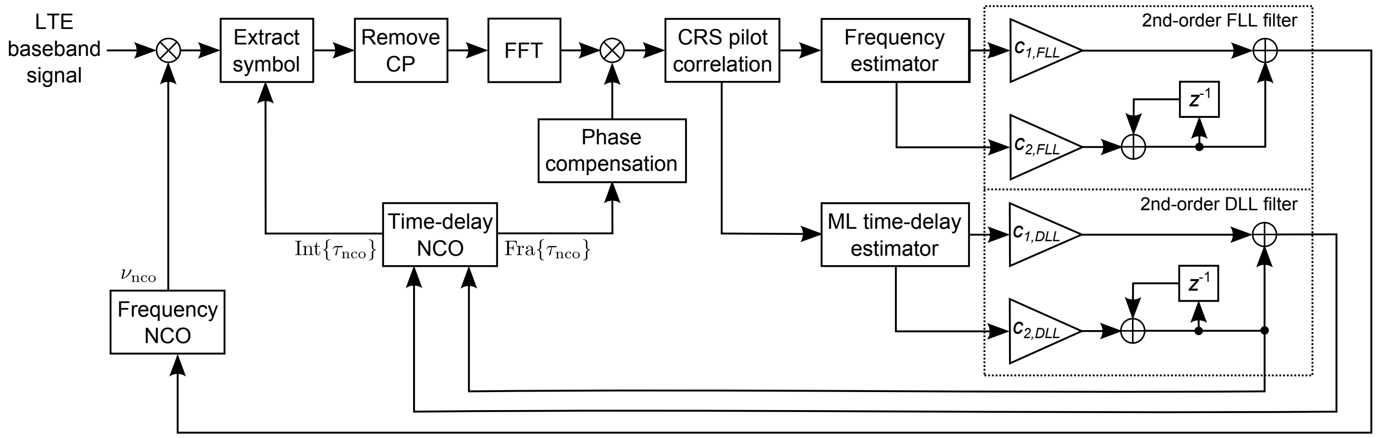

Fig. 1. Tracking architecture for downlink synchronization.

## II. DOWNLINK SYNCHRONIZATION OF LTE BSS

Clock synchronization between LTE BSs is presented in this section. Cell detection and signal acquisition are assumed to be already completed. The CRSs are used to obtain time-delay and frequency estimates for the tracking loops. Then, downlink synchronization of the LTE signals is achieved with the filtered time-delay measurements.

### A. Signal model

The downlink access of LTE is based on the orthogonal frequency division multiplexing (OFDM) modulation with resources allocated in time and frequency over a 10-ms radio frame [3]. The subcarrier spacing $F_{\mathrm{sc}}$ is equal to 15 kHz, resulting in an OFDM symbol period $T = 1/F_{\mathrm{sc}}$ of 66.67 µs. Among the several types of reference signals defined in the standard [3], the CRS is transmitted in all downlink subframes, when a cell supports data transmission. Thus, this reference signal is here used for tracking purposes.

At the transmitter, the discrete-time signal model is

$$x(k,m) = \sqrt{\frac{2C}{N}} \sum_{n=-N/2}^{N/2-1} b(k,n) \cdot e^{j\frac{2\pi nm}{N}}, \quad 0 \leq m \leq N-1, \tag{1}$$

where $C$ is the power of the band-pass signal, $N$ is the total number of subcarriers, $b(k,n)$ is the complex-valued symbol transmitted at the $k$-th OFDM symbol and $n$-th subcarrier, being $b(k,0) = 0$ to avoid problems with DC offsets. Then, the last $L$ samples of $x(k,m)$ are added at the beginning of the OFDM symbol in order to form the cyclic prefix (CP).

At the receiver, an $N$-point discrete Fourier transform (DFT) is applied after the removal of the CP. The resulting received signal at the $k$-th symbol is written as

$$X(k,n) = H(k,n) \cdot b(k,n) \cdot e^{j2\pi(n\tau + k\nu + nk\xi)/N} + w(k,n), \tag{2}$$

where $H(k,n)$ is the channel response, $\tau$ is the time-delay, $\nu$ is the carrier frequency offset (CFO), $\xi$ is the sampling clock frequency offset (SFO), and $w(k,n)$ is thermal noise, which is statistically uncorrelated with $w(k,n) \sim \mathcal{CN}\left(0, \sigma_{\mathrm{W}}^2\right)$. The effect of inter-carrier interference (ICI) due to the frequency offsets is not considered in (2) for sake of simplicity, but it can be found in [11] and [12].

