S. Bartoletti, N. Decarli, B. M. Masini, C. Giovannetti, A. Zanella, A. Bazzi, R. A. Stirling-Gallacher, "Integration of sensing and localization in V2X sidelink communications," IEEE Communications Magazine, vol. 62, no. 8, pp. 185-191, Aug. 2024.

The file is available at:

https://doi.org/10.1109/MCOM.001.2300748

Integration of Sensing and Localization in V2X Sidelink Communications

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***Abstract*—This paper investigates the evolution of vehicle-to-everything (V2X) sidelink communications technology, focusing on its integration with sensing and localization capabilities in vehicular scenarios. The study encompasses the detection and localization of device-free objects (sensing) as well as connected vehicles (positioning), across both sub-6 GHz and millimeter-wave frequencies. An overview of architectural elements, signal processing procedures, and features affecting performance is provided. In addition, the paper discusses implementation challenges to be addressed and possible issues concerning security and privacy, also elaborating on future research directions.**

***Index Terms*—Sidelink Positioning, Joint Communication and Sensing, Radar, V2X Sidelink**

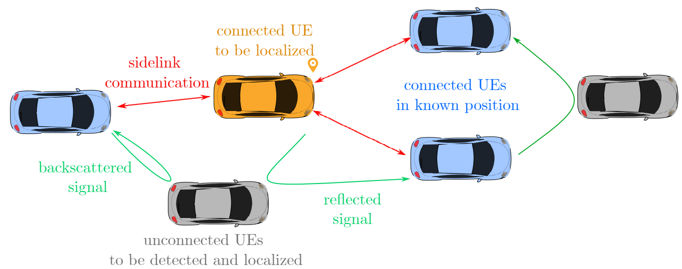

Fig. 1. Illustration of a V2X scenario where sidelink communications are used to localize connected UEs as well as unconnected, device-free ones.

I. Introduction and Motivation

SENSING and positioning technologies play a crucial role in vehicular scenarios, providing accurate, real-time information about the location and movement of vehicles, people, and assets. Beyond facilitating communication through vehicle-to-everything (V2X) connectivity, they enable applications like coordinated manoeuvring to optimize traffic flow and safety, and they support collective perception to share sensor data among vehicles. This context-awareness is crucial for autonomous driving systems, particularly in environments with both connected and non-connected vehicles. Over the years, diverse wireless technologies offered varying levels of localization and sensing accuracy to suit different usage scenarios [1]. Advancements in wireless communication networks, including expanded bandwidth, massive arrays, and high carrier frequency, are enabling additional services beyond data transmission using the same infrastructure and spectrum, such as integration of sensing, localization, and communication, which is emerging as a promising paradigm for future 6G networks [1]–[3].

This work has been conducted, in part, in the framework of the WiLab-Huawei Joint Innovation Center and supported, in part, by the European Union under ERC Grant 101078411, and in part within the MOST – Sustainable Mobility National Research Center and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4 – D.D. 1033 17/06/2022, CN00000023). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

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In the context of V2X communication, sidelink (SL) is more efficient for communication among nearby devices compared to uplink (UL) and downlink (DL) thanks to its lower latency and signalling overhead. Furthermore, SL can be supported by user equipments (UEs) independently of network coverage [4]–[6]. Recent studies and standardization efforts have emphasized the potential of SL measurements for both sensing and positioning, setting the stage for their seamless integration into SL communications [7]–[9]. This integration offers two primary advantages, as depicted in Fig. 1: facilitating accurate device-based positioning in areas with poor network coverage or high congestion and enabling device-free object sensing by leveraging reflections of SL signals.

This paper discusses the integration of sensing and localization within V2X SL communications. It tackles associated challenges and opportunities while shedding light on future research directions based on preliminary performance evaluations.

