Performance Analysis of Hybrid GNSS and LTE Localization in Urban Scenarios

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Abstract—Severe performance degradation of Global Navigation Satellite Systems (GNSS) is produced in urban scenarios, mainly due to dense multipath and non-line-of-sight (NLoS) conditions. Thus, the integration of GNSS with additional positioning systems, such as the location methods in Long Term Evolution (LTE) cellular systems, may cope with these challenging scenarios. This work proposes a generic evaluation model to assess the performance of hybrid GNSS and LTE positioning in representative urban environments. This assessment considers field GNSS observables and simulated LTE time-of-arrival (ToA) measurements. The evaluation results show the need to enhance hybrid positioning solutions within future cellular standards.

I. INTRODUCTION

Current fourth-generation (4G) and future fifth-generation (5G) cellular systems are expected to provide complementary positioning technologies to Global Navigation Satellite Systems (GNSS), mainly in urban or harsh environments with low satellite visibility. As an example, the Long Term Evolution (LTE) standard in [1] is adopted worldwide and supports dedicated positioning services based on time-difference of arrival (TDoA) methods. Thus, hybrid GNSS and LTE solutions are expected to enhance the localization accuracy and robustness of each system stand-alone.

Hybrid localization of GNSS and cellular systems has been studied in the literature with trilateration algorithms, such as in [2] and [3]. The results show the importance of using additional ranging measurements when there is a lack of visible satellites. Thus, the use of hybrid positioning methods may be necessary to fulfil high accuracy and reliability requirements introduced by navigation applications, such as E911 emergency services [4] or 5G mission-critical applications [5]. However, the main efforts of the 3GPP consortium have been focused on LTE stand-alone positioning, such as in [6], where TDoA-based methods are shown to fulfil a horizontal accuracy of 50 meters for the 67% of 911 calls required in [4]. In this sense, the hybrid GNSS and LTE approach has not been extensively evaluated in representative urban scenarios.

This paper aims to provide a simple methodology to assess the performance of hybrid GNSS and LTE solutions. For this purpose, a simple and generic evaluation model is proposed by considering field GNSS observables, visibility of satellites in urban scenarios, real LTE base station (BS) locations, and simulated LTE measurements. The performance analysis is also aimed to motivate the inclusion of enhanced hybrid positioning within future 4G and 5G standards.

The outline of the paper is as follows: Section II introduces the expected LTE ranging performance, Section III describes the hybrid localization algorithm, Section IV describes the proposed evaluation model, Section V shows the performance results, and Section VI draws the conclusions and future work.

II. LTE RANGING PERFORMANCE

The most accurate positioning methods in LTE are based on GNSS and TDoA measurements, as it is reviewed in [7]. The TDoA estimates are computed with downlink and uplink LTE pilot signals [1], resulting in the observed TDoA (OTDoA) and uplink TDoA (UTDoA) location methods [8], respectively. Since the physical propagation channel is the same for both OTDoA and UTDoA methods, the main performance difference between both methods is due to inter-cell or inter-UE interference. The LTE standard specifies a dedicated positioning reference signal (PRS) for OTDoA measurements, which mitigates the interference between serving and neighbour BSs by using a mutting pattern [8]. In contrast, the sounding reference signal (SRS) used for UTDoA has only a power control mechanism, which is not dedicated for positioning. In addition, considering a LTE system bandwidth of 10 MHz, the BS transmit power is set, in [6], to 46, 30 and 24 dBm for an outdoor macro cell, outdoor small cell and indoor small cell, respectively, while the transmit power of the user equipment (UE) is 23 dBm. Thus, interference cancellation may be required in UTDoA in order to achieve a similar positioning performance to OTDoA.

Since the network operator can dedicate resources to mitigate interference, the major source of ranging error is multipath. Thus, this section focuses on the assessment of the LTE positioning performance in multipath scenarios without interference, by considering PRS ranging measurements. This OTDoA analysis can also be extended to UTDoA positioning, by assuming similar received power and ranging estimators.

A. Threshold-based Ranging Estimator

Ranging measurements are typically based on the maximum likelihood (ML) time-delay estimation (TDE). Considering additive white Gaussian noise (AWGN) channels, the ML estimator results in the matched filter or crosscorrelation between received and pilot signals. However, in urban scenarios, a ranging bias is introduced due to multipath. Thus, threshold-based ranging estimators are widely used for multipath mitigation [9], due to their low complexity. These techniques estimate the time delay τ by finding the first peak of the correlation function above the likelihood threshold Λ_{thr} . Then, the TDE is defined as [9]

$$\hat{\tau} = \min_{\tau_{\min} \le \tau < \tau_{\max}} \{\tau\} \quad \text{s.t.} \quad \Lambda(\tau) \ge \Lambda_{\text{thr}}, \tag{1}$$

where the estimation range is bounded by τ_{\min} and τ_{\max} , and the likelihood function is

$$\Lambda(\tau) = \sum_{k \in \mathcal{K}} \left| \sum_{n \in \mathcal{N}} X(k, n) \cdot b^*(k, n) \cdot e^{-j\frac{2\pi n\tau}{N}} \right|^2, \quad (2)$$

being X(k, n) the frequency received signal and $b^*(k, n)$ the conjugate pilot at k-th OFDM symbol within the set of pilot symbols \mathcal{K} , and n-th subcarrier within the set of pilot subcarriers \mathcal{N} from a total of N subcarriers. Several methods to design the threshold Λ_{thr} are provided in [9]. A heuristic approximation of the likelihood threshold is here defined as

$$\Lambda_{\rm thr} \simeq \frac{1}{4} \cdot \max\left\{\Lambda\left(\tau\right)\right\}. \tag{3}$$