### B. Tracking architecture

Time delay and frequency offsets are tracked with a classical architecture based on a second-order delay lock loop (DLL) and a second-order frequency lock loop (FLL), as it is shown in Figure 1. After the DFT, the pilot symbols of the CRS are first wiped-off as

$$Y(k,n) = X(k,n) \cdot b^*(k,n), \tag{3}$$

where $b^*(k,n)$ is the conjugate pilot. Then, the time delay is estimated based on the maximum likelihood (ML) criterion as

$$\hat{\tau} = \arg\max_{\tau} \left\{ \sum_{k\in\mathcal{K}} \left| \sum_{n\in\mathcal{N}} Y(k,n) \cdot e^{-j\frac{2\pi n\tau}{N}} \right|^2 \right\}, \tag{4}$$

where $\mathcal{K}$ is the set of CRS symbols to integrate, and $\mathcal{N}$ is the set of CRS subcarriers. The CFO estimation is performed with the phase difference between adjacent CRS symbols [13],

$$\hat{\nu} = \frac{N}{2\pi N_{\mathrm{slot}}} \arg\left\{ \frac{1}{P} \sum_{k\in\mathcal{K}} \sum_{n\in\mathcal{N}} Y^*(k-7,n)\, Y(k,n) \right\}, \tag{5}$$

where $N_{\mathrm{slot}}$ is the number of samples per slot (i.e. half subframe), which contains 7 OFDM symbols considering normal CP configuration, and $P$ is the total number of phase differences integrated. As it can be noticed, the pattern of the CRS is considered in $\mathcal{K}$ and $\mathcal{N}$. In order to avoid any bias on the frequency estimation, the magnitude of $Y(k,n)$ should be constant between adjacent symbols. Thus, the number of CRS symbols integrated is limited by the coherence of the channel $H(k,n)$. In addition, some symbols should be avoided or weighted due to inter-cell interference, since a single-frequency network (SFN) is considered. Therefore, only those CRS symbols with the same subcarrier allocation are used, with the possibility to discard those symbols with high inter-cell interference.

These estimates determine the time-delay and frequency error that is introduced in the tracking loops, as it is shown in Figure 1. The loop filter coefficients of first and second order, i.e. $c_1$ and $c_2$, respectively, are calculated according to [14]. The filtered measurements are then fed into the numerically-controlled oscillator (NCO) to compensate the offsets in the time and frequency domains.

### C. Proposed downlink synchronization

Once the receiver is in tracking, synchronization between receiver and BSs can be performed. In order to ensure good accuracy, two main assumptions are considered during the synchronization process:

- the receiver is at a static known position, and
- there is line-of-sight (LoS) between BS and receiver.

The proposed downlink synchronization is based on the compensation of each ToA estimate by using the time of flight (ToF) or travel time of the signal from BS to UE, assuming known their locations. The ToA estimates are integrated in the time delay of the NCO $\boldsymbol{\tau}_{\text{nco}}$, which is a vector with $M$ time-delay updates for every BS during the synchronization process. Thus, they are obtained by removing or compensating the effect of the SCO $\xi$ and its derivative $\rho$ from $\boldsymbol{\tau}_{\text{nco}}$. This is achieved by applying a linear least-squares (LS) fitting to $\boldsymbol{\xi}_{\text{nco}}$, which is a vector with $M$ sampling period updates, as

$$\begin{bmatrix}\bar{\xi}\\ \bar{\rho}\end{bmatrix} = \left(\mathbf{A}^T\mathbf{A}\right)^{-1}\mathbf{A}^T\boldsymbol{\xi}_{\text{nco}}, \qquad (6)$$

where $\bar{\xi}$ is the mean of the sampling period estimates, $\bar{\rho}$ is the mean of the sampling period drift estimates, and $\mathbf{A} \in \mathbb{R}^{M\times 2}$ is a matrix with unit entries on the first column and $[0, 1, \ldots, M-1]^T$ on the second column. The model order of the LS fitting should be in accordance to the stability of the oscillator at the receiver.