II. V2X Sidelink Communication

SL refers to direct communications between UEs in a network, either with or without the assistance of other network entities, such as base stations or next generation Node Bs (gNBs). Thus, SL communication extends coverage to planned cellular networks and enables low-latency connectivity for V2X. Sidelink in 5G NR-V2X has been standardized in Release 16 and enhanced in the following releases of the Third Generation Partnership Project (3GPP).

A. Current Sidelink Communication

Today's sidelink technology, standardized with 3GPP Release 16, presents two distinct operational modes: mode 1 and mode 2. Mode 1 necessitates resource allocation by the gNB for the UE-to-UE link, whereas mode 2 empowers autonomous resource management among UEs without gNB intervention. Specifically, mode 2 employs a distributed, self-allocation scheme to autonomously select and distribute resources among UEs in either periodic or aperiodic fashion. Owing to its local and sensing-based resource allocation, mode 2 is inherently more susceptible to packet collisions and interference compared to mode 1.

Although SL communications were initially envisioned for frequency ranges spanning 410-7125 MHz (FR1) and 24.2-52.6 GHz (FR2) with bandwidth up to 400 MHz, practical usage has primarily been confined to FR1 with a maximum bandwidth of 20 MHz, despite support for bandwidths up to 100 MHz in FR1. This constrained bandwidth diminishes the pool of available physical resources, consequently elevating the likelihood of collisions, particularly when employing autonomous resource allocation schemes.

B. Enhanced Sidelink Communication

Enhanced features for SL communications have been introduced starting with 3GPP Release 18. Such advancements target an improved data rate, power saving and coverage enhancements, yet the main benefit consists in making SL applicable for a wider range of use cases.

a) Support for FR2: Communication using FR1 was initially designed to operate in broadcast mode, while unicast and groupcast modes have been defined at later stages. Broadcast is the main mode expected for the transmissions of content for basic safety like cooperative awareness messages (CAMs) or that used for sensor sharing like collective perception messages (CPMs). When moving to FR2, the larger bandwidth, and the use of multiple antennas makes it more interesting for high-throughput unicast or groupcast communications, which may be particularly useful for coordinated manoeuvres. Thus, the two frequency ranges could cover different applications and use cases. As known, the path loss is less favourable at FR2, while it can be compensated through the use of antenna arrays with proper beam management.

b) Beam management at FR2: Beam management becomes necessary for proper communication between UEs when adopting antenna arrays at FR2. It consists of initial beam alignment, beam tracking, and beam recovery. Initial beam alignment is necessary to establish the mmWave link between the transmitter and the receiver. As the directivity increases, a higher number of beams has to be tested, causing a rise in overhead. When antenna arrays are used at both transmitter and receiver, beam alignment at transmitter side is not sufficient, since also the receiver must steer its receiving beam towards the transmitter. Then, beam tracking is the technique used to deal with the beam misalignment, due to high mobility and the use of narrow beams. Finally, beam recovery is the process of detecting link failure, due, for example, to vehicle blockage, and finding an alternative beam pair to restore the communication.

There are several V2X specific techniques proposed in the literature for beam management using, e.g., power measurements or traffic light signalling and road topology [5], [10]. All these processes can be improved by leveraging the data from the sensors mounted on vehicles, to obtain a more reliable estimation of the UE positions and to enhance beam pointing. For example, in [6] different methods for initial beam selection are shown for 5G NR SL and vehicle-to-vehicle applications. To speed up the initial beam alignment, it is extremely helpful to know the position of the neighbouring vehicles. Results show that inaccurate positioning leads to a severe worsening of signal-to-noise ratio (SNR). In [11], a 3D-based positioning scheme for adaptive beam alignment and selection is proposed for group-based secure V2X routing.

Therefore, beam management is by definition linked to the vehicles' position information, providing a first point of strong synergy between SL communication and localization.

