A New Approach to Positioning Error Mitigation: How to Learn Via Safety Messages

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***Abstract*—Accurate positioning of vehicles and vulnerable road users is critical for ensuring road safety. Today's localization relies on the Global Navigation Satellite System (GNSS), but it is often compromised by signal obstructions due to urban infrastructures, buildings, and other vehicles. To overcome these limitations and enhance GNSS localization accuracy, a cooperative positioning method is put forth that leverages direct vehicular communications and the onboard sensors of the vehicle. In the proposed approach, a real-time algorithm selects the vehicle with the lowest positioning error as the anchor node and mandates the anchor to broadcast its coordinates via a suitable message. The receiving vehicles whose sensing region includes the anchor can determine the distance from it and update their position estimate accordingly. In turn, these vehicles may serve as secondary anchors, extending the correction process to vehicles beyond the first tier. By jointly exploiting direct vehicular communications and the local estimate of the distance from the anchor, the proposed approach achieves accurate vehicle localization. In a reference urban intersection, taking into account imperfect direct vehicle-to-vehicle communications and the first tier only, the percentage of vehicles improving the estimate of their position lies between 36% and 54%, depending on the penetration rate of the connected vehicles; these values raise to 62% and 88% when the secondary anchors contribute to propagate the error correction. Furthermore, the statistical distribution of the positioning error exhibits a significant shift toward lower error values, raising the probability that the error is lower than 6 m from 0.05 when no correction is introduced, to 0.87 when all the vehicles are connected and imperfect communications are considered.**

***Index Terms*—GNSS Localization, Cooperative Positioning, Road Safety, V2V communications.**

I. Introduction and State of the Art

Vehicle positioning is essential for autonomous vehicles' operation and advanced driver assistance systems, particularly in challenging environments such as urban canyons or GNSS-denied areas. A growing body of research has investigated cooperative and hybrid localization methods that integrate information from multiple sources, such as satellites, cellular systems, or road infrastructures. LEO satellite-based positioning has recently gained attention due to its global coverage and potential as an alternative to traditional GNSS. However, relying on LEO satellites alone does not guarantee higher accuracy. To address this limitation, the work in [1] proposed a cooperative positioning method that corrects LEO-derived positions using relative angle estimations between devices. Vehicular communications offer valuable information that can be repurposed for localization too. In [2], a solution was put forth to estimate the distance between vehicles using the timing of Cooperative Awareness Messages within the C-V2X resource grid. A more comprehensive cooperative localization strategy was presented in [3], where a Vehicle-to-Vehicle (V2V)-based algorithm optimized the position estimate via a double-layer consistency check (CC) to enhance accuracy. LIDAR sensors can further enhance localization, particularly in urban environments where GNSS signals are often obstructed. The study in [4] is an example in this respect, as it utilizes LIDAR-based distance and angle measurements combined with V2X communications. Further, the authors of [5] introduced a distributed positioning framework which features a scalable distributed Kalman filtering implementation. The method provides significant accuracy gains while remaining compatible with off-the-shelf vehicular communication hardware.

Unlike the previously mentioned solutions, the current work introduces a simple, lightweight algorithm that operates nearly in real-time. It relies on an anchor vehicle and either one or two communication hops, leveraging V2V direct transmissions to enhance the GNSS positioning accuracy of the vehicles. Namely, the anchor is identified as the vehicle that currently experiences the lowest positioning error; as such, it advertizes its coordinates via a short safety message to allow the vehicles that correctly receive it to improve the estimate of their position. By doing so, it is shown by a simulative approach that a significant error mitigation is achieved.

The remainder of this paper is organized as follows: Section II illustrates the proposal. Section III details the assumptions in modeling the GNSS positioning error. Section IV introduces the radio access technology which enables V2V communications and the Key Performance Indicators (KPIs) computed to estimate the quality of the proposed approach. Section V proves the promising reduction in the error positioning estimate of the new solution, and Section VI concludes the paper.

II. The Proposal

To enhance GNSS-based localization accuracy, this study proposes a two-hop cooperative positioning algorithm that exploits direct V2V communications and onboard sensors.

