Highlights

From Collaborative Awareness to Collaborative Information Enhancement in Vehicular Networks

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- This article presents an extended version of a recently proposed vehicular message type, named Cooperative Enhancement Message (CEM), that extends the capability of current protocols, i.e. Cooperative Awareness Messages (CAM) and Collective Perception Messages (CPM) specified by ETSI [1, 2, 3], so as to enable more advanced cooperative applications for connected vehicles. Further, it defines a novel dedicated transmission protocol, named CEM protocol, that allows connected vehicles to share Global Navigation Satellite System (GNSS) raw data. It is worth mentioning that such data is essential to the evolution of both mobile devices and intelligent transportation systems.
- It provides an extended analysis of the impact of the CEM traffic on the network performance through a newly developed open-source simulation framework, i.e., a dedicated version of ms-van3t [4, 5]. This framework offers a modular and integrated Vehicle-to-Everything (V2X) system too allowing for the evaluation of the impact of new communication protocols on Intelligent Transportation Systems (ITS) applications. IEEE 802.11p and Cellular-V2X (C-V2X) technologies are compared with different transmitting power to assess the most suitable standard that may support the proposed protocols.

From Collaborative Awareness to Collaborative Information Enhancement in Vehicular Networks*

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ABSTRACT

An increasing number of innovative technologies are fostering Intelligent Transportation Systems (ITS), thus setting the milestones of future paradigms in vehicular mobility. Among these technologies, Positioning Navigation and Timing (PNT) systems and low-latency communication networks play a fundamental role. This synergy can enable cooperative approaches leading to innovative, advanced services. Research contributions proposing these approaches rely on hypothetical protocols not being yet in place. An extension of current protocols is advisable to push forward the state-of-the-art solutions in PNT collaborative applications. To this aim, this work proposes a new type of vehicular message, namely Cooperative Enhancement Message (CEM), along with a related open protocol to permit the use of Global Navigation Satellite Systems (GNSS) raw measurements in vehicular networks. CEM aims at enabling information sharing beyond what is currently allowed by Cooperative Awareness Messages (CAM) and Collective Perception Messages (CPM). It complements such paradigms supporting the enhancement of localization accuracy, precision, and integrity guaranteed by state-of-the-art cooperative algorithms. Furthermore, a validation of the proposed study is accomplished through a novel network simulation framework. Contextually, the paper presents an analysis assessing network performance when concurrent CEM and CAM transmissions are intended to supply cooperative vehicle applications in IEEE 802.11p and Cellular-V2X.

1. Introduction

Thanks to the remarkable localization capabilities of modern navigation systems, several new successful paradigms in urban mobility have been enabled. A growing number of integrated systems can ensure relative positioning and navigation capabilities with respect to nearby objects and agents by gathering heterogeneous information from different on-board sensors. Despite of the growing availability of such sensors, Global Navigation Satellite System (GNSS) receivers still allow for the estimation of absolute timing and position, thus supporting a plethora of Location Based Services (LBS) at the application layer. Position, Velocity and Time (PVT) estimates have become so relevant in applications that they are often overrated in terms of accuracy and assumed for granted on a continuous base.

However, harsh conditions in urban environment (e.g., multipath, fading, occlusions) impair the quality of the positioning solution of GNSS and hybrid, integrated positioning and navigation units. Such estimation uncertainties are often not accounted for by frameworks in the context of vehicular communications. On the other hand, many proposed Cooperative Positioning (CP) algorithms give the transmission of data for granted, without considering the issues related to the communication network.

Current GNSS navigation systems still present several intrinsic limitations such as sensitivity to multi-path, interferences, and unfavorable visibility conditions of the sky. To mitigate such impairments and to generally improve the accuracy and precision of the PVT solutions, specific protocols can be leveraged through communication networks

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to implement high-accuracy services, e.g. Differential GNSS and Real Time Kinematic (RTK). Benefiting from sub-meter accuracy positioning solutions and merging further information from vehicular sensors, the use of such messages as CAM specified by European Telecommunication Standards Institute (ETSI) is going to foster a set of promising applications [6]. Such messages are indeed periodically transmitted by vehicles and Road Side Unit (RSU), with the purpose of enabling an enhanced awareness on the surrounding situation on the road, built in a cooperative fashion.

In line with the growing interest towards Cooperative Intelligent Transportation Systems (C-ITS) [7], vehicular communications are also expected to support novel paradigms in positioning and navigation technologies that are gathered in the literature under the name of CP [8]. To meet this trend, the data transmitted via CAM may not be sufficient, and additional GNSS measurements need to be exchanged among cooperating and connected network nodes. The naive exchange of the PVT solutions obtained by means of GNSS receivers cannot supply the novel approaches addressed by CP.