For a certain BS, the synchronized ToA estimates are finally obtained as

$$\begin{aligned}\tau_{\text{sync}} &= \frac{1}{M}\sum_{m=0}^{M-1}\left(\tau_{\text{nco}}(m) - m\cdot\left(\bar{\xi} + \frac{(1+m)}{2}\bar{\rho}\right)\right) - \tau_{\text{d}} = \\ &= \tau + \tau_{\text{e}} - \tau_{\text{d}}, \qquad (7)\end{aligned}$$

where $\tau_{\text{d}}$ is the ToF between receiver and BS, $\tau$ is the true ToA, and $\tau_{\text{e}}$ is the composite synchronization error, which is formed by noise, multipath-induced error, estimation bias, and possible errors on the *a-priori* known BS and receiver positions. The proposed synchronization is valid for BSs with precise clocks. Otherwise, the resulting synchronization error should be periodically corrected.

## III. OPPORTUNISTIC TOA POSITIONING

The methodology proposed for synchronization of multiple BSs allows opportunistic positioning, because the receiver only needs the BS locations and the ToF from each BS to a known location. According to the LTE standard [2], the receiver can only compute its position standalone by means of satellite-based methods. The rest of LTE positioning methods are managed by the network, who configures and coordinates the positioning service among BSs and receiver. This centralised strategy limits the localization capabilities of the receiver using LTE signals. For instance, LTE BSs from different networks can be tracked, but they cannot be used for positioning because they do not share the same E-SMLC. Thus, the downlink synchronization of LTE BSs allows standalone positioning with ToA, as well as it facilitates opportunistic positioning between signals of different networks or even technologies. This section describes the main considerations for opportunistic ToA positioning and its application with LTE signals.

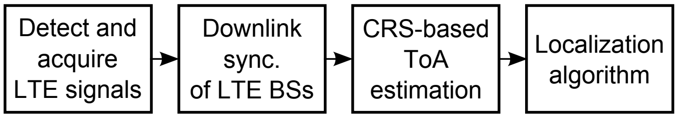

Fig. 2. Proposed opportunistic ToA positioning with CRSs in LTE.

### A. Opportunistic solution

Opportunistic positioning is aimed at calculating the position of the receiver independently of the system under use. This implies that the system will not support the receiver with any assistance data for positioning. In LTE, the location of the BSs may be obtained in public databases, but there are no time stamps to indicate the exact start time of the radio frame for each BS. As result, there are clock biases between BSs that cannot be corrected with a localization algorithm based on ToA estimates. Thus, the downlink synchronization of BSs presented in the previous section is proposed to allow the use of ToA measurements for standalone positioning. This does not require any communication between the receiver and the LTE network, resulting in opportunistic positioning.

The proposed opportunistic solution for LTE is shown in Figure 2. Once the LTE signals from several BSs have been detected and acquired, tracking loops are used with the CRSs to obtain stable measurements of time-delay and frequency offsets. Then, the UE should remain static at a known position with LoS conditions in order to estimate the ToF between BSs and UE. The downlink synchronization is completed with the correction of the timing offsets between BSs, being the UE able to move within the coverage of the BSs tracked. The outputs of the DLL filter are used as ToA estimates. Finally, the UE position is calculated with a localization algorithm able to compute the two-dimensional (2D) coordinates and the clock bias at the receiver, thus a minimum of three BSs is required. In case only two BSs are used, the problem becomes ill-conditioned, and the clock bias has to be solved separately. An ad-hoc solution is to compensate the clock drift by using the SFO estimated during the synchronization. Since a very accurate modelling of the clock drift is required, the clock parameters should be periodically updated at static positions. In addition, the position solution with only two BSs is ambiguous, because there are two possible solutions, specially critical when the receiver location intersects the line between the two BSs. As it is proposed in [15], this ambiguity can be solved using a Kalman filter with a motion model, which is able to remove one of the two position solutions by limiting the receiver movement in terms of speed and heading direction. The UE position (among the two possible solutions) can also be determined by the received power of neighbour BSs, which can be WiFi, GSM, UMTS or LTE transmitters at known locations. Finally, a coarse GNSS position can be used as initial location estimate in the localization algorithm. Thus, the clock drift is still a major issue, because the ambiguity on the position could be properly solved in most of the cases.