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In the first step of the algorithm, a selection mechanism identifies the vehicle with the most accurate GNSS position estimate and designates it as the anchor node. The anchor is responsible for the broadcasting of a one-shot message that includes its position estimate. A Decentralized Environmental Notification Message (DENM), i.e., an already standardized safety message, can serve the purpose. The message recipients in radio and sensing visibility with the anchor leverage the anchor coordinates in the message to determine their distance from the anchor, which is then employed to update their position estimate, thus refining the localization accuracy. The improvement requires the vehicles to estimate their distance from the anchor, which can be accomplished thanks to the vehicle onboard sensors, such as LIDARs and RADARs. In the second step of the algorithm, the vehicles that previously corrected their position, referred to as secondary anchors, repeat the process. They broadcast a new message carrying their corrected positions intended for the vehicles beyond the original anchor's range. This enables the correction to propagate, extending accurate localization throughout the area where the anchors reside.

III. GNSS Error Modeling

To understand the potential of the proposed scheme, its behavior is examined in a reference setting, namely, the urban intersection portrayed in Fig.1, whose center coincides with the origin $(0, 0)$ of the coordinate system.

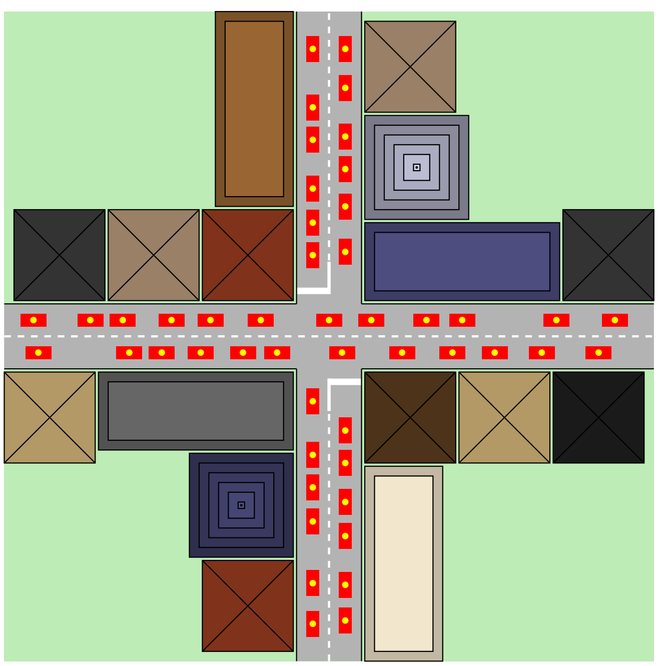


Fig. 1. The examined urban intersection.

It is assumed that e_{GNSS}, the GNSS error (in meters) that vehicles experience, displays two terms. The former is a deterministic, location-based contribution, which monotonically increases for an increasing distance from the (x_0, y_0) point where its minimum is observed. The latter takes into account the error due to the quality of the adopted GNSS receiver and is modeled as the absolute value of a zero-mean Gaussian Random Variable (RV) with a location-dependent standard deviation σ, denoted by $\mathcal{N}(0, \sigma)$. More accurately,

$$e_{\text{GNSS}} = \min\left[e_{\text{GNSS}_{\max}}, f(x, y) + |\mathcal{N}(0,\, g(x, y) \cdot \sigma_{\text{rx}})|\right] \quad (1)$$

where $e_{\text{GNSS}_{max}}$ is the upper bound to the e_{GNSS} above which measurements are unreliable, $f(x, y)$ is

$$f(x, y) = k_1 \cdot \sqrt{(x - x_0)^2 + (y - y_0)^2},\ k_1 = 0.5\,, \quad (2)$$

$$g(x, y) = k_2 \cdot f(x, y)\,, \quad k_2 = 2 \quad (3)$$

and σ_{rx} takes on different values for different receiver types. Namely, three receiver categories are envisioned, the Standard Positioning Service (SPS), the Satellite-Based Augmentation System (SBAS), and the Differential GNSS (DGNSS) [5], with

$$\sigma_{rx} = \begin{cases} 3.60, & \text{SPS receiver} \\ 1.44, & \text{SBAS receiver} \\ 0.40, & \text{DGNSS receiver} \end{cases} \quad (4)$$

IV. Radio Access Technology and KPIs

A. NR-V2X SL

The solution we put forth to decrease the positioning error heavily relies on direct V2V communications; hence, it is crucial to realistically model the impact of: (i) the radio access strategy; (ii) non-ideal communications.