C. Communication Performance and Challenges

The communication performance and challenges in V2X SL are intricately tied to the frequency range adopted. FR1 has better coverage than FR2 but limited bandwidth (maximum of 100 MHz) which affects the data rate and the ability to support bandwidth-intensive applications. In addition, with the increasing number of connected vehicles and devices, multi-user interference issues arise as a drawback of typical non-directional antennas and lower path loss. Differently, channel bandwidth at FR2 is much larger so that, jointly with directive antennas, more resources can be efficiently allocated to different users, thus significantly reducing collisions and multi-user interference. The effect of propagation changes significantly between FR1 and FR2. For example, non-line-of-sight (NLOS) conditions and fading strongly depend on the carrier frequency. Blockage becomes more significant as the carrier frequency increases, while the wave penetration into objects decreases [4]. MmWaves are also more susceptible to atmospheric absorption, which can be exacerbated by adverse weather conditions, e.g. rain and fog.

In this context, on the one hand, the utilization of sensing data and UE location can be leveraged to improve SL communication, e.g. for optimizing beamforming. On the other hand, the integration of positioning and sensing with SL communication introduces additional complexity, which includes resource allocation with demanding evaluation of bandwidth allocation, modulation and coding scheme (MCS) selection, and techniques for mitigating path loss, to achieve optimal performance as discussed in the subsequent sections.

III. V2X Sidelink Positioning

SL positioning refers to the use of SL measurements to estimate a connected vehicle's position, whether absolute or relative to another vehicle. Significant efforts have been made to define procedures and signalling mechanisms to support SL positioning across various scenarios, including in-coverage, partial coverage, and out-of-coverage scenarios, in the Release 18 specifications (see, e.g. 3GPP TS 38.859 and 23.700).

A. Positioning Measurements and Methods

Similar to the DL case, where a DL-positioning reference signal (PRS) is used for positioning, a new SL-PRS has been

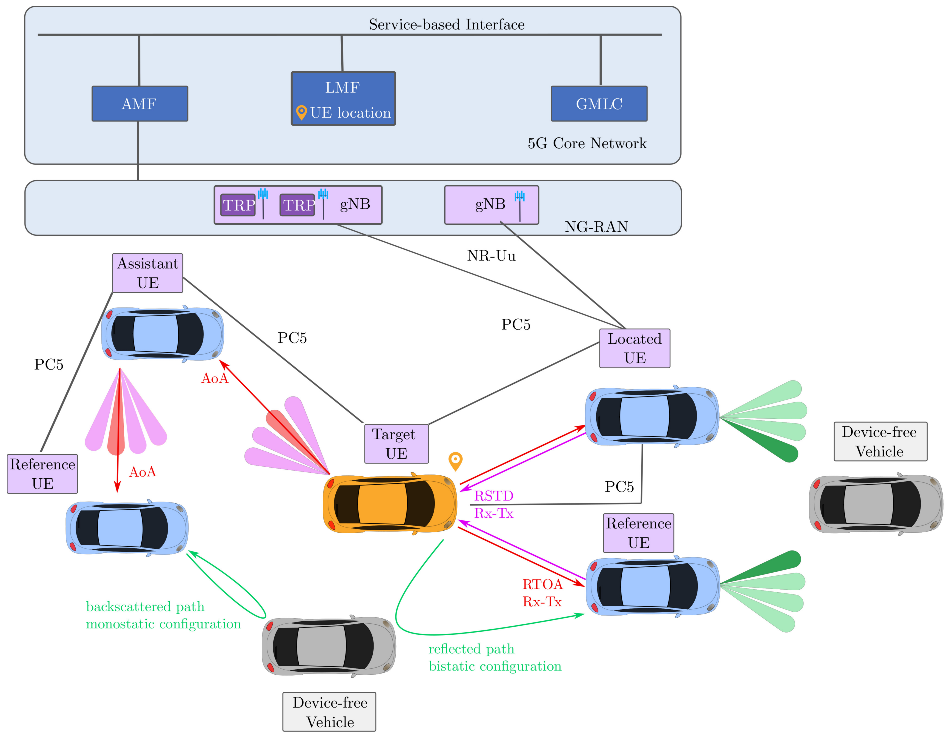

Fig. 2. Architectural elements involved in 5G sidelink positioning and sensing. The example illustrates the role of reference UEs (including assistant and located UEs) cooperating to localize a target UE through AoA and timing measurements (red and purple lines). Examples of sensing are also illustrated via angle and timing measurements of signals reflected by device-free vehicles.