In SFN networks, the acquisition, tracking and positioning performance can be degraded due to inter-cell interference [4], especially in networks with high data traffic load. Interference cancellation techniques can be implemented as in [16]. Otherwise, the opportunistic solution is fully applicable with signals transmitted at different frequency bands.

### B. Localization algorithm

Localization algorithms using wireless communications have been widely studied in the literature, such as in [17] and [18]. Thus, many techniques can be applied to achieve the opportunistic position solution. The non-linear least squares (NLS) method is here introduced, since it is one of the most common and well-known techniques.

Let us define the distance or range between the receiver and the $L$ most powerful BSs as

$$d_i = c\tau_{\mathrm{d},i} = |\mathbf{x} - \mathbf{x}_i| = \sqrt{(x - x_i)^2 + (y - y_i)^2}, \quad (8)$$

where $c$ is the speed of light, $\tau_{\mathrm{d},i}$ is the ToF between receiver and BS $i$, being $i = 1, \ldots, L$, $\mathbf{x} = [x, y]^{\mathrm{T}}$ is the position of the receiver, and $\mathbf{x}_i = [x_i, y_i]^{\mathrm{T}}$ is the position of BS $i$. The estimated distances or pseudoranges are computed as

$$\hat{\mathbf{d}} = \mathbf{d} + b + \mathbf{e}, \quad (9)$$

where $\mathbf{d} = [d_1, d_2, \ldots, d_L]^{\mathrm{T}}$, $b$ is the clock bias, and $\mathbf{e} = [e_1, e_2, \ldots, e_L]^{\mathbf{T}}$ are pseudorange errors. The NLS minimization is formulated as [18]

$$\hat{\boldsymbol{\theta}} = \arg\min_{\boldsymbol{\theta}} \left\{ \|\mathbf{d} - \hat{\mathbf{d}}\|^2 \right\}, \quad (10)$$

where $\boldsymbol{\theta} = [x, y, b]^T$, being its estimation $\hat{\boldsymbol{\theta}}$. The solution to this problem can be obtained with numerical search methods, such as the Gauss-Newton algorithm [18]. Using this method, the approximate solution at the $\ell$-th iteration results in [14]

$$\hat{\boldsymbol{\theta}}_\ell = \hat{\boldsymbol{\theta}}_{\ell-1} + \left(\mathbf{D}^T \mathbf{D}\right)^{-1} \mathbf{D} \cdot \hat{\mathbf{e}}, \quad (11)$$

where the Jacobian matrix of $\boldsymbol{\theta}$ is

$$\mathbf{D} = \begin{bmatrix} \frac{x_1 - x}{d_1} & \frac{y_1 - y}{d_1} & -1 \\ \frac{x_2 - x}{d_2} & \frac{y_2 - y}{d_2} & -1 \\ \vdots & \vdots & \vdots \\ \frac{x_L - x}{d_L} & \frac{y_L - y}{d_L} & -1 \end{bmatrix}, \quad (12)$$

and $\hat{\mathbf{e}} = \mathbf{d} - \hat{\mathbf{d}}$ is the estimation of the pseudorange error. As a remark, the Gauss-Newton algorithm may imply a high computational cost and requires a good initialization of the estimation parameters $\boldsymbol{\theta}$ [18].

The precision of the localization algorithm is dependant on the location of the BSs. The geometric dilution of precision (GDOP) is a metric to measure the geometric quality of the position determination, and it is computed as [14]

$$\mathrm{GDOP} = \sqrt{\mathrm{tr}\left\{\boldsymbol{\Sigma}_{\boldsymbol{\theta}}\right\}} = \sqrt{\mathrm{tr}\left\{\left(\mathbf{D}^{\mathrm{T}}\mathbf{D}\right)^{-1}\right\}}, \quad (13)$$

where $\boldsymbol{\Sigma}_{\boldsymbol{\theta}}$ is the covariance matrix of $\boldsymbol{\theta}$.

