Performance Limits of V2I Ranging Localization with LTE Networks

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Abstract—**Emerging vehicle-to-infrastructure (V2I) cellular networks are specially attractive for vehicular localization, in order to fulfil the stringent location requirements posed by autonomous and assisted driving applications. This work assesses the ultimate capabilities of fourth generation (4G) cellular technologies for vehicular navigation, so it can be applicable for current Long Term Evolution (LTE) deployments as predecessors of fifth generation (5G) technologies. Our results show the performance limits of V2I ranging localization with current 4G networks in highway scenarios. They indicate the need to use the maximum LTE bandwidth of 100 MHz with dedicated networks, in order to ensure target position accuracies below 1 meter.**

I. INTRODUCTION

The future of road transportation is led by autonomous and assisted driving. The automotive industry envisages the implementation of innovative road assistance applications within the following decade, such as automated overtake, collision avoidance or high-density platooning [1], and the full automation of vehicles by 2030 [2]. These applications pose tremendous challenges in terms of high accuracy positioning, high reliability and fast response of the location information. Thus, vehicle localization plays a key role for the fulfilment of this vision. Current positioning technologies are mainly based on Global Navigation Satellite Systems (GNSS) assisted by radars, cameras and inertial sensors. Although their positioning viability has been proved with prototype self-driving cars, the interaction between vehicles and the environment has not been realised yet. Current fourth generation (4G) Long Term Evolution (LTE) cellular networks are expected to connect each vehicle with every surrounding network element, known as vehicle-to-everything (V2X) communications [3]. In this context, the exploitation of current 4G networks for localization is of special interest in order to enhance the existing vehicle navigation systems [4], especially in harsh environments such as tunnels or urban canyons.

There are practically no studies on the achievable positioning performance of current LTE networks for vehicular applications. Recent contributions are focusing on the disruptive technologies to be adopted in the fifth generation (5G) of cellular networks [5], [6], [7], [8], [9], such as optimized waveforms, wide bandwidth, massive MIMO, millimetre wave (mmWave), device-to-device (D2D), or high-density networks. In contrast, this is a novel contribution because it assesses the ultimate capabilities of current standard 4G technologies for vehicular navigation, so it can be applicable for current LTE deployments as predecessors of 5G technologies.

This paper is organised as follows. LTE vehicular positioning is introduced in Section II, and standard channels are characterized in Section III. Then, the LTE performance limits of ranging-based V2I positioning are assessed in Section IV. Finally, conclusions and future work are drawn in Section V.

II. LTE VEHICULAR POSITIONING

The current LTE standard, known as LTE-Advanced Pro, specifies three air interfaces applicable to vehicular scenarios [3]: downlink transmissions from base station (BS) or road-side-unit (RSU) to vehicle, based on orthogonal frequency-division multiple access (OFDMA); uplink transmissions from vehicle to BS or RSU, based on single-carrier frequency-division multiple access (SC-FDMA); and sidelink transmissions between vehicles, also based on SC-FDMA. Using these communication channels, the current specification supports proximity, fingerprinting and trilateration location methods [10]. The most accurate methods are based on the trilateration of ranging measurements, such as observed time-difference of arrival (OTDoA), uplink time-difference of arrival (UTDoA), terrestrial beacon systems (TBS) and assisted GNSS (A-GNSS). The LTE standard [11] supports the dedication of positioning resources by means of the positioning reference signal (PRS) in the downlink for OTDoA and TBS, while the sounding reference signal (SRS) is re-used in the uplink for UTDoA. There is also a protocol to exchange the location information between the different network elements, which is called LTE positioning protocol (LPP) [12]. However, there is no protocol for cooperative positioning between vehicles, in order to aid GNSS positioning methods [4].

The existing positioning mechanisms are applicable to V2X communications. But, the positioning capabilities of cellular location methods have not been characterized for LTE vehicular networks. In this sense, the ultimate performance of ranging-based location methods with LTE vehicle-to-infrastructure (V2I) communications needs further investigation, which is the focus of this work.