defined in 3GPP TS 38.214. The sidelink control information (SCI) can be used for reserving/indicating one or more SL-PRS resources. SL PRS transmissions can be performed using unicast, groupcast, and broadcast modalities. Similar to legacy SL communications, radio resources for SL-PRS signals can be allocated either in a network-centric or in a UE autonomous mode.

Three main positioning methods have been defined: *(i)* round trip time (RTT); *(ii)* SL-time difference of arrival (TDoA); *(iii)* SL-angle of arrival (AoA); in particular:

- **RTT**-based methods rely on the time difference between the transmission and reception of the SL signal at subframe level (namely, RX-TX timing measurement). Both single or double-sided RTT are defined with one or multiple devices. The distance between two UEs can be obtained from the RTT measurement. Therefore, geometrically, the one RTT measurement leads to a circumference centered at the transmitting UE and with radius equal to the distance between the two UEs.
- **SL-TDoA**-based methods may rely on: *(i)* the measurement of the time difference between the reception by the target UE (see next definition) of multiple signals transmitted by synchronized UEs (namely, reference signal time difference (RSTD) measurements) or *(ii)* the measurement of the time difference between the reception by multiple UEs of the same signal transmitted by the target UE (namely, relative time of arrival (RTOA) measurements). Geometrically, a single TDoA measurement leads to an hyperbola with foci at the two transmitting nodes (in the RSTD-based case) or receiving nodes (in the RTOA-based case).
- **SL-AoA**-based methods rely on the relative angle between two UEs (namely, measurements of azimuth of arrival and zenith of arrival). Such angle measurements can be obtained by measuring the reference signal received power at different transmission or reception beams, or by adopting array-processing techniques to exploit the phase information. Geometrically, a single AoA measurement leads to the relative direction between the transmitting and receiving UE.

B. Architectural Elements

The measurements defined above are performed between multiple UEs. Among the architectural elements defined in 3GPP TR 23.700, there are several types of UEs that contribute to the SL positioning procedures. In particular:

- *Target UE*: An UE whose distance, direction and/or position is measured with the support from one or multiple reference UEs using SL.
- *Reference UE*: An UE supporting positioning of target UE, e.g. by transmitting and/or receiving reference signals for positioning, providing positioning-related information, etc. using SL.
- *Located UE*: A reference UE for which the location is known or is able to be known using Uu based positioning.
- *Assistant UE*: An UE supporting SL positioning between a reference UE and a target UE over PC5, when the direct SL positioning between the reference and target UE cannot be supported.

Fig. 2 illustrates the main architectural entities involved in the SL positioning, including the communication interfaces, i.e. the NR-Uu and SL NR-PC5. In the case of network coverage, the access and mobility management function (AMF) initiates a control plane location service. This initiation can occur either on behalf of a specific UE or upon request from a location service client, which is any network element interacting with the Gateway Mobile Location Center (GMLC) to access and process location data. The client's location can be situated anywhere within the network architecture, even within the UE itself. The location service request is subsequently forwarded to the location management function (LMF), also known as the location server. The LMF is responsible for coordinating and computing the user's position.

The 3GPP introduces three SL positioning modes: network-based, UE-based, and UE-only operations. Depending on the mode, location estimation can be performed by the LMF in the core network or by a server UE (which could be the target UE or a reference UE). Regardless of the mode, exchanging collected SL measurements between UEs and/or the network is essential.