The estimation range is set by $\tau_{\min} = -T_s$ and $\tau_{\max} = T_s$, where the sampling period is $T_s = T/N$, being $T = 1/F_{sc}$ the OFDM symbol period with subcarrier spacing $F_{sc} = 15$ kHz.

B. Accuracy of Threshold-based Ranging Estimates

The threshold-based ranging estimators attain the minimum achievable variance for AWGN channels, which is defined by the Cramér-Rao bound (CRB), written in [9] and [10] as

$$\operatorname{var}\left(\tau\right) \ge \operatorname{CRB}(\tau) = \frac{T^2}{8\pi^2 \cdot \operatorname{SNR} \cdot \sum_{n \in \mathcal{N}} p_n^2 \cdot n^2}, \quad (4)$$

where SNR is the signal-to-noise ratio, and p_n^2 is the relative power weight of subcarrier *n*. Then, the carrier-to-noise ratio is $C/N_0 = \text{SNR} \cdot B$. Considering the PRS, the signal bandwidth is defined as $B_{\text{PRS}} = N_{\text{PRS}} \cdot F_{\text{sc}} = (12 \cdot N_{\text{RB}} - 4) \cdot F_{\text{sc}}$, where N_{RB} is the number of resource blocks (RB). The rootmean-square error (RMSE) of the threshold-based estimator in (1) is here computed with 1000 Montecarlo simulations for a integration period equal to *T* and AWGN channel. The resulting RMSE attains the CRB for medium to high C/N_0 , as it can be seen in Figure 1. Their RMSE departs from the CRB given a threshold C/N_0 equal to $(C/N_0)_{\text{thr}} = 60$ dB-Hz.

Nevertheless, the performance of these techniques is limited by multipath, which induces a bias on the TDE. The 3GPP LTE standard defines multipath channel models based on tapped-delay line (TDL) models in [11] and geometry-based stochastic channel models (GSCM) in [12]. Let us consider the widely adopted TDL models, known as Extended Pedestrian A (EPA), Extended Vehicular A (EVA) and Extended Typical



Fig. 1. RMSE and CRB of the threshold-based ranging estimates with PRS for LTE system bandwidths over AWGN and ETU multipath channels.

TABLE I. RMSE (IN METERS) OF THRESHOLD-BASED RANGING ESTIMATES FOR $C/N_0 = 70$ DB-Hz using LTE PRS and 3GPP TDL MULTIPATH CHANNEL MODELS (1000 MONTECARLO SIMULATIONS).

Multipath channel		System bandwidth (MHz)						
Model	Conditions	1.4	3	5	10	15	20	
EPA	$P_{\rm LoS} = 0.87$	32.11	24.12	21.49	13.41	9.81	6.83	
	$P_{\rm NLoS} = 0.13$	27.44	25.54	24.81	17.47	14.94	12.20	
	LoS/NLoS	31.52	24 31	21.96	14 01	10.66	7 76	
	LODITIEOD	01102	2	21.20	1 1101	10.00	/1/0	
EVA	$P_{LoS} = 0.81$	96.35	43.95	25.22	10.38	6.14	4.86	
	$P_{\rm NLoS} = 0.19$	119.24	54.93	36.33	16.82	11.07	10.63	
	LoS/NLoS	101.21	46.14	27.58	11.89	7.32	6.37	
ETU	$P_{LoS} = 0.63$	102.43	52.37	30.60	13.26	7.74	5.42	
	$P_{\rm NLoS} = 0.37$	111.51	65.19	37.75	20.34	14.19	8.99	
	LoS/NLoS	105.86	57.39	33.34	16.29	10.66	6.95	

Urban (ETU), which have a delay spread of 410 ns, 2.51 μ s and 5 μ s, respectively. As it is shown in Figure 1 and Table I, the RMSE of the threshold-based estimator is also computed over these multipath TDL models. Considering a LTE system bandwidth of 10 MHz, as in [6], the ranging accuracy is between 10 and 20 meters depending on the multipath channel.

The LoS and NLoS conditions are also considered within these multipath models. By assuming LoS only if the first path gain normalized by the channel gain is above -6 dB, the highest NLoS probability occurs with the ETU model, and the smallest with the EPA model. As it is shown in Table I, the ranging accuracy is degraded for NLoS conditions. The ranging accuracy can be enhanced with advanced multipath mitigation techniques, which have been proposed for LTE OTDoA in [13] and [14]. However, these advanced techniques are out of the scope of this paper.