## IV. RESULTS

Opportunistic ToA positioning is assessed in this section with a example scenario using two and three LTE BSs. Real LTE signals are emulated in the laboratory considering the true location of two BSs in a deployed network, and a third BS is added to complement the analysis. First, the receiver is static at a known position, in order to achieve the proposed downlink synchronization. Then, the receiver follows a dynamic trajectory, where opportunistic ToA positioning is applied. The RF signals are captured with a universal software radio peripheral (USRP) board and post-processed with the LTE software receiver in MATLAB. Results are shown at ranging and position level, with special attention on the position bias.

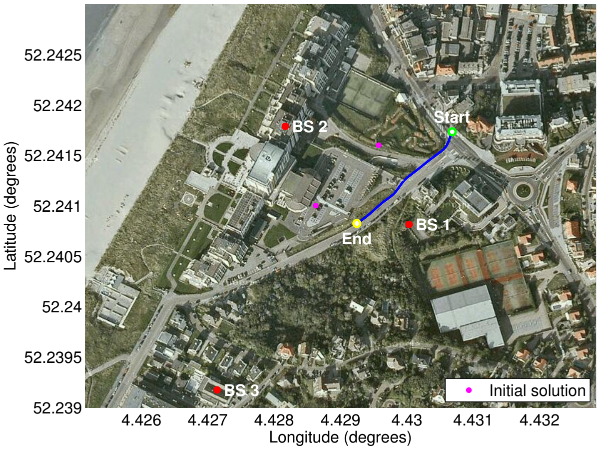

Fig. 3. Emulated scenario at the ENL for opportunistic ToA positioning with three LTE BSs at 816 MHz using 1.4-MHz signal bandwidth.

### A. Test-bed description

The example experiment is conducted in the European Navigation Laboratory (ENL) at the European Space Agency (ESTEC, The Netherlands). Similarly to the test-bed used in [19], three LTE BSs are emulated with two Spirent E2010S network emulators, and the trajectory of the receiver is applied with a Spirent VR5 HD spatial channel emulator. The BSs transmit on the same carrier frequency of 816 MHz at band 20 with a bandwidth of 1.4 MHz. As it is shown in Figure 3, the location of the BS 1 and BS 2 is based on a commercial network in the municipality of Noordwijk, The Netherlands, whose information is provided in [20]. The location of BS 3 is added in order to complete the study case. This scenario is defined to have LoS conditions between the three BSs and the receiver trajectory, which is depicted with a blue line in Figure 3. The receiver is stopped at a known position during 100 seconds, approximately, and then moves at a speed of 0.5 meters per second for 143 meters. The expected ToA is shown in Figure 4. Since the purpose of this experiment is to assess the synchronization-induced bias on the UE localization, the received SNR is defined according to the UE link budget, and only AWGN channel is considered.

The RF front-end of the receiver is based on a USRP equipped with DBSRX2 daughterboard. An external reference clock is used with a 10-MHz reference signal, generated by an active hydrogen maser. This reference oscillator is a type of atomic clock with better stability than off-the-shelf crystal oscillators, but similar experimental results should be obtained if signal tracking is maintained [19]. The sampling frequency is set to 2 MHz, and downsampled to 1.92 MHz in MATLAB. For sake of simplicity, the cell detection and acquisition is aided with prior knowledge of the cell IDs. This acquisition could be achieved without assistance data by implementing an interference cancellation technique [16]. Then, the received signal is tracked using the architecture described in Section

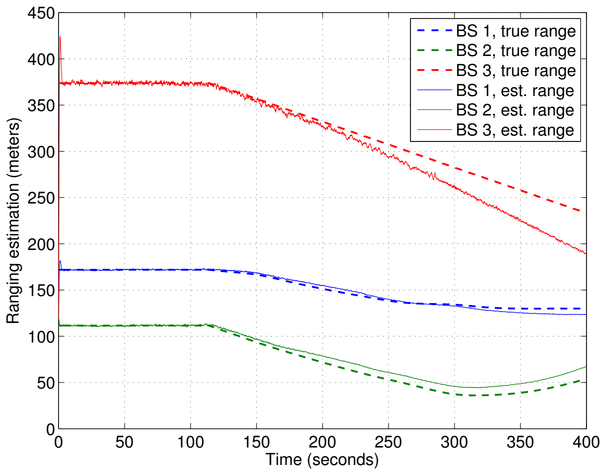

Fig. 4. ToF measurements or ranging estimation of the BSs after applying the proposed synchronization method.