C. Positioning Performance and Challenges

The feasibility and quality of a specific timing or angle measurement depend on many factors, including the frequency range of operation and whether single or multiple antennas are employed. In fact, RTT and SL-TDoA measurements are obtained from time of arrival (ToA) measurements of the SL signal, which are more accurate when wide bandwidth signals are used. Differently, SL-AoA measurements require to use antenna arrays, whose number of elements determines the angular resolution. Thus, in principle, FR2 is more effective for positioning, since large bandwidth is available and antenna arrays are usually considered. Nevertheless, path loss should be compensated through beamforming. An additional requirement is the need for synchronized reference nodes to perform TDoA-based positioning methods. The case of SL positioning might be particularly challenging due to the need of synchronizing multiple dynamic reference UEs.

As a numerical example, Fig. 3 considers the SL measurement quality in terms of Cramér-Rao Lower Bound (CRLB) of RTT-based ranging at FR1 (at $5.9\,\text{GHz}$) and FR2 (at $50\,\text{GHz}$), varying the bandwidth and introducing the beamforming gain using multiple antennas at FR2. The CRLB represents the best performance achievable by any unbiased range estimator [1]. Results show that increasing the bandwidth within the same frequency range improves distance estimation accuracy. However, shifting to a higher frequency range (e.g., from FR1 to FR2) incurs higher path loss, offsetting this advantage. Hence, leveraging multiple antennas and a MIMO configuration is crucial to overcome the path loss and obtain reliable measurements at FR2. In addition to the observations from the results in Fig. 3, it is worth noticing that the Doppler shift gets worse at FR2 than FR1 but can be mitigated by using numerologies with larger subcarrier spacing.

In any case, approaching the accuracy shown in Fig. 3 is challenging for different reasons: *(i)* while CRLB is a theoretical bound for positioning accuracy, high-resolution signal processing is needed for precise position measurements in practical scenarios, thus increasing algorithm complexity; *(ii)* limited resolution impacts performance, potentially compromising accuracy in the case of multipath components interfering with the ToA peak; *(iii)* utilizing beamforming to offset path loss necessitates some prior knowledge of the position, adding additional iterations and processing steps; and *(iv)* while at FR2 the wider bandwidth (i.e., larger amount of resources available) and the use of beamforming mitigate inter-vehicle interference, at FR1 inter-vehicle interference should be taken into account due to larger antenna beamwidth and limited bandwidth, i.e. with a lower number of radio resources to be shared among a larger number of users.

To emphasize point *(iv)*, Fig. 4 displays the CRLB of RTT-based ranging in the ITS band for FR1 with a 10 MHz wide signal. The interference level of SL NR-V2X is characterized by using a system level simulator, realized starting from

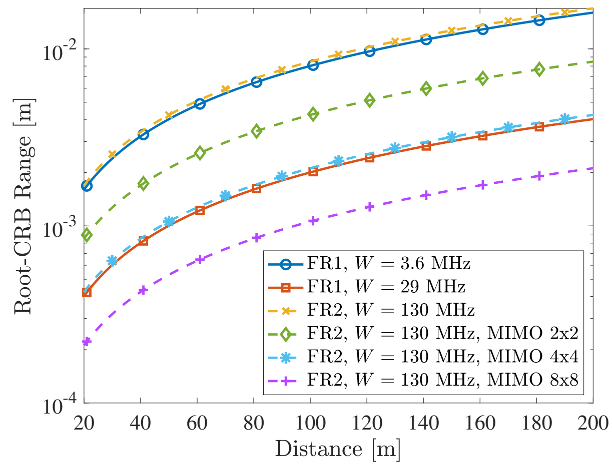

Fig. 3. Example of ranging accuracy (CRLB) for UE localization considering 1000 bytes data packet and the exploitation of pilot symbols (DMRS) varying the frequency range, bandwidth, and considering the beamforming gain from multiple antennas at FR2.