In this paper, we therefore aim at filling this gap and tackle the above issue by:

- designing a novel vehicular message type, named CEM, that extends the capability of the CAMs and CPM specified by ETSI [1, 2, 3], so as to enable more advanced cooperative applications for connected vehicles;
- defining a new dedicated transmission protocol, named CEM protocol, that exploits CEMs to let connected vehicles share Global Navigation Satellite System (GNSS) raw data. It is worth mentioning that such data is essential to the evolution of both mobile devices and intelligent transportation systems;
- analysing the impact of the additional CEM traffic on the network performance through a newly developed open-source simulation environment, i.e., a dedicated version of ms-van3t [4, 5]. This provides a modular and integrated Vehicle-to-Everything (V2X) simulation and emulation tool tailored to evaluate the impact of new communication protocols on ITS applications.

Additionally, we have integrated in the ms-van3t simulation/emulation framework a set of real-world paths that were recorded through a highly accurate GNSS Inertial Navigation Sytem (INS) positioning and navigation unit. This permits testing the feasibility and performance of CP solutions, which is of utmost importance to gain an understanding of the behavior of the network and advanced ITS applications. This data complements a simulation framework that allows for the evaluation of both CP approaches leveraging the proposed CEM protocol, and for V2X applications at a larger extent. The present work is conceived as a toolbox for an actual implementation of CP algorithms. However, case studies that assess performance gaps between conventional and collaborative approaches are already present in the literature and are out of the scope of this paper.

An early overview of this study can be found in our conference paper [9]. However, this manuscript significantly extends the content of [9] as set forth below:

1. It presents a more comprehensive presentation of background and GNSS-based Cooperative Positioning approaches, including machine learning techniques;
2. It integrates the CEM protocol with the ETSI Transport and Networking layers;
3. It defines a new type of container for the dissemination of data coming from other ranging sensors (e.g., LiDARs, cameras, etc.);
4. It introduces a new version of our open simulation framework, with the inclusion of the ETSI Transport and Networking layers and an additional module for transparently computing latency and Packet Reception Ratio;
5. It presents a new set of results obtained through an extensive simulation campaign, aimed at determining the network performance of the CEM protocol. The novel results come with a comparison between the usage of IEEE 802.11p [10] and Cellular Vehicle-to-Everything (C-V2X) Mode 4 [11], as underlying access technologies to enable CP approaches.

The remainder of this paper is structured as follows. Sec. 2 summarizes the fundamental aspects of ITS and of the GNSS technology, along with the most promising cooperative navigation approaches in vehicular networks. Sec. 3 introduces the CEM protocol and its message structure, while Sec. 4 extends the use of CEM to other sensors. Sec. 5 describes the simulation environment adopted to obtain the results presented and discussed in Sec. 6. Finally, Sec. 7 draws some conclusion and possible direction for future research.

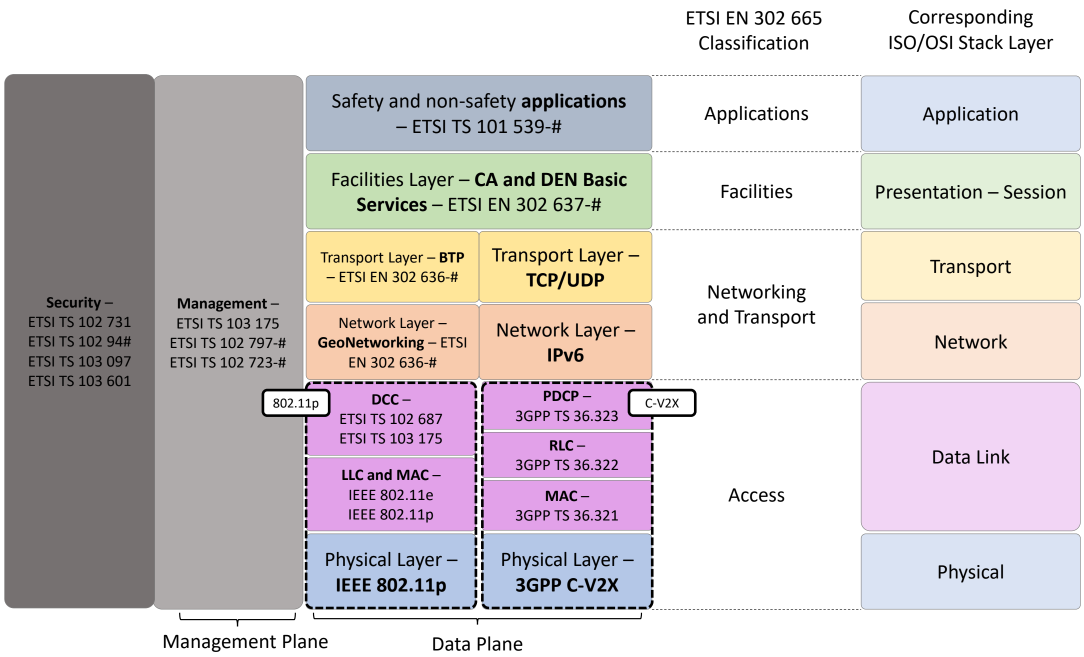


Figure 1: Standardized network stack for a connected vehicle, as foreseen by ETSI. Each layer corresponds to a given ISO/OSI layer, and all the relevant standards (by either ETSI, IEEE or 3GPP) are reported below each protocol.