II. The time-delay and frequency estimates are obtained with the CRS symbols, where those symbols with high inter-cell interference are not considered. The integration time is set to 100 ms, and the noise bandwidth of the DLL and FLL is set to 0.5 Hz and 1 Hz, respectively. As it is described in Section III-B, the NLS algorithm is implemented with the Gauss-Newton search, using the ToA measurements filtered by the DLL. Two scenarios are defined by considering only two or three BSs. In both cases, the localization algorithm is computed considering two initial solutions, as it is shown in Figure 3. The best position solution is assumed to be chosen.

### B. *Ranging performance*

Once the tracking loops are locked, the proposed downlink synchronization is performed during the first 100 seconds. For this purpose, the LS fitting in (6) is applied to the sampling period NCO updates over 90 seconds (after the lock-in of the tracking loops). The resulting LS estimates are used as in (7) to obtain synchronized ToA measurements. The values of $\bar{\xi}$ and $\bar{\rho}$ are also projected after the downlink synchronization in order to minimize the residual clock drift. The ToA estimates are compared with the true ranges in Figure 4. As it can be seen, there is a residual sampling period that is not compensated during the LS fitting. This results in a ranging error that increases over time, as it is shown in Figure 5. The standard deviation of the synchronization error with static UE is approximately 0.5 meters for BS 1 and BS 2, and 1.4 meters for BS 3. This difference is due to the dependency between ranging accuracy and received power, as it is shown in Figure 6 by using the SNR estimator in [21]. The precise synchronization achieved does not ensure that the projected sampling period is free of error, neither accounts for drifts on the oscillator. Even if the receiver oscillator is the same for both BSs, the ranging errors are different due to the decoupled estimation applied to each BS in the LS fitting.

### C. *Position performance*

The NLS localization algorithm, presented in Section III-B, is used to calculate the UE position considering only two and three BSs, and the resulting position errors are analysed.

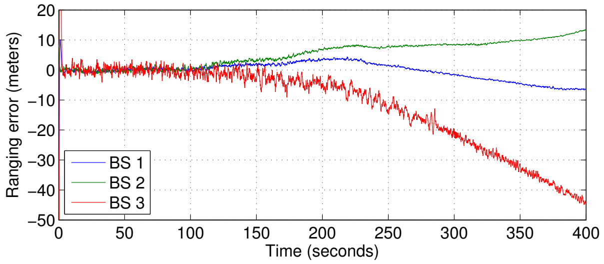

Fig. 5. Ranging errors with respect to the true range between BSs and receiver, using the proposed downlink synchronization.

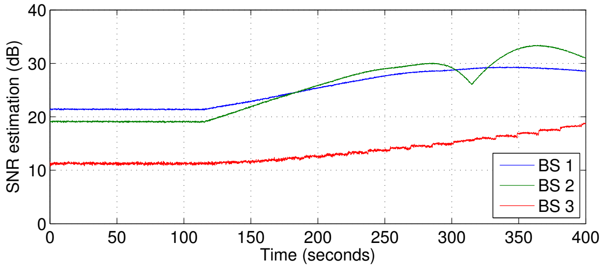

Fig. 6. SNR estimation of the LTE received signals from three BSs.

In the first case, the synchronized ToA estimates of the two most powerful BSs (i.e. BS 1 and BS 2) are used to compute the 2D coordinates, while the clock bias cannot be estimated. Two initial solutions at fixed positions, shown in Figure 3, are introduced in the Gauss-Newton search, and the UE position solution with minimum error is considered. The resulting position error is shown in Figure 7. The bias of the position with two BSs is below one meter during the first 100 seconds (i.e. UE static position). In contrast, the residual sampling period error increases over time, and it produces a considerable position bias. The maximum position error is 20 meters at 330 seconds due to the ambiguity on the ToA solution. Still, the residual error on the clock is expected to introduce a higher bias at long term. Thus, the use of only two BSs for opportunistic ToA positioning requires accurate signal tracking and precise clock at the BSs and at the receiver, or periodic downlink synchronization of the two BSs.