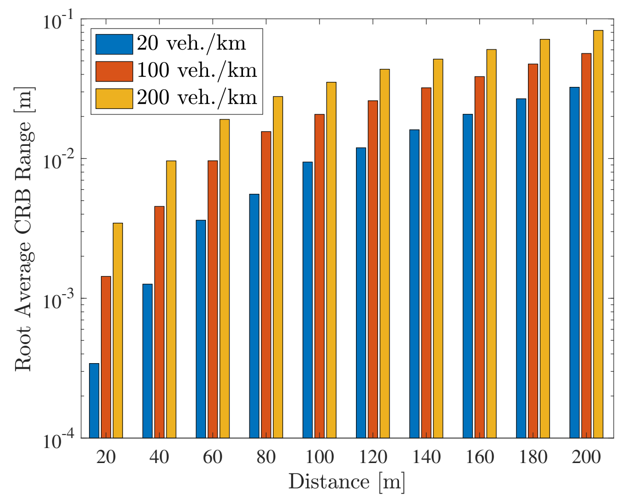

Fig. 4. Example of ranging accuracy (CRLB) at FR1 (ITS band) in the presence of interference from other vehicles in the same band, considering 1000 bytes data packet and the exploitation of pilot symbols (DMRS).

the open-source simulator WiLabV2Xsim [12]. While FR1's lower path loss enables ranging over greater distances between UEs, inter-vehicle interference escalates with higher vehicle densities.

Without angle information, several range measurements from different SL signals need to be exchanged for the final position estimation, thereby amplifying overall positioning latency. This becomes critical as positioning demands grow more stringent with higher levels of vehicle automation, ensuring rapid responses during manoeuvres like overtaking. Recently, proposals of using multiple arrays or extremely large arrays (thus leveraging near-field techniques) at the vehicle side, even at FR1, have been formulated for SL positioning in these stringent contexts [7], [8]. These techniques allow for each vehicle to determine the position of the neighbours by analysing the signals received with SL only, without need for measurements obtained at different sources (i.e., single-anchor localization techniques, where the receiving vehicle is the anchor itself), thus ensuring the lowest possible latency.

IV. V2X Sidelink Sensing

SL sensing refers to the detection and localization of device-free objects (e.g., unconnected road users) through radar techniques using SL measurements. 3GPP (3GPP TS 22.137, Rel. 19) and ETSI's recently started focusing on integrated sensing and communication (not only for SL) by outlining diverse use cases and potential requirements.

A. Sensing Measurements and Methods

Monostatic sensing and bistatic/multistatic sensing are two promising configurations for SL sensing.

a) Monostatic sensing: consists in using a co-located transmitter (TX) and receiver (RX). The high SNR coming from the small distance between the TX/RX antenna and the target in SL monostatic setup (smaller, for example, than the typical distance between a target and a base station) can lead to potentially high accuracy in ToA/AoA estimation. For AoA estimation, antenna arrays are required at least on the RX side. Note that implementing monostatic sensing necessitates the use of a full-duplex radio system.

b) Bistatic/Multistatic sensing: involves transmitters and receivers placed on different vehicles, possibly equipped with multiple antennas. In this case, multi-antenna configurations can be used for AoA/angle of departure (AoD) estimation. Additionally, ToA-based and TDoA-based sensing could be achieved. Two main challenges must be considered for the implementation of bistatic/multistatic sensing: *(i)* the need for tight synchronization (e.g., at sub-nanosecond level) between the transmitting and receiving vehicle; and *(ii)* the need for precise knowledge of the position of both TX and RX vehicles. While requirement *(i)* is needed only for TDoA-based sensing but not for AoA/AoD-based sensing, requirement *(ii)* is always needed for bistatic sensing operations.