As regards point (i), we select the New Radio Vehicle-to-Everything Side Link (NR-V2X SL) standard, and in greater detail, the Mode 2 operating mode, to support vehicular communications [6]. This Mode is deemed the reference solution for safety services. Among the two radio access strategies Mode 2 envisions, we focus on the Semi-Persistent Scheduling (SPS) scheme, which enables a vehicle to autonomously select and reserve radio resources for periodic transmissions without network assistance. The vehicle monitors the status of radio resources over a defined observation window to identify available time-frequency resources based on recent usage. It then selects resources with the lowest likelihood of collision and reserves them for several consecutive transmissions.

As regards point (ii), we model the channel following the specifications provided in [7], i.e., we account for the presence of a distance-dependent attenuation law, multipath fading, and log-normal shadowing. Furthermore, the probability that the transmitting and receiving vehicles are in Line-Of-Sight (LOS) and Non-Line-Of-Sight (NLOS) is introduced. In greater detail, a V2V link is in LOS state if the two vehicles are on the same street. The circumstance where the LOS path is blocked by other vehicles cannot occur, as all vehicles are assumed to be of the same type, i.e., passenger cars. In a specular manner, a V2V link is in NLOS state if the two vehicles are on different streets.

To assess the performance of the proposed solution, it is mandatory to evaluate the Packet Delivery Ratio (PDR) that the vehicles experience. As a matter of fact, the more realistic the PDR evaluation is, the more accurate the estimate of solution effectiveness. Hence, we examine the setting where the messages transmitted by the anchor nodes struggle to gain access to the radio channel against safety packets transmitted at the lowest possible periodicity by all the vehicles. Under the above assumptions, we compute the PDR as a function of the distance between the transmitting and receiving vehicles in LOS and NLOS conditions via an accurate simulative approach.

B. Key Performance Indicators

To gain a thorough understanding of the potential of the proposed scheme, we first evaluate the ratio of the number of vehicles that improve their position to the total number of vehicles at the intersection after the first and second communication hop from the anchor, denoted as $R^{(fh)}$ and $R^{(sh)}$, respectively, for a given value of the penetration rate of connected vehicles, which we denote by α, $\alpha \in (0, 1]$. Accordingly,

$$R^{(fh)} = \frac{N_{corr}^{(fh)}}{N_{to\_corr,tot}} \tag{5}$$

$$R^{(sh)} = \frac{N_{corr}^{(fh)} + N_{corr}^{(sh)}}{N_{to\_corr,tot}} \tag{6}$$

where $N_{corr}^{(fh)}$ is the number of positions corrected after the first hop, $N_{corr}^{(sh)}$ is the number of positions corrected after the second hop, and $N_{to\_corr,tot}$ is the overall number of positions that necessitate a correction.

We further complement these evaluations by computing the Cumulative Distribution Function (CDF) of the positioning error, in the circumstance of imperfect communications, for different α values.

V. Numerical Results

The reference intersection scenario was recreated in MATLAB. The layout consists of two 200 meter-long roads, with two 5-meter-wide lanes per driving direction. Vehicles are randomly placed on the road, maintaining a minimum gap of 1 meter between them and are equipped with sensors that provide full 360-degree coverage within a 200-meter range. Additionally, each vehicle is fitted with one of three types of GNSS receivers (4), with each type assigned randomly with equal probability. The vehicular density is 0.12 vehicle/m, as in [8]. In (1), we assume that $e_{\text{GNSS}_{max}}$ is equal to 200 m; furthermore, the minimum of the deterministic function in (2) occurs at the intersection center, i.e., $(x_0, y_0) = (0, 0)$.

In every simulation run, the vehicle closest to the location where the GNSS error e_{GNSS} is minimum is designated as the anchor; as such, it broadcasts the one-shot DENM that the vehicles in radio visibility will leverage to improve their position estimate after the first communication hop. A position correction occurs only if at least one chassis point of the anchor vehicle is in geometric visibility with a chassis point of the target vehicle. Two scenarios are examined. The first assumes ideal channel communications, enabling vehicles to exchange messages flawlessly, and serves as the benchmark setting. The second incorporates transmission imperfections in the V2V sidelink communications, due to channel effects and the concurrent transmission of safety messages, e.g., cooperative awareness messages, over the radio channel. So, if the message from the anchor fails to be successfully received, the vehicle position cannot be corrected.

In turn, the vehicles that improve their position estimate after receiving the anchor's message act as secondary anchors; other vehicles that are in radio visibility with them have a chance to reduce their GNSS error after the second communication hop, provided they successfully receive the message with the updated position of the secondary anchor.