C. LoS Probability in Urban Scenarios

The LoS probability depends on the distance and height of the mobile device with respect to the BS. This probability is defined for the urban macro-cell (UMa) scenario in [12] as

$$P_{\rm LoS} = \left(\min\left(\frac{18}{d_{\rm BS}}, 1\right) \cdot \left(1 - e^{-\frac{d_{\rm BS}}{63}}\right) + e^{-\frac{d_{\rm BS}}{63}}\right) \cdot (1 + C_{\rm h})$$
(5)

where $d_{\rm BS}$ is the horizontal distance between receiver and BS, and $C_{\rm h}$ is a height compensation term, which depends on the height of the receiver. Although the TDL models have a fixed LoS probability, as it shown in Table I, the LoS probability in (5) can be used to select the adequate channel model.

III. HYBRID GNSS AND LTE LOCALIZATION

Hybrid localization is supported by the LTE standard [8], but there is no specification of the location algorithms. Thus, the network operators use proprietary hybrid solutions with the available location methods. These solutions are typically based at the network location server or evolved serving mobile location centre (E-SMLC), because most of the measurements and network information are gathered and processed by the E-SMLC. In LTE, there are mobile-based or network-based location methods, depending on whether the position is computed at the mobile receiver or at the E-SMLC. However, the standard does not allow to provide (to the receiver) the location information gathered at the E-SMLC, such as the location of the LTE BSs or their transmission time, which prevents the computation of the OTDoA location at the receiver. An example of mobile-based location method is assisted GNSS (A-GNSS), because LTE mobile devices integrate GNSS chipsets able to compute the location with and without assistance data. Therefore, the GNSS pseudoranges and the OTDoA or UTDoA measurements are processed at the E-SMLC to compute the hybrid GNSS and LTE localization. This section describes a general network-based hybrid location algorithm, considering only the downlink LTE positioning approach. Nonetheless, the derivation is also applicable to the uplink location approach.

A. General Location Solution

Let us consider a three-dimensional (3D) mobile location $\mathbf{x} = [x, y, z]^{\mathrm{T}}$ to be unknown and M satellite or terrestrial transmitters, whose location is known and equal to $\mathbf{x}_m = [x_m, y_m, z_m]^{\mathrm{T}}$ for $m = 1, \ldots, M$. The distance or range between the receiver and the *m*-th transmitter is defined as

$$r_m = c \cdot \tau_m = \|\mathbf{x}_m - \mathbf{x}\|,\tag{6}$$

where c is the speed of light, τ_m is the propagation time delay or difference between ToA $t_{m,RX}$ and transmission time $t_{m,TX}$, i.e., $\tau_m = t_{m,RX} - t_{m,TX}$, and $\|\cdot\|$ is the Euclidean distance. The measured distance or observed pseudorange at the mobile receiver is

$$\rho_m = c \cdot \hat{\tau}_m = \|\mathbf{x}_m - \mathbf{x}\| + c \cdot \delta t + e_m, \tag{7}$$

where $\hat{\tau}_m$ is the time-delay estimate, δt is the unknown receiver clock offset, and e_m is the pseudorange error. The vector of unknown parameters is then $\boldsymbol{\theta} = [x, y, z, \delta t]^{\mathrm{T}}$. Thus, the solution to this problem is formulated with the well-known nonlinear least squares (NLS) minimization [15]

$$\hat{\boldsymbol{\theta}} = \arg\min_{\boldsymbol{\theta}} \left\{ \|\boldsymbol{\rho} - \hat{\boldsymbol{\rho}}\|^2 \right\},\tag{8}$$

where $\boldsymbol{\rho} = [\rho_1, \dots, \rho_M]^{\mathrm{T}}$, and $\hat{\boldsymbol{\rho}} = [\hat{\rho}_1, \dots, \hat{\rho}_M]^{\mathrm{T}}$ is the vector of approximate pseudoranges, which is defined by

$$\hat{\rho}_m = \|\mathbf{x}_m - \hat{\mathbf{x}}\| + c \cdot \delta t + \alpha_m, \tag{9}$$

being $\hat{\mathbf{x}} = [\hat{x}, \hat{y}, \hat{z}]^{\mathrm{T}}$ the estimated position, $\hat{\delta t}$ the estimated receiver clock offset, and α_m the pseudorange correction.