III. V2I MULTIPATH CHANNEL CHARACTERIZATION

This section characterizes representative multipath channels for V2I scenarios. This study uses the 3GPP LTE standard propagation models [13], which are based on those developed by the WINNER project [14]. Outdoor environments in urban and rural areas are only considered in this work, for frequency bands between 2 and 6 GHz.

A. Propagation Scenarios

Three standard propagation scenarios are considered relevant for vehicular positioning. They are based on the typical urban micro-cell (UMi), typical urban macro-cell (UMa), and rural macro-cell (RMa) scenarios, which correspond to the WINNER B1, C2, and D1 models [14], respectively. The UMi scenario represents urban network deployments of small cells. The antenna height of the cellular stations and vehicles is well below the rooftop of the surrounding buildings, which are distributed according to a Manhattan-like grid. Given the short coverage of the small cells, there is a predominance of line-of-sight (LoS) conditions, with exceptional blockage due to traffic or buildings. The UMa scenario is defined by a vehicle located outdoors at the street level, while the BSs are clearly above the surrounding buildings. Since the street level is often reached by a single diffraction over the rooftop, the propagation conditions are mainly characterized by non-line-of-sight (NLoS). Finally, the RMa scenario represents communications in large areas with low building density. The BSs are well above the average building height, thus LoS conditions are expected in most of the cases. Future work should consider specific vehicular channel models.

B. Propagation Models

The simulation of these propagation scenarios is based on the WINNER radio channel models [14]. These models were developed under the WINNER project, in order to generate geometry-based stochastic channels for different environments. Furthermore, they can be simulated with the open-source codes of the WINNER II channel model implemented in Matlab, called WIM2 [15]. Given the channel input parameters, the code returns as output the channel impulse response (CIR). The WINNER channel model can be then configured according to the standard parameters:

1) Propagation conditions: The LoS and NLoS propagation conditions can be fixed for a certain model, or determined by the LoS probability described in Table 4-7 of [14]. In this case, the LoS probability is defined by the distance d between vehicle and BS or RSU for the UMi model as

$$P_{\mathrm{LoS}} = \min\left(\frac{18}{d}, 1\right) \cdot \left(1 - e^{-\frac{d}{36}}\right) + e^{-\frac{d}{36}}, \qquad (1)$$

for the UMa model as

$$P_{\mathrm{LoS}} = \min\left(\frac{18}{d}, 1\right) \cdot \left(1 - e^{-\frac{d}{63}}\right) + e^{-\frac{d}{63}}, \qquad (2)$$

and for the RMa model as $P_{\mathrm{LoS}} = e^{-\frac{d}{1000}}$.

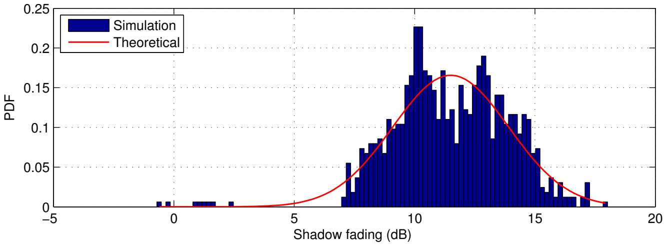


Fig. 1. Shadow fading characterization for urban macro-cell scenario under LoS conditions and $\sigma_{\mathrm{sf}} = 4$dB.

2) Pathloss models: The pathloss models are defined according to the propagation conditions and scenarios in Table 7.2-1 of [13]. These models mainly depend on the distance between vehicle and BS or RSU, carrier frequency, street width, and average building height.

3) Shadow fading: The shadow fading or shadowing is defined as the variability in the received power due to signal obstructions, which can be accurately represented as a random Gaussian variable with standard deviation σ_{sf}. A high contribution of shadowing is expected in urban areas, while a reduced standard deviation is expected in flat rural environments. The shadow fading contribution in V2I scenarios is defined in [16], according to the network deployment and vehicle position. An example of the probability density function (PDF) of this shadow fading is shown in Figure 1.

4) Multipath: The multipath components can follow random delay distributions or fixed clustered delay line (CDL) models [14]. In the first case, multipath delays are randomly generated following an exponential distribution with a specific delay spread, which is defined in Table 4-5 of [14]. In the second case, the multipath delays are tabulated in [14]. Given random or fixed tap delays, time-varying multipath components are generated. In this study, the CDL models are not used, and the reproducibility of the channel models is ensured with a sufficient number of channel realisations.