B. Architectural Elements

Device-free sensing can make use of relative time, angle, or power measurements derived from signals transmitted by connected users (e.g., reference UEs). These signals are reflected by the target object and received by the reference UEs in either a monostatic or multistatic configuration. These measurements can subsequently be fused in a distributed or centralized manner. The available types of measurements and configurations depend on whether the transmission is unicast, multicast, or broadcast. Currently, beam management procedures for unicast at FR2 are being defined in 3GPP, but it is envisaged that FR2 SL transmission will also support broadcast and multicast in the future, for example through beam sweeping. The 3GPP work is currently limited to the support of SL beam management (including initial beam pairing, beam maintenance, and beam failure recovery) by enhancing existing SL channel state information (CSI) methods and reusing Uu beam management concepts wherever possible. Such procedures have a direct impact on the sensing operation:

a) Beam alignment between users: The process related to beam management, already described in Sect. II-B, inherently supports sensing through AoD and AoA measurements. When aligning beams, vehicles can detect passive targets effectively in the bistatic case. By combining AoD/AoA data with vehicle positions, coarse target localization is achievable. This highlights the crucial interplay between positioning and sensing functions. The obtained target position can be considered as a starting point for iterative positioning techniques leading to higher resolution. The beam pairing case, in the presence of a device-free target, is exemplified on the right part of Fig. 2.

b) Exploitation of multiple beams: Once the best communication beam pair is established (e.g., through beam alignment or by leveraging CSI), the transmitting vehicle can continue the beam tracking operation and perform radar sensing jointly with ad-hoc sensing beams. For example, the transmitting vehicle can split its available power in part to *communication beam* towards the intended receiver, and in part to a *sensing beam* sweeping the environment around (monostatic configuration) [9]. In this case, the target is localized with respect to the transmitting vehicle (relative positioning). Bistatic operations could be considered as well, by including multiple beams at the receiving vehicle too. In this case, proper techniques need to be employed to distinguish between the communication/sensing components and suppress their mutual interference.

C. Sensing Performance and Challenges

Similar to SL positioning, sensing could benefit from the large operating bandwidth and finer beams envisioned when considering FR2 operations, despite the poorer path loss.

Differently, when considering FR1, the main limitation for ToA estimation is the small bandwidth that is normally available (e.g., 10 MHz or 20 MHz for ITS). This poses the same limits of active ToA-based localization schemes but with the additional drawback of the poorer path loss due to the passive reflection of the sensed object. However, when considering SL communication for sensing, the interference is managed by a proper ad-hoc resource allocation mechanism. This stands in contrast to other radar sensors, which require dedicated techniques to mitigate uncontrolled interference [13]. Fig. 5 shows the CRLB of ToA-based ranging in the

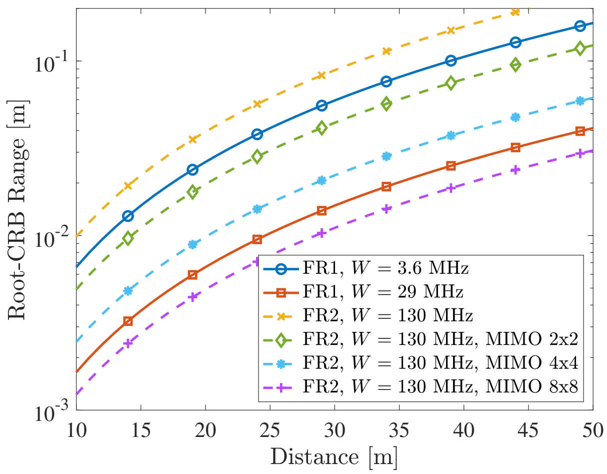

Fig. 5. Example of ranging accuracy (CRLB) for localization of a passive target through monostating sensing. Results are obtained by considering 1000 bytes data packet and the exploitation of all the available symbols varying the frequency range, bandwidth, and considering the beamforming gain from multiple antennas at FR2.

monostatic sensing setup. The signal parameters mirror those in Fig. 3, i.e. varying the bandwidth and introducing the beamforming gain using multiple antennas at FR2. In this monostatic sensing scenario, results are derived assuming a 1 m^2 radar cross-section (e.g., a vulnerable road user as the target). The outcomes align with those in Fig. 3, indicating that while widening bandwidth improves range estimation accuracy, transitioning to a higher frequency range (e.g., from FR1 to FR2) escalates path loss, counterbalancing this advantage. Therefore, leveraging multiple antennas and a multiple input multiple output (MIMO) configuration is crucial to overcome path loss and obtain reliable measurements at FR2. Notably, in the monostatic sensing case, the path loss intensifies due to the signal's round-trip due to target backscattering. On the other hand, all symbols are known and can be used, not just pilot ones as in the active localization case, and this can further enhance the accuracy. Range information can then be fused with angle estimation to obtain target localization [14]. The impact of inter-vehicle interference is anticipated to yield results similar to those showcased in Fig. 4.