Considering $M \ge 4$, an iterative method, i.e., Gauss-Newton (GN) algorithm [15], is here used to solve (8). The GN solution at the ℓ -th iteration is

$$\hat{\boldsymbol{\theta}}\left(\ell\right) = \hat{\boldsymbol{\theta}}\left(\ell-1\right) + \left(\mathbf{G}^{\mathrm{T}}\mathbf{G}\right)^{-1}\mathbf{G}^{\mathrm{T}}\cdot\hat{\mathbf{e}},\tag{10}$$

where $\hat{\mathbf{e}} = \boldsymbol{\rho} - \hat{\boldsymbol{\rho}}$ and the geometry or Jacobian matrix of $\boldsymbol{\theta}$ is

$$\mathbf{G} = \begin{bmatrix} \frac{x_1 - \hat{x}}{\hat{\rho}_1} & \frac{y_1 - \hat{y}}{\hat{\rho}_1} & \frac{z_1 - \hat{z}}{\hat{\rho}_1} & -1\\ \frac{x_2 - \hat{x}}{\hat{\rho}_2} & \frac{y_2 - \hat{y}}{\hat{\rho}_2} & \frac{z_2 - \hat{z}}{\hat{\rho}_2} & -1\\ \vdots & \vdots & \vdots & \vdots\\ \frac{x_M - \hat{x}}{\hat{\rho}_M} & \frac{y_M - \hat{y}}{\hat{\rho}_M} & \frac{z_M - \hat{z}}{\hat{\rho}_M} & -1 \end{bmatrix}}.$$
 (11)

B. Hybrid Location Solution

The location solution derived in the previous section can also be used for the hybrid approach, where the pseudoranges are computed from more than one satellite or terrestrial system. Let us consider P location systems with a total number of transmitters equal to

$$L = \sum_{p=1}^{P} M_p, \tag{12}$$

where M_p is the number of synchronized transmitters for the *p*-th system. Since each system operates in a certain frequency band, the RF front-end may introduce a different clock offset for each system. Thus, additional unknowns are added for the hybrid location problem, resulting in $\boldsymbol{\theta}_{\text{hyb}} = [x, y, z, \delta \mathbf{t}]^{\text{T}}$ with $\delta \mathbf{t} = [\delta t_1, \dots, \delta t_Q]$ for $Q \leq P$ clock offsets. Thus, the hybrid GN solution at the ℓ -th iteration is

$$\hat{\boldsymbol{\theta}}_{\text{hyb}}\left(\ell\right) = \hat{\boldsymbol{\theta}}_{\text{hyb}}\left(\ell-1\right) + \left(\mathbf{H}^{\text{T}}\mathbf{H}\right)^{-1}\mathbf{H}^{\text{T}}\cdot\hat{\mathbf{e}}_{\text{hyb}},\qquad(13)$$

where $\hat{\mathbf{e}}_{\text{hyb}} = \boldsymbol{\rho}_{\text{hyb}} - \hat{\boldsymbol{\rho}}_{\text{hyb}}$, being $\boldsymbol{\rho}_{\text{hyb}} = [\rho_1, \dots, \rho_L]^{\text{T}}$ and $\hat{\boldsymbol{\rho}}_{\text{hyb}} = [\hat{\rho}_1, \dots, \hat{\rho}_L]^{\text{T}}$ the observed and approximate pseudoranges of multiple systems, respectively. The hybrid geometry matrix is defined by

$$\mathbf{H} = \begin{bmatrix} \mathbf{A}_{xyz} & -\mathbf{A}_{\delta t} \end{bmatrix},\tag{14}$$

where the Jacobian matrix of the 3D location is

$$\mathbf{A}_{xyz} = \begin{bmatrix} \mathbf{a}_1, \dots, \mathbf{a}_m, \dots, \mathbf{a}_L \end{bmatrix}^{\mathrm{T}},$$
(15)

being $\mathbf{a}_m = \begin{bmatrix} \frac{x_m - \hat{x}}{\hat{\rho}_m} & \frac{y_m - \hat{y}}{\hat{\rho}_m} & \frac{z_m - \hat{z}}{\hat{\rho}_m} \end{bmatrix}^{\mathrm{T}}$, and the Jacobian matrix of the clock offsets $\mathbf{A}_{\delta t}$ is a $L \times Q$ matrix filled with ones for any *m*-th pseudorange corresponding to the *q*-th clock and filled with zeros otherwise, e.g.

$$\mathbf{A}_{\delta t} = \begin{bmatrix} \mathbf{1}_{M_1 \times 1} & \mathbf{0}_{M_1 \times 1} & \cdots & \mathbf{0}_{M_1 \times 1} \\ \mathbf{0}_{M_2 \times 1} & \mathbf{1}_{M_2 \times 1} & \cdots & \mathbf{0}_{M_2 \times 1} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0}_{M_Q \times 1} & \mathbf{0}_{M_Q \times 1} & \cdots & \mathbf{1}_{M_Q \times 1} \end{bmatrix}$$
(16)

for P = Q, being 1 and 0 vector of ones and zeros, respectively. Thus, the number of observed pseudoranges required to compute the hybrid solution is $L \ge 3 + Q$.

C. GNSS Pseudorange Corrections

System and propagation errors are corrected within the computation of the approximate GNSS pseudoranges in (9). The navigation message provides general corrections, which are then included in α_m , resulting in the following expression

$$\hat{\rho}_{\text{GNSS},m} = \|\mathbf{x}_{\text{GNSS},m} - \hat{\mathbf{x}}\| + c \cdot \left(\hat{\delta t} - \delta t_{\text{GNSS},m}\right) + T_m + I_m$$
(17)

where $\mathbf{x}_{\text{GNSS},m}$ is the location of the *m*-th GNSS satellite, $\delta t_{\text{GNSS},m}$ is the satellite clock offset, T_m is the tropospheric error, and I_m is the ionospheric error. Additional corrections can be used to enhance the accuracy of the approximate pseudoranges, such as in precise point positioning (PPP). One of these corrections is the GPS-Galileo time offset (GGTO), which is the clock offset between the GPS and Galileo reference times [16]. The receiver front-end usually introduces an additional offset between GPS and Galileo pseudoranges, which may be calibrated and re-used to remove one clock offset unknown within the multi-constellation or hybrid location algorithm.