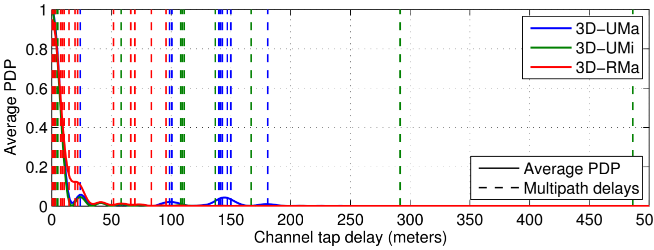
C. Channel Characterization

The multipath impact on the positioning performance can be first characterized with the average power delay profile (PDP). The PDP determines the intensity of a received signal through a multipath channel as a function of time delay (the difference in travel time between the LoS and multipath arrivals). The average PDP is calculated with the mean absolute value of the discrete CIR for every ℓ-th realisation, $h_\ell(m)$, which is expressed as

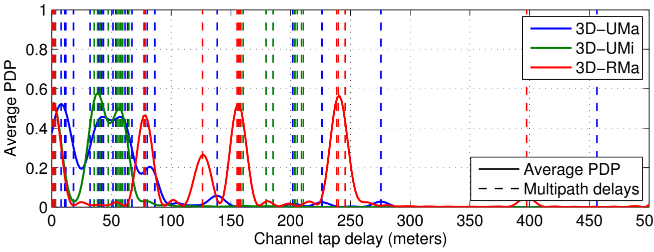
$$\mathrm{PDP}(m) = \frac{1}{N} \sum_{\ell=0}^{N-1} \left|h_\ell(m)\right|^2, \qquad (3)$$

where N is the number of averaged channel realisations.

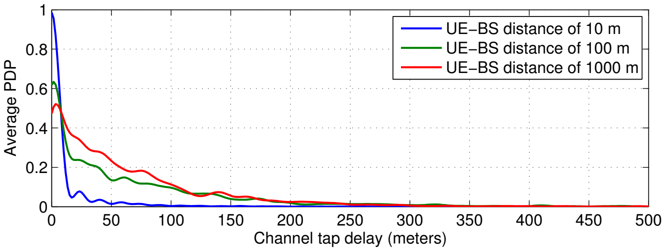
Let us first compare the PDP of the UMa, UMi and RMa models in LoS conditions, as it shown in Figure 2a. The predominance of the LoS component ensures a low impact of the multipath components on the positioning error. In contrast,



(a) LoS conditions



(b) NLoS conditions



(c) Distance-dependent LoS conditions with UMa model

Fig. 2. Channel characterization of urban macro-cell (UMa), urban micro-cell (UMi) and rural macro-cell (RMa) multipath models with 1000 realisations and channel bandwidth of 20 MHz.

the predominance of dense multipath in NLoS conditions is expected to introduce a significant positioning error, as it is shown in Figure 2b. This is specially severe in the urban scenarios due to the overlapping multipath components, which may degrade the performance of conventional multipath mitigation techniques. In the case of the rural scenario, the channel contribution is more sparse, and the resolvability of the multipath components enables the direct application of low-complexity multipath mitigation mechanisms.

According to these results, the UMa channel model results in a harsh environment for vehicular localization. However, the density of multipath components depends on the distance between the vehicle and the BS. Thus, instead of fixing LoS or NLoS realisations, the propagations conditions can be determined according to this distance. As it is shown in Figure 2c, the LoS contribution of the UMa multipath channel decreases for a high distance between vehicle and BS, while the delay spread increases. Thus, the coverage of the vehicular localization deployments is an important factor to be assessed.

IV. ACHIEVABLE V2I RANGING LOCALIZATION

The ultimate V2I positioning accuracy of LTE is mainly limited by multipath and the network deployment along the road. This section shows extensive simulation results on ranging localization with different network deployments along a highway, given the current LTE standard capabilities.