V. Security and Privacy Aspects

In V2X scenarios, privacy and security are key aspects in the exposure of sensing services. Dedicated ongoing work on this topic is planned in 3GPP SA 3 and the ETSI Industry Specification Group for Integrated Sensing and Communications (ISG ISAC).

The primary security and privacy risks in sensing and location-based services involve unauthorized access to sensing and localization data, coupled with identification details, and the potential manipulation of this data. Privacy issues arise even for passive targets due to the potential association of identification information with sensing data, for example by communicating and fusing sensing results from passive and active sensors, or by operating in private areas. Existing countermeasures, mainly conceived for localization, encompass robust access control mechanisms and encryption protocols, as well as obfuscation and aggregation techniques to prevent information on the individual user/vehicles from being retrieved. When sensing results are obtained by cooperative and distributed processing of signal measurements (RTT/TDoA/AoA), the system is more susceptible to eavesdroppers and attackers during the inter-node communication of measurements.

Physical layer threats in V2X SL pose significant challenges, allowing unauthorized eavesdroppers to intercept SL signals and potential attackers to disrupt them. Countermeasures like signal obfuscation are necessary against eavesdroppers, requiring techniques to transmit signals with added artifacts [15]. However, the main challenge lies in enabling legitimate receivers to decipher obfuscated signals through dedicated cryptographic protocols. Malicious attackers can also interfere with SL signals, causing *(i)* denial of service through jamming or *(ii)* injecting false information via spoofing/tampering attacks. Such attacks can mislead road users, posing potentially fatal consequences.

The integrity risk level changes depending on the network elements involved, the positioning mode, and the type of measurements used. Indeed, malicious devices can try to be admitted in the process as reference/assistant/located UEs and provide altered assistance data or fake information about their position, timestamp, or local measurements. As for the positioning mode, UE-only modes might be subject to attacks from malicious target or reference UEs. Network-based modes, which necessitate sharing measurements within the network, are more vulnerable to eavesdropping due to the dissemination of information in the network to reach the LMF. As for the type of measurement, SL-AoA may be susceptible to jamming signals directed at specific angles, altering the beam detection and tracking, while SL-RTT and TDoA can suffer from overshadowing, i.e. smarter interference where a delayed replica of the signal is transmitted with amplified power, thereby altering ToA estimates.

VI. Conclusion and Outlook

While standardization efforts are still in the early stages, the primary use cases for integrating localization and sensing have already been defined for selected domains such as smart transportation, smart cities, and low-altitude UAV operations. However, current technical solutions are primarily focusing on downlink and uplink rather than sidelink communications, which have inherent limitations and trade-offs associated with bandwidth, frequency range, path loss, inter-vehicle interference, and the availability of multiple antennas. Significant research efforts are still needed to address these challenges.

This paper has shed light on the intricate landscape of utilizing different frequency ranges for sidelink communications in vehicular scenarios. In FR1, the link budget presents advantages for accurate localization and sensing over short distances, despite encountering challenges such as limited resolution and issues posed by multipath and interference. On the contrary, FR2 boasts a broader bandwidth, enabling enhanced resolution for positioning and sensing. However, implementing beamforming entails multiple steps and may introduce latency issues. We discussed two approaches for positioning and sensing using beamforming, based on *(i)* beam alignment and *(ii)* multiple beams, with distinct challenges and complexities.

Another research direction involves addressing security and privacy aspects, particularly by developing techniques to distinguish legitimate signals from interfering ones and to mitigate the inherent integrity risks of sidelink communication.

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