To seize the probability of successful message delivery in the urban environment, MoReV2X—a fully-fledged NR-V2X SL simulator [6]—was generalized to support the urban environment modeling and determine the proper PDR curves. The set of the NR-V2X sidelink (SL) PHY layer parameters we selected is summarized in Table I. The proper Block Error Rate (BLER) curves were retrieved from an open-source dataset built through a link-level simulator described in [9].

TABLE I
Main NR-V2X SL PHY Layer Parameters

Parameter	**Value**
Center frequency, f_c	5.9 GHz
Channel bandwidth	20 MHz
SCS	30 kHz
Number of subcarriers	12
RB bandwidth	$30 \cdot 12 = 360$ kHz
Modulation type	16 QAM
TB code rate	0.49
SCI code rate	0.08
Total number of subchannels	$N_f = 4$
Transmission power, P_t	23 dBm
Shadowing std. dev. LOS, σ_{LOS}	3 dB
Shadowing std. dev. NLOS, σ_{NLOS}	4 dB
Receiver sensitivity level	-103.5 dBm
Thermal noise PSD	-174 dBm/Hz
Noise figure	9 dBm

Fig. 2 displays the PDR as a function of $d_{t,r}$ for V2V communications, that we determined via simulation. The figure showcases the LOS and NLOS PDR curves for two different penetration rates, namely, $\alpha = 0.2$ and $\alpha = 1$, which have been selected as the representative lower and upper bounds. It is relevant to outline that the shape of the PDR curves is inherently influenced by the specific urban layout that we examined.

Next, Fig. 3(a) shows $R^{(fh)}$ as a function of the penetration rate α and the corresponding 95% confidence intervals computed over 500 simulation runs, for the ideal and imperfect communication scenarios. The comparison between the two curves reveals that the algorithm's performance is good even under imperfect communications. Specifically, for $\alpha = 0.2$,

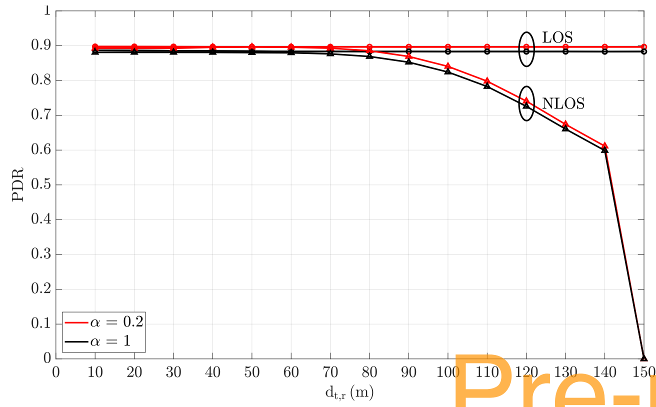
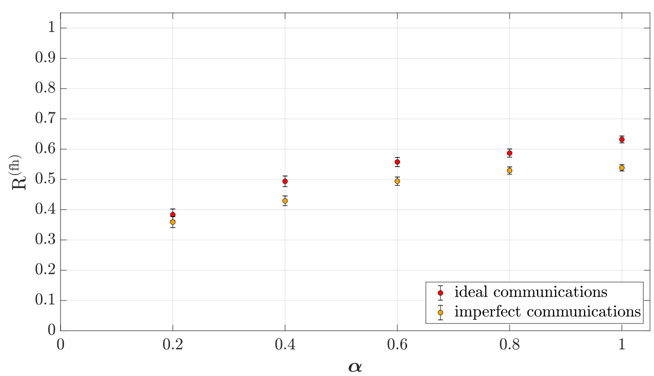
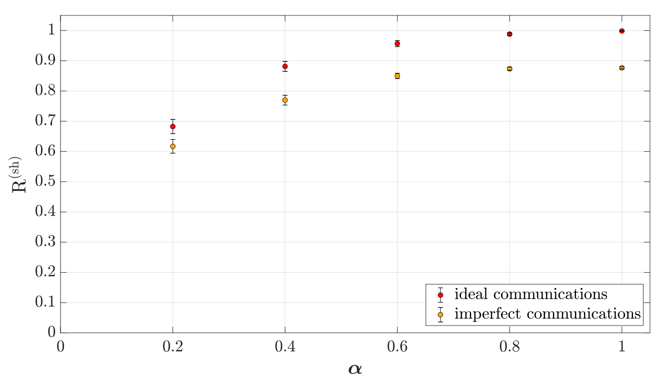


Fig. 2. Packet Delivery Ratio as a function of $d_{t,r}$.

the fraction of improved position estimates is just below 0.4 in the ideal communication case and approximately 0.35 when communications are imperfect. When $\alpha = 1$, $R^{(fh)}$ consistently exceeds 0.5, indicating that a single communication hop is enough to correct more than half of the position estimates. Similarly, Fig. 3(b) reveals that when the error correction mechanism is replicated over two hops, in the case of imperfect communications, for $\alpha = 0.2$ the ratio of improved positions over the total increases to $R^{(sh)} = 0.62$; furthermore, it asymptotically settles at 0.88 from $\alpha = 0.6$ onward.