The localization problem can be relaxed by using three BSs in order to solve the receiver clock unknown. Considering the same procedure as in the previous case, the ToA estimates are here synchronized with the average estimation of the LS fitting values (i.e. $\bar{\xi}$ and $\bar{\rho}$) over the three BSs (i.e. coupled estimation). Since the initial solution for the clock bias is set to zero, this coupled synchronization of ToA estimates provides a good initialization of the NLS algorithm. The position errors using three BSs are compared with the results using two BSs in Figure 7. As it can be noticed, the position bias using three BSs is around 10 meters with a static UE. The performance improves as the UE moves closer to BS 3, achieving a localization accuracy of 0.36 meters. In addition to the improvement of the SNR, the results obtained with three BSs are mainly due to the geometry of the UE with respect to the BSs. As it is shown in Figure 7, the GDOP is really high at the beginning, implying a poor geometry, and it improves as the UE moves with its trajectory. Finally, the clock bias estimated by the NLS algorithm is shown in Figure 8. The

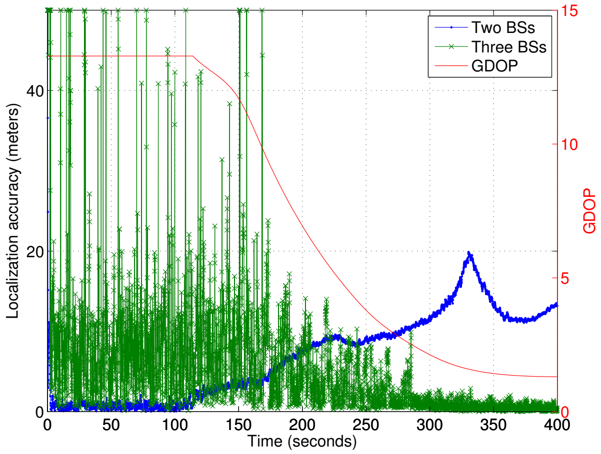

Fig. 7. Position errors obtained with opportunistic ToA positioning using two and three LTE BSs, and GDOP of the experimental scenario.

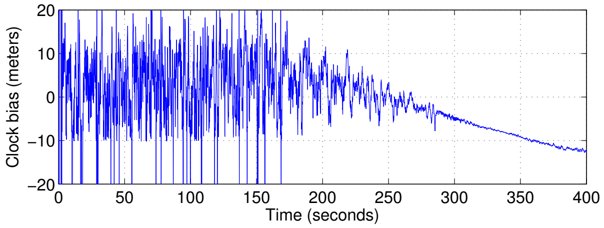

Fig. 8. Clock bias estimation of the NLS algorithm using three BSs.

resulting clock error mostly coincides with the residual drift of the position solution obtained when using only two BSs.

The results obtained in the laboratory validate the precise synchronization achieved with the proposed method, allowing the use of LTE signals as signals of opportunity for standalone positioning. An optimization of the localization algorithm to maximize the accuracy with respect to the number and quality of BSs in view is left for future work, with special interest on handover situations. This study can be complemented with additional sources of error, such as multipath or interference.

## V. CONCLUSION

This paper proposes a method to synchronize Long Term Evolution (LTE) base stations (BSs) for opportunistic time-of-arrival (ToA) positioning. This downlink synchronization allows the receiver to compute its position standalone, since network-based positioning methods using ranging measurements might not be available in current network deployments. The proposed synchronization is achieved by using the time-of-flight (ToF) between BSs and receiver, and considering the known position of the receiver during the synchronization process. The synchronization procedure is validated by using real LTE signals emulated in the laboratory, considering a receiver that follows a certain dynamic trajectory in a realistic scenario with two and three LTE BSs. The proposed solution can achieve a localization accuracy below one meter by using 100 ms of integration time and three BSs, transmitting with 1.4-MHz bandwidth in line-of-sight (LoS) conditions. The optimization of the opportunistic ToA localization algorithm using LTE signals is left as future work.

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