A. *Simulation Methodology*

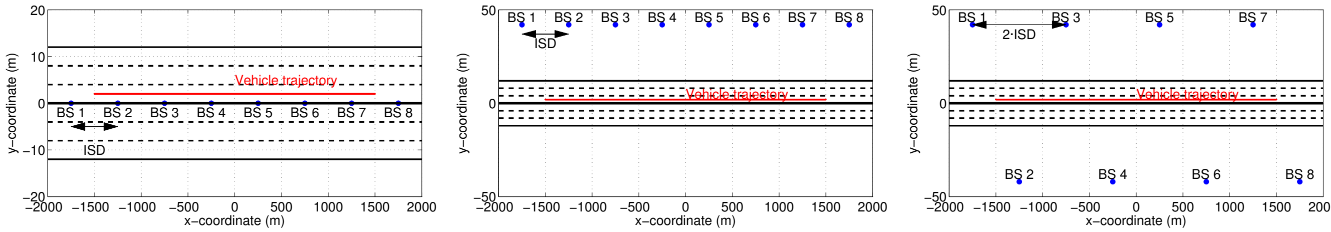
This study considers two network deployments specified in the standard (TR 36.885) [16], where the BSs or RSUs are at the centre or side of the road, and a proposed deployment with BSs or RSUs at both sides of the road [6], as it is shown in Figure 3. The inter-site distance (ISD) is equal to 500 or 100 meters. One component carrier (CC) of 20 MHz or carrier aggregation (CA) of 100 MHz is considered to achieve a coherent time-delay estimation (TDE) over one symbol. The network deployments are assumed to have a very tight synchronization and interference-avoidance mechanisms. Ranging estimates at four BSs or RSUs are considered for UTDoA positioning.

The UTDoA ranging measurements are simulated by computing the link budget, the TDE computation and the UTDoA position calculation. First, the network layout is defined by the location of the BSs and the vehicle, according to the network deployments shown in Figure 3. The corresponding network layout is used to compute the pathloss, shadowing and LoS probability. The output of this link budget is the signal-to-noise ratio (SNR) for each detectable BS or RSU. The received signal is computed with the circular convolution between the transmitted LTE SRS pilots and the CIR of the multipath model, plus the noise contribution for the corresponding SNR. Then, the time delay is estimated with a threshold-based estimator, by determining the maximum peak of the correlation between the received signal and the pilots above a certain threshold. The time-delay estimates from the four most powerful BSs or RSUs are finally used to compute the UTDoA position with a classical least-squares (LS) algorithm. The position accuracy is assessed for 2180 realisations over the vehicle trajectory shown in Figure 3.

B. *Nominal Positioning Performance*

The V2I positioning performance with LTE networks is first assessed for nominal conditions. Current LTE networks are deployed with macro-cell layouts in urban and rural environments. Thus, an ISD of 500 metres is a representative configuration, and the UMa and RMa channel models are considered with distance-dependent LoS conditions. In addition, the system bandwidth is set to 20 MHz, which is the maximum for one LTE CC.

The cumulative density function (CDF) of the UTDoA position accuracy is shown for each deployment and channel model in Figure 4. On the one hand, the network deployment of BSs at the centre of the road results in the worst positioning performance and dilution of precision, due to the low diversity on the direction of arrival between the different ranges. This is improved by locating the BSs at one or both sides of the road. On the other hand, the dense multipath with overlapping components of the UMa channel model introduces a more severe degradation of the position accuracy than the sparse



(a) Deployment 1 (TR 36.885) (b) Deployment 2 (TR 36.885) (c) Deployment 3 (proposed)

Fig. 3. Network deployments under study for highway scenarios.

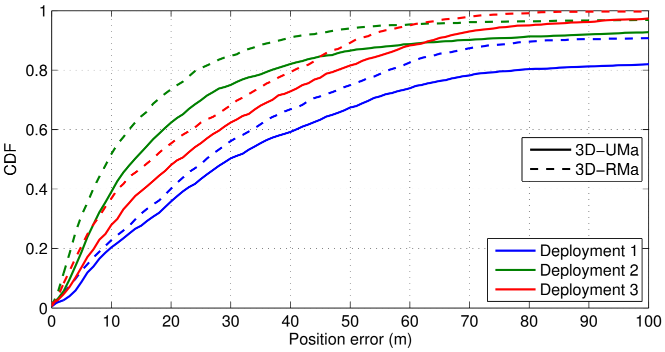


Fig. 4. CDF of the UTDoA position accuracy for highway network deployments, over urban and rural channel models with distance-dependent LoS conditions, LTE system bandwidth of 20 MHz and ISD equal to 500 metres.