2. Preliminaries and Existing Solutions

In this section, we provide some background on ITS and vehicular communications, alongside an introduction on GNSS raw data and on the cooperative applications that are envisioned in a GNSS-based system. Finally, we introduce the message formats that have been specified for the transfer of GNSS raw data, and the data messages that have been defined to enable vehicular services.

2.1. ITS and Vehicular Networks

The latest advancements in wireless technologies are envisioned to enable high levels of automation on connected and autonomous vehicles, which are becoming nowadays a reality. Indeed, sensors alone are not enough to enable the so-called Society of Automotive Engineering (SAE) L4 automation, which can basically autonomously manage a vehicle with minimal intervention from the driver [12]. Advanced Driver-Assistance Systems (ADAS) system based solely on sensors have a limited view of the road (for instance, considering a camera or LiDAR, they may be blocked by obstacles and fail to detect potentially hazardous situation) and are subject to errors which make them unsuitable to enable highly automated maneuver management. It it thus evident how vehicles need to exchange data between them to enable more advanced use cases, such as See Through, in which vehicles can exchange data collected through cameras and other sensors (such as LiDARs) to facilitate overtaking and improve road safety [13]. Connecting vehicles together by means of wireless links goes under the broad name of Vehicular Networks and V2X communications. This led to the development of the ITS concept, defined as the application of technology, communications and information processing to improve the environmental impact, the performance and the safety of transportation systems.

The cooperation and data exchange between vehicles includes also the transmission and reception of raw GNSS data. As detailed later, this enables several approaches which would not be possible without vehicular networks. IEEE, 3GPP and ETSI have standardized different layers of the network stack for vehicular communications. In particular, ETSI foresees the connected vehicle network architecture depicted in Fig. 1. As can be seen, ETSI mainly defines all the layers from Networking and Transport to Applications, as part of the ITS-G5 set of standards, with a special focus on the so-called Facilities Layer. Its main aim is to provide support to ITS Applications and V2X services working at the Application Layer, including several crucial features to manage the transmission and reception of standardized vehicular messages [14]. These messages include, among the most important ones: *(i)* Cooperative Awareness Messages (CAMs), periodic messages transmitted with a frequency between 1 Hz and 10 Hz and storing kinematic and dynamic data such as vehicle position, heading, speed, acceleration, alongside additional information such as steering wheel angle and turn indicator status [15]; *(ii)* Decentralized Environmental Notification Messages (DENMs), event-based messages leveraged to notify vehicles and infrastructure nodes about hazards and other events on the road [16]; (iii) Infrastructure to Vehicle Information Messages (IVIMs), to carry road signage information [17]; *(iv)* many other less commonly used messages, such as Radio Technical Commission for Maritime Services Extended Messages (RTCMEMs) [17] and Services Announcement Essential Messages (SAEMs) [18].

Below the Facilities layer and alonside the IPv6 stack, ETSI defines the so-called ITS-G5 Transport and Networking layers. These layers include, respectively, Basic Transport Protocol (BTP) [19] and GeoNetworking [20]. The first is a lightweight connectionless transport protocol, comparable to UDP and containing port numbers which are used to determine the destination service (e.g., the one managing CAMs, or the one managing DENMs) when ITS messages are received by vehicles. According to ETSI, two types of BTP headers are foreseen: either BTP-A, for interactive sessions, in which the recipient is expected to provide a reply, or BTP-B, which is used for non-interactive message dissemination. GeoNetworking is instead a network layer protocol which defines several ways of performing geographical routing of messages, and describes different types of addressing schemes.

These European standards are flexible enough to be encapsulated into either IEEE 802.11p, a dedicated V2X Wi-Fi amendment based on IEEE 802.11a [10], or 3GPP C-V2X, representing the application of cellular technologies to vehicular networks [21]. The latter supports an infrastructure-less communication mode, called Mode 4 [11], which can be used as an alternative, or in conjunction with, IEEE 802.11p. In Section 6, we thus evaluate how the usage of both access technologies can support the transmission of the proposed CEMs.