D. LTE ToA Measurements

The LTE standard specifies downlink and uplink TDoA estimates, called reference signal time difference (RSTD) and relative time-of-arrival (RTOA) measurements [17], respectively. Since ToA and TDoA measurements result in the same location performance for the current problem [18], our study considers only ToA measurements. Thus, similarly to GNSS, the LTE ToA approximate pseudoranges are

$$\hat{\rho}_{\text{LTE},m} = \|\mathbf{x}_{\text{LTE},m} - \hat{\mathbf{x}}\| + c \cdot \left(\hat{\delta t} - \delta t_{\text{LTE},m}\right), \quad (18)$$

where $\mathbf{x}_{\text{LTE},m}$ is the location of the *m*-th LTE BS, and $\delta t_{\text{LTE},m}$ is the BS clock offset with respect to a GNSS reference time, which is assumed to be known by the network.

IV. PROPOSED HYBRID EVALUATION MODEL

A model to evaluate the performance of hybrid GNSS and LTE localization is proposed in this section. This model intends to provide a simple methodology to representatively assess hybrid positioning in urban scenarios. The proposed evaluation model considers real GNSS observables and simulated LTE measurements. The overall architecture of the model is shown in Figure 2.

A. GNSS Elevation Mask over Real Observables

Urban scenarios can be accurately characterized by means of advanced channel models, such as the land mobile multipath channel model [19], or by using ray-tracing techniques [2]. However, the simulation complexity of these methods can increase substantially when considering multiple GNSS constellations. Although multipath is a major source of ranging error in urban environments, the proposed model is aimed to characterize the GNSS signal availability, as a result of the signal obstructions due to surrounding buildings. For this purpose, 3D city models can be used to simulate the signal availability [20], but there may not be public access to them. Thus, we propose a generic model to represent an urban scenario, based on the elevation mask of an urban street.



Fig. 2. Overall architecture of the proposed hybrid evaluation model.



Fig. 3. Elevation mask for a straight street model with north direction depending on the ratio between building height and street width.

Let us consider a straight street with north direction, as it is shown in Figure 3(a). The elevation mask φ of the GNSS signals can be approximated with the ratio between the building height h and the street width d, i.e., 1:R, where R = d/h. Thus, the street proportion can be used to characterize a certain environment, e.g. ratio 1:1 for deep urban, ratio 1:2 for urban, or ratio 1:3 for suburban. For sake of simplicity, the diffraction region at the edge of the building [20] is not considered, the height of the buildings is set to h and the reference position is at the center of the street. Assuming that the azimuth λ follows a north-clockwise convention, the elevation mask is defined as

$$\varphi = \left| \operatorname{atan} \left(\frac{2 \cdot \cos(\lambda)}{R} \right) \right|. \tag{19}$$

The elevation mask of this generic model can be seen with a sky plot for a ratio equal to 1:1, 1:2, and 1:3 in Figure 3(b), where the maximum elevation mask is 63.43, 45, and 33.69 degrees, respectively.

Considering this generic model, real GNSS observables are obtained from GNSS references stations (GRS) in open-sky conditions, which are available in public databases. For instance, the international GNSS service (IGS) provides observables from multiple GNSS constellations in standard formats, such as the receiver independent exchange format (RINEX). These real GNSS observables contain ionospheric, tropospheric and clock errors, among others. In order to simulate a representative urban environment, the elevation mask in (19) is applied to these observables. Since the proposed model only considers visible and healthy satellites, i.e., satellites in LoS with minimum multipath contribution, this model is especially convenient to assess the performance of multi-GNSS professional receivers, where unhealthy satellites are discarded.

B. LTE Simulation of Real Deployments

Since LTE OTDoA and UTDoA are network-based methods, LTE pseudoranges cannot be easily obtained from commercial mobile devices. Thus, the research community typically relies on experimental equipment, such as softwaredefined radio (SDR). Due to the limited access to these terrestrial ranging observables, LTE ToA observables are simulated in this work according to real network deployments.

The conventional and theoretical design of cellular networks is based on the hexagonal cell layout of three-sectorial BSs. However, real deployments are also designed according to implementation and demand criteria, resulting in different cell layouts. Thus, the proposed model considers the location and height of the commercial cell towers, which is typically a public information. This information is used to evaluate a realistic geometry for LTE ToA localization, and to address representative signal levels. For sake of simplicity, the network synchronization offset between BSs is assumed to be known.