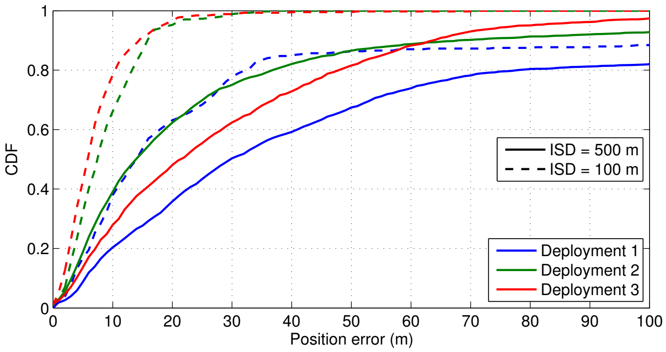


Fig. 5. CDF of the UTDoA position accuracy for nominal and dedicated network deployments along the highway, over the UMa channel model with distance-dependent LoS conditions and LTE system bandwidth of 20 MHz.

RMa channel model. The non-resolvable UMa multipath results in an additional ranging bias that the conventional threshold-based estimator is not able to mitigate. Therefore, these nominal V2I configurations do not fulfil a position accuracy below one meter at the 95% of the cases demanded by emerging vehicular applications, as it is shown in Table I.

C. Impact of the Network Density

The LTE standard defines heterogeneous networks formed by macro cells and small cells, in order to enhance the communication coverage. Similarly, dedicated network deployments can be considered to enhance the achievable positioning capabilities. Let us assume a dense deployment of RSUs along the highway, by defining an ISD equal to 100 meters, in order to assess its impact with respect to the nominal deployment of BSs every 500 meters along the road. For this assessment, the harsh UMa channel model is only assumed, while maintaining a 20-MHz system bandwidth.

The positioning performance of the dedicated network deployment is compared with the one of the nominal macro-cell deployment in Figure 5. The high density of RSUs results in a significant improvement for RSUs at one or both sides of the road (i.e., deployment 2 and 3), while there is a limited improvement for RSUs at the centre of the road (i.e., deployment 1). As it is shown in Table I, the positioning performance is specially enhanced for deployment 3 with a gain of around four times. Still, the achievable positioning accuracy is roughly below 20 meters at the 95% of the cases.

TABLE I
95%-CDF OF THE V2I POSITION ERROR FOR HIGHWAY SCENARIOS.

BW (MHz)	**ISD (m)**	**Chan. model**	**LoS cond.**	**95%-CDF (m) for deploym.**		
				1	**2**	**3**
20	500 m	RMa	Dist.-dep.	> 100	55.3	59.8
20	500 m	UMa	Dist.-dep.	> 100	> 100	79.0
20	100 m	UMa	Dist.-dep.	> 100	19.5	18.3
20	100 m	UMa	Always	> 100	10.7	8.7
100	100 m	UMa	Always	12.3	1.3	1.4

D. Impact of the LoS Propagation Conditions

The presence of NLoS conditions results in a significant ranging bias. The impact of this NLoS bias is here assessed by considering a dedicated network deployment over the UMa channel with fixed or distance-dependent LoS conditions. The selection of fixed LoS conditions, i.e., always LoS, in the WINNER channel model ensures the presence of the LoS component in the multipath channel realisations, as it is shown in Figure 2a. Thus, a LTE system bandwidth of 20 MHz and ISD equal to 100 meters are considered to assess the impact of LoS propagation conditions.

As it is shown in Figure 6, the presence of the LoS component improves the position accuracy by ten meters in deployment 2 and 3, while it has no improvement for deployment 1. However, the position accuracy at the 95% of the cases, summarized for each deployment in Table I, does not reach the stringent vehicular requirements.