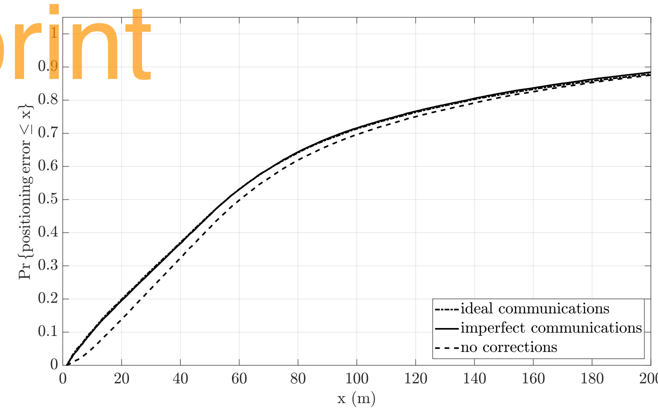
(a) After the first communication hop.



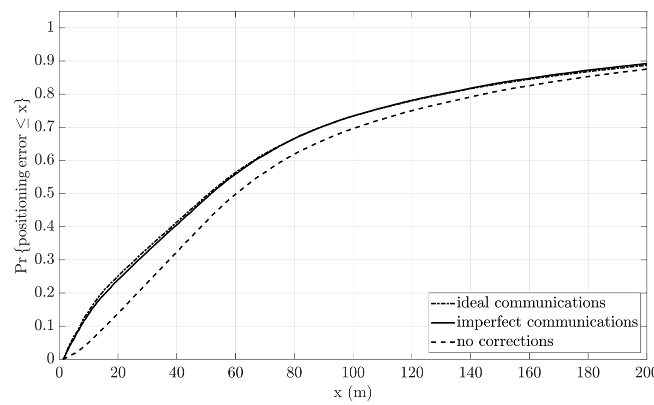
(b) After the second communication hop.

Fig. 3. Fraction of corrected vehicular positions.

To further quantify the benefits of the proposed method after the first and second communication hop, we computed the CDF of the positioning error, referring again to the ideal (dot-dashed line) and imperfect, i.e., realistic communication scenario (solid line), for several values of the penetration rate α. The reference case corresponding to no error corrections was also considered (dashed line). Fig. 4(a) and (b) report the CDF of the positioning error after the first and second communication hop, respectively, when $\alpha = 0.2$. They reveal that the correction mechanism is successful at reducing the localization error, although the improvement is modest, due to the low connectivity level. Fig. 5(a) showcases the CDF



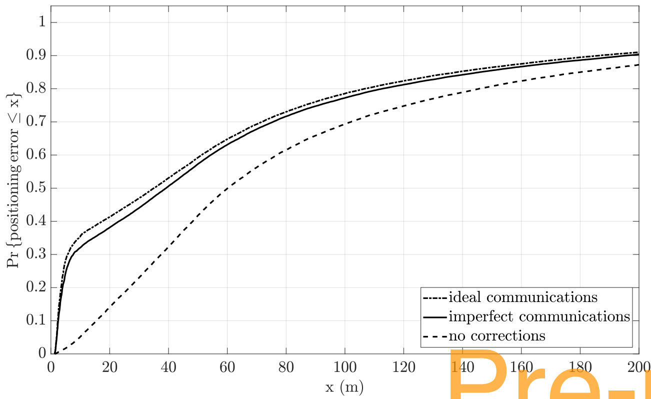
(a) After the first communication hop.