The distance between receiver and BS, i.e., $d_{\rm BS}$, is used to calculate the propagation losses, by following the link budget parameters defined in [21]. Given a certain transmit power and antenna pattern, the received C/N_0 for each BS is then computed. According to [22], the subcarrier SNR detection threshold for neighbour cells is SNR_{sc} = -13 dB, which results in $(C/N_0)_{\rm thr} = {\rm SNR}_{\rm sc} \cdot N_{\rm PRS} \cdot B_{\rm PRS} \simeq 84.3$ dB-Hz for a 50-RB PRS. Thus, the proposed methodology assumes the detection of those LTE BSs with received C/N_0 above this threshold, i.e., LTE BSs are only visible if $C/N_0 > (C/N_0)_{\rm thr}$. The LTE ToA observables are then simulated as

$$\tau = d_{\rm BS}/c + \tau_{\rm m} + w, \tag{20}$$

where $\tau_{\rm m}$ is the time-delay error induced by multipath, and $w \sim \mathcal{N}(0, \sigma_w)$ is the AWGN component. The 3GPP standard channel models described in [11] are applied to the simulated LTE signals. The LoS probability computed in (5) is used to select the adequate channel model for each link, i.e., EPA if $P_{\rm L0S} \geq 0.87$, EVA if $0.87 > P_{\rm L0S} \geq 0.63$, and ETU if $P_{\rm L0S} < 0.63$. Then, the LTE ranging observable is estimated with the threshold-based estimator in (1). Finally, the observables from different BSs are arranged in ascending order according to their geometric dilution of precision (GDOP), written as [23]

$$GDOP = \sqrt{\operatorname{tr}\left\{ \left(\mathbf{G}^{\mathrm{T}} \mathbf{G} \right)^{-1} \right\}}.$$
 (21)

Let us define $\mathbf{Q} \doteq (\mathbf{G}^{\mathrm{T}}\mathbf{G})^{-1}$, where \mathbf{G} is expressed in Earthcentered Earth-fixed (ECEF) coordinates. Then, the submatrix \mathbf{Q}_{xyz} is transformed to east north up (ENU) coordinates, as in [24, p.149], in order to define the horizontal dilution of precision (HDOP), i.e., HDOP = $\sqrt{q_{ee} + q_{nn}}$, and the vertical dilution of precision (VDOP), i.e., VDOP = $\sqrt{q_{uu}}$.

The proposed model mainly considers a realistic geometry of BSs, multipath effects and SNR levels, in order to simulate representative LTE ToA measurements. Future work is aimed

TABLE II. GNSS REFERENCE STATIONS IN THE NETHERLANDS, VISIBLE LTE BSS AT THEIR LOCATION, AND HDOP AND VDOP USING ONLY 4 LTE BSS.

Code	Lat.	Lon.	LTE BSs	HDOP	VDOP
AMEL	53.45	5.76	3	-	-
APEL	52.21	5.96	20	2.79	0.13
CAB2	51.97	4.93	6	> 20	> 20
DELF	51.99	4.39	20	1.48	6.73
DLF1	51.99	4.39	20	1.47	5.96
DLF5	51.99	4.39	20	1.47	4.84
IJMU	52.46	4.56	7	14.98	> 20
KOS1	52.17	5.82	6	11.77	> 20
SCHI	53.48	6.16	1	-	-
TERS	53.36	5.22	3	-	-
TXE2	53.04	4.85	1	-	-
VLIE	53.30	5.09	6	> 20	> 20
VLIS	51.44	3.60	13	4.71	> 20
WSRA	52.91	6.60	-	-	-
WSRT	52.91	6.60	-	-	-

to consider more advanced channel models [12], which include distance-dependent LoS conditions.

V. RESULTS

The objective of this section is to validate the proposed model and to assess the hybrid GNSS and LTE positioning performance. First, real GNSS data from Dutch reference stations is combined with simulated LTE data, by considering commercial LTE networks deployed in The Netherlands, in order to assess the proposed model. Second, field GNSS measurements in The Hague are also combined with simulated LTE data to analyse the hybrid GNSS and LTE performance.

A. Evaluation Setup

The evaluation setup is described in the following points:

1) GNSS data from reference stations: Real GNSS measurements from the 10th March 2016 are obtained from the Dutch permanent GNSS array (DPGA), which is a network of GNSS receivers with continuous operation at reference stations. This work only considers those reference stations within the Dutch territory and with public availability. The GRSs used are listed in Table II, and their location is shown in Figure 4(a). Further details of these reference stations can be found in [25]. The RINEX files obtained from these public databases are processed with the open-source functions of the goGPS software [26]. The observables and ephemeris of the GPS, Galileo and GLONASS constellations are only considered in this work, but it could be easily extended to include the BeiDou navigation satellite system (BDS). Since the observation interval is equal to 30 seconds, 2880 GNSS epochs (within 24 hours) are used. Representative urban GNSS pseudoranges are then obtained by applying the elevation mask described in Section IV-A to the real GNSS observables of the reference stations. Three different scenarios result from this procedure: open sky conditions, urban street with ratio 1:1, and urban street with ratio 1:2.