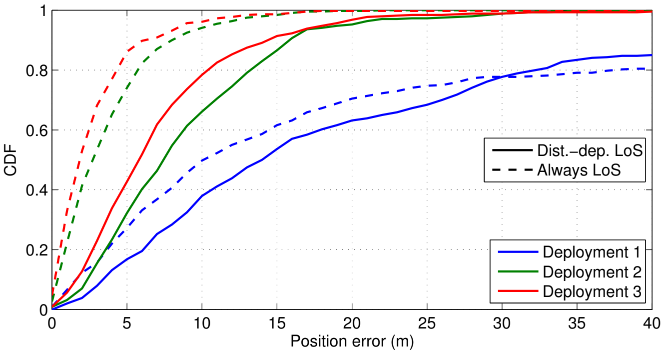


Fig. 6. CDF of the UTDoA position accuracy for 20-MHz dedicated network deployments along the highway (i.e., ISD equal to 100 meters), over the UMa channel model with fixed and distance-dependent LoS conditions.

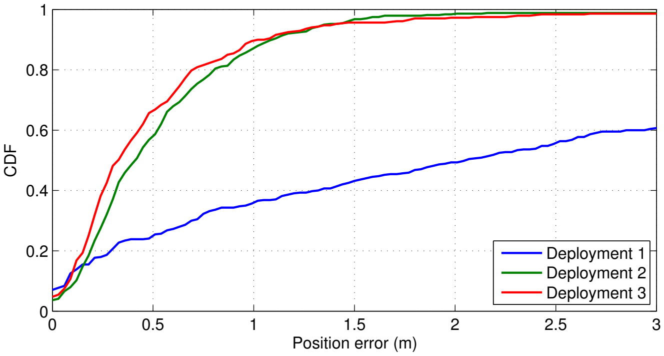


Fig. 7. CDF of the UTDoA position accuracy for 100-MHz dedicated network deployments along the highway (i.e., ISD equal to 100 meters), over the UMa channel model with fixed LoS conditions.

E. Impact of the System Bandwidth

The vehicle position accuracy can be further improved by using the maximum LTE system bandwidth of 100 MHz with 5 CCs in a coherent TDE approach. In order to assess the impact of the system bandwidth, a dedicated network deployment with ISD equal to 100 meters and the UMa LoS channel model are assumed. The resulting positioning accuracy is shown in Figure 7. The precise ranging measurements obtained with the high bandwidth signals significantly enhance the positioning performance of each network deployment. However, only deployments 2 and 3 with RSUs at one or both sites of the road are able to achieve a vehicle position accuracy slightly above one meter at the 95% of the cases, as it can be seen in Table I. Despite the high bandwidth, the bad geometry of deployment 1 limits the positioning performance. In addition, the harsh urban environment, characterized by close-in multipath, degrades the performance of conventional threshold-based estimators. These results highlight the ultimate V2I capabilities of the LTE standard, and they show the need to use a system bandwidth of 100 MHz to achieve high-accuracy positioning with V2I deployments. The use of advanced multipath mitigation techniques and angle measurements are left for future work, in order to ensure the high-accuracy and reliable positioning demanded by autonomous and assisted driving applications.

V. CONCLUSION

This paper has studied the performance limits of vehicle-to-infrastructure (V2I) ranging-based localization with Long Term Evolution (LTE) networks, in order to fulfil the stringent location requirements of autonomous and assisted driving applications. This study considers standard multipath channel models and representative vehicular deployments for highway scenarios. The vehicle position accuracy is shown to be driven by the distance between base stations along the road, the line-of-sight (LoS) conditions, and the system bandwidth. The achievable LTE positioning performance is around one meter in the 95% of the cases for urban multipath with LoS, when dedicated base stations are located at one or both sides of the road every 100 meters with a carrier aggregated bandwidth of 100 MHz. These network and propagation conditions bound the ultimate ranging-based localization performance necessary to fulfil the vehicular location requirements. Therefore, future work is aimed at studying advanced ranging- and angle-based localization techniques, in order to relax the limitations of LTE positioning in urban and highway V2I scenarios.

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