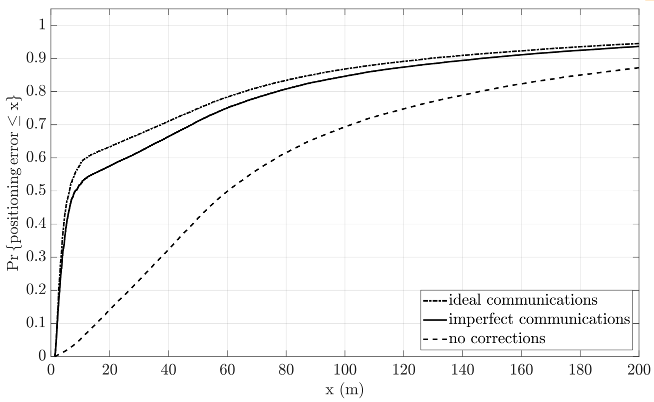
(b) After the second communication hop.

Fig. 4. CDF of the positioning error; $\alpha = 0.2$.

after the first communication hop for $\alpha = 0.6$. Compared to Fig. 4(a), the localization error is significantly reduced. As a meaningful example, Fig. 5(a) reveals that the probability that a vehicle has a positioning error below 10 m is almost 0.6 in the case of ideal communications, and about 0.53 in the case of imperfect communications. Fig. 5(b) quantifies the further improvement due to the presence of the secondary anchors. Fig. 6(a) clearly shows that the correction mechanism drastically improves positioning accuracy after the first hop, when all vehicles are connected, i.e., when $\alpha = 1$. Specifically, more than 63% of the corrected positions exhibit an error below 6 m in the case of ideal communications, and more than 55% in the case of imperfect communications. Fig. 6(b) further confirms this improvement after the second hop. Specifically, more than 99% of the corrected positions exhibit an error

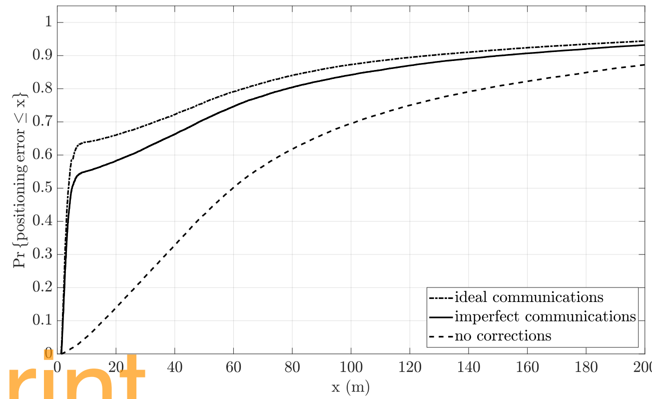


(a) After the first communication hop.

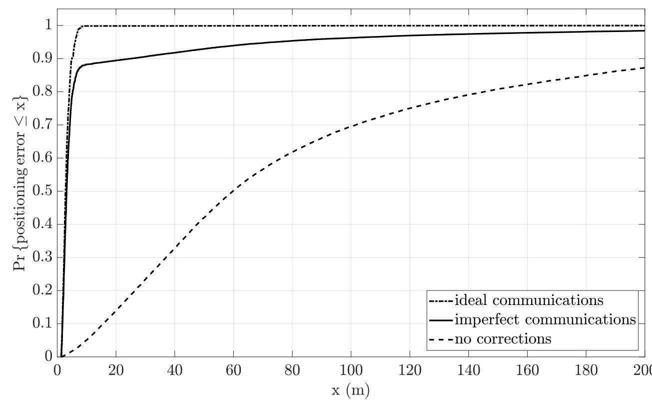


(b) After the second communication hop.

Fig. 5. CDF of the positioning error; $\alpha = 0.6$.



(a) After the first communication hop.



(b) After the second communication hop.

Fig. 6. CDF of the positioning error; $\alpha = 1$.

below 6 m in ideal communications, and more than 87% in imperfect communications.

VI. Conclusions and Future Work

This work introduced a novel, distributed positioning method to reduce the error that affects GNSS receivers in a vehicular environment. In the proposed approach, the vehicle with the lowest positioning error in a given area is identified as the anchor node, responsible for broadcasting its coordinates in a DENM via direct V2V communications. The vehicles that correctly receive this one-shot message and are able to determine the distance from the anchor update their position estimate. In turn, they may serve as secondary anchors, extending the correction process to vehicles beyond the first tier. The study showed that, by jointly exploiting direct vehicular communications and the estimate of the distance from the anchors, a significant reduction of the positioning error is achieved. The solution appears promising and deserves further investigation from various perspectives. Among them, plans are to: (i) introduce the election mechanism to identify the anchor, to realistically estimate the overall delay that the position update mechanism requires in the challenging mobile environment; (ii) assess the scheme performance for different functions describing the GNSS positioning error, also derived from existing experimental campaigns.

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