2) GNSS data from field campaign: GNSS observables are collected by a single-frequency mass-market GNSS receiver within a dedicated navigation van from the European Space Agency (ESTEC, The Netherlands). A mass-market GNSS antenna is installed on the roof of the van. The mobile tests are conducted in The Hague, following the trajectory shown in



(b) Vehicle trajectory and LTE BSs in The Hague (origin at $52.065^{\circ}N$, $4.27^{\circ}E$)

Fig. 4. Location of the receiver and LTE BSs evaluated in The Netherlands.

Figure 4(b). The reference trajectory of the vehicle is obtained with the Novatel SPAN and iMAR-FSAS receiver. This receiver combines differential GNSS measurements and the inertial navigation system (INS) into a real-time kinematic (RTK) and a tightly-coupled GNSS/INS positioning solution, resulting in a precise accuracy below one meter. The observation interval is equal to one second, and the GNSS pseudoranges (from GPS, Galileo and GLONASS constellations) were obtained between 06:36:17 and 09:59:17 UTC of the 10th March 2016.

3) Simulated LTE observables: The LTE observables are simulated based on the procedure described in Section IV-B and Figure 2. The location and height of the commercial Dutch LTE BSs (from different network providers) can be found in a public database of the Dutch antenna bureau [27]. The BS location is provided in World Geodetic System 1984 (WGS84) coordinates with an accuracy of 15 meters. The average transmit power of these BSs is above 40 dBm, and their carrier frequency is around 800, 1800 or 2600 MHz. Thus, the mobile device is assumed to provide ToA measurements from the different frequency bands and network operators.

The reference location of the GRSs and the field campaign of the Hague is used to determine the visible LTE BSs at each epoch. For this purpose, the LTE BSs location is converted from WGS84 to ECEF coordinates, by adding the height of the cell tower to the geoid in the case of GRSs and to the altitude of the reference trajectory in the field campaign. For sake of simplicity, a maximum BS transmit power of 46 dBm, a system bandwidth of 10 MHz and carrier frequency of 816 MHz are assumed for every LTE BS. Considering the procedure described in Section IV-B, the available LTE ToA measurements are computed with the corresponding observation interval for a maximum of 20 BSs. The number of LTE BSs for each GRS is shown in Table II, as well as the HDOP and VDOP when using only four LTE BSs. The GRSs with at least four or eight detectable BSs are marked in Figure 4(a). The LTE BS locations for the field campaign scenario are shown in Figure 4(b), where there are always 20 visible LTE BSs for each position of the trajectory.

4) Hybrid GNSS and LTE positioning platform: The real GNSS pseudoranges and the simulated LTE ToA measurements are combined within the NLS solution, which is solved with the GN algorithm. The unknowns are the 3D position and the receiver clock offset for each system, i.e., GPS, Galileo, GLONASS and LTE. Assistance data from the closest reference station is used to correct the GNSS pseudoranges, and the synchronization offset between LTE BSs is assumed to be known. The initial approximate position used at each epoch is obtained from the reference GRS location and reference vehicle trajectory (depending on the scenario), and the initial clock offsets are considered equal to zero. The hybrid multi-GNSS and LTE platform is evaluated with the 3D position error, i.e., $\varepsilon_{\mathbf{x}} = \|\mathbf{x} - \hat{\mathbf{x}}\|$, which is computed in ECEF coordinates, and the 2D or horizontal position error, which is calculated in ENU coordinates. The cumulative density function (CDF) of the 2D and 3D position errors is then computed only for the position fixes.

B. Multi-GNSS Performance

The multi-GNSS solution is assessed with the 2D and 3D position errors. Considering the proposed evaluation model, the GNSS data from the GRSs is used to represent open sky conditions, deep urban scenarios with a street ratio of 1:1, and urban scenarios with a street ratio of 1:2. As it is shown in Figure 5, the best GNSS performance is obtained with full satellite visibility, while its performance is degraded with a considerable reduction of the number of satellites in the urban scenarios. The GNSS results of the field measurements in The Hague indicate that the environment may have a mixture between the resulting elevation mask of the street model with ratio 1:1 and the one of ratio 1:2, being closer to the second.

C. LTE Stand-alone Performance

Since there is a LoS probability of LTE signals below 50% in most of the locations, the ETU channel model is mainly used to characterize the effect of multipath in these simulations. Thus, the main difference between the represented urban scenarios is the geometry of the LTE BSs used for positioning. The position errors are then divided depending on the HDOP of the LTE BSs surrounding the GRSs, and they are compared with the overall LTE stand-alone performance



Fig. 5. Position accuracy and satellite availability of the multi-constellation A-GNSS approach.

for the locations in The Hague. As it can be seen in Figures 6(a) and 6(b) by considering only 4 BSs, the LTE positioning performance in The Hague is similar to the performance obtained for the locations of those reference stations with HDOP around 2. In addition, the low vertical diversity of the LTE BS heights poses major difficulties to achieve an accurate 3D location with LTE, as it could be expected. However, the performance can be considerably enhanced when using 8 BSs in both scenarios, as it shown in Figure 6(c).

D. Hybrid GNSS and LTE Performance

The results of the multi-GNSS and LTE stand-alone solutions highlight that the appropriate definition of the proposed evaluation model can lead to a representative assessment of the positioning performance in urban scenarios. Thus, the street model with ratio 1:1 and HDOP < 2 can be considered characteristic features of harsh urban environments. Using this case, the CDF of the 2D position error is shown for each approach in Figure 7(a). The multi-GNSS solution has a better positioning performance than the LTE stand-alone with 4 and 8 BSs. However, LTE achieves a full position availability, in contrast to a probability of position fix equal to 86.8% for the multi-GNSS approach. For the field trajectory case shown in Figure 7(b) and 7(c), multi-GNSS also outperforms LTE in both cases, since the scenario is not as harsh as in the proposed model with ratio 1:1. The hybrid solution achieves



(c) 2D LTE position error with 8 BS

Fig. 6. Position accuracy of LTE stand-alone approach.

 TABLE III.
 PERFORMANCE OF GNSS AND LTE POSITIONING WITH STAND-ALONE AND HYBRID APPROACHES.

GRS	Prob.	CDF 2	2D positio	n error	CDF 3D position error			
	fix (%)	50%	67%	95%	50%	67%	95%	
Multi-GNSS	86.8	3.42	5.24	22.50	6.63	9.41	43.72	
LTE (4 BS)	100	17.73	22.49	35.45	50.46	75.07	>100	
LTE (8 BS)	100	11.94	15.52	26.39	51.37	73.72	>100	
Hybrid (4 BS)	100	9.33	12.39	22.51	16.25	22.17	59.65	
Hybrid (8 BS)	100	7.75	10.13	18.14	14.60	20.21	53.54	
			CDF 2D position error			CDF 3D position error		
	Prob.	CDF 2	2D positio	n error	CDF 3	BD positio	n error	
The Hague	Prob. fix (%)	CDF 2 50%	D positio 67%	n error 95%	CDF 3 50%	3D positio 67%	n error 95%	
The Hague Multi-GNSS	Prob. fix (%) 98.3	CDF 2 50% 2.05	2D positio 67% 2.86	n error 95% 9.94	CDF 3 50% 4.48	3D positio 67% 5.94	n error 95% 22.78	
The Hague Multi-GNSS LTE (4 BS)	Prob. fix (%) 98.3 100	CDF 2 50% 2.05 17.36	2D positio 67% 2.86 23.66	n error 95% 9.94 >100	CDF 3 50% 4.48 67.26	BD positio 67% 5.94 >100	n error 95% 22.78 >100	
The Hague Multi-GNSS LTE (4 BS) LTE (8 BS)	Prob. fix (%) 98.3 100 100	CDF 2 50% 2.05 17.36 10.13	2D positio 67% 2.86 23.66 13.02	n error 95% 9.94 >100 23.13	CDF 3 50% 4.48 67.26 59.30	BD positio 67% 5.94 >100 90.90	n error 95% 22.78 >100 >100	
The Hague Multi-GNSS LTE (4 BS) LTE (8 BS) Hybrid (4 BS)	Prob. fix (%) 98.3 100 100 100	CDF 2 50% 2.05 17.36 10.13 5.69	2D positio 67% 2.86 23.66 13.02 7.89	n error 95% 9.94 >100 23.13 17.87	CDF 3 50% 4.48 67.26 59.30 9.03	BD positio 67% 5.94 >100 90.90 12.73	n error 95% 22.78 >100 >100 37.18	

an average performance between multi-GNSS and LTE, with a full position availability. A summary of the evaluation results is provided in Table III.

These results show the limitations of LTE positioning due to multipath. Thus, advanced multipath mitigation techniques and a high signal bandwidth should be used in LTE, in order to achieve a high positioning accuracy. In addition, the hybrid location performance could be improved with weighted LS (WLS) or Kalman filter solutions. Further enhancements on hybrid localization should be then considered within future 4G and 5G standards for accurate and robust navigation.



(a) 2D position error with GRS observables, ratio 1:1 and LTE $\mathrm{HDOP} < 2$



(c) 3D position error with field observables

Position error (metres)

60

80

Fig. 7. Position accuracy of GNSS, LTE and the hybrid approaches.

40

20

n

VI. CONCLUSIONS

This work assesses the hybrid positioning performance of Global Navigation Satellite Systems (GNSS) and Long Term Evolution (LTE) cellular systems in urban scenarios. A simple and generic methodology is proposed to evaluate the hybrid approach, by representing an urban environment with a certain elevation mask and real LTE base station (BS) locations. The proposed model is assessed with field GNSS observables and simulated LTE ranging measurements. The results show that the multi-constellation GNSS performance is mainly limited by satellite visibility, while the LTE positioning accuracy is mainly bounded by multipath. Assuming a LTE bandwidth of 10 MHz and outdoor urban scenarios, multi-GNSS achieves the best position accuracy, while LTE and the hybrid approach obtain a full position availability, being the hybrid solution more accurate than LTE stand-alone. Further enhancements of the hybrid solution should be considered for accurate and robust localization within future 4G and 5G applications.

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