Starting from the vehicular stack architecture presented earlier, several projects have been funded and are currently ongoing, with the aim of creating smart vehicle infrastructures supporting testing and deployment of V2X applications. Among them, it is worth mentioning 5G-CARMEN[1], a project aimed at creating a smart and connected corridor between Modena, Italy and Munich, Germany. These smart vehicle infrastructures include both equipped vehicles and Road Side Units (RSUs), which can support Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications thanks to ETSI ITS-G5. In 5G-CARMEN, both communication modes are supported by means of C-V2X and 5G connectivity, while other projects such as the Aveiro Open Lab[2] also leverage IEEE 802.11p communication [22]. In parallel, the HANSEL project, an ESA funded activity (ESA ITT number AO/1-9494/18/NL/CRS), has included Differential GNSS (DGNSS) CP among the innovative approaches for navigation in smart cities. The proof-of-concept relied on 4G/LTE physical layers [23] for the exchange of raw GNSS data among smart devices [24]. We remark that our proposed CEM protocol has been designed to be easily implemented and tested on similar architectures, after equipping the vehicles (and possibly also the RSUs) with proper GNSS receivers.

2.2. GNSS Raw Measurements and Observables

It is well known that the position information estimated by using GNSS is a core output of navigation units for vehicular applications, where is used in synergy with the measurements done by other sensors [25, 26]. The PVT inference is performed processing a set of ranging measurements, named *pseudoranges*, which carries ranging information between visible GNSS satellites and the receiver antenna, affected by the time bias of the user receiver. Receivers are also able to estimate other quantities from the received signals, providing them as output of the positioning process (*observables*). Such parameters are, for example, the rate of change of such pseudoranges (which is related to the Doppler shift), and the Carrier-to-Noise ratio of the received navigation signal, that, in GNSS is typically evaluated as the ratio between the unfiltered signal power and the power spectral density of the noise (C/N_0) [27]. The current trend in modern GNSS receivers, is to provide the uncorrected pseudoranges (*raw GNSS measurements*) as outputs together with the set of observables.

Broad use of raw GNSS measurements in high-end receivers has recently pushed receiver manufacturers to their disclosure in mass-market devices, as well [28, 29, 30, 23]. Incremental use of such measurements paved the way for several applications in both mobile devices and transportation systems [24]. Modern multi-constellation, multi-frequency receivers can exploit dozens to even hundreds of channels to track as many GNSS signals, transmitted by all the available satellite systems over different bandwidths. The availability of large sets of raw measurements obtained from multiple constellations and over multiple bandwidths, opens the door to new positioning solutions, for example in

[1] https://5gcarmen.eu/
[2] https://aveiro-living-lab.it.pt/

terms of tight integration with other sensor measurements. In this work we address their use for cooperative positioning, as detailed in the following section.

2.3. GNSS-based Cooperative Applications

Provided the availability of a large number of GNSS measurements and positioning data at different locations, cooperative applications aim at exploiting such information for the improvement of accuracy, integrity, and reliability of the positioning solutions [31]. At the same time, they also enable an augmentation framework for those network paradigms and services that take advantage of positioning data. With the intent of reaching these goals, the ability of vehicles to cooperate with each other was indeed recognised as a promising trend in [32], and later in [33], and it is now intended to be supported by current and next generation networks [34]. In line with the literature on CP, any connected receiver (e.g., vehicle) that is capable of independently estimating its own absolute position will be referred to in this work as either *agent* or *node*. By analyzing the recent literature, a set of valuable examples of collaborative applications can be identified as applications of interest in vehicular networks.

GNSS-based ranging. These techniques combine GNSS observables from two nodes to estimate their inter-node distance, even in non Line-of-Sight (nLOS) conditions. As an example, differential techniques (i.e. DGNSS), are able to provide relative ranging with a low computational effort and minimum delay [35].

Multi-agent cooperative positioning and navigation. Few studies have addressed the problem of tightly integrating asynchronous, non-independent, non-stationary, inter-agent distances [36]. Multi-agent cooperative/collaborative navigation, Bayesian filtering such as Extended or Unscented Kalman Filter and Sequential Monte Carlo methods like Particle Filter (PF) have been shown suitable to perform sensor fusion. Maximum Likelihood (ML) solutions have recently been explored to integrate such quantities, among these, [37] proposes a scheme to first estimate the distances between neighboring vehicles using the weighted least square of double difference scheme and leverages a novel machine learning technique called constrained Self-Organizing Map (SOM). These advanced navigation filters can perform a tight integration of heterogenous measurements and GNSS legacy observables, to improve estimation accuracy in harsh environments [38, 39, 24]. The same approach has also been applied to relative distance measurements based on the Impulse Radio Ultra Wideband (IR UWB) technology [40, 7], or alternative sensors working in Line-of-Sight (LoS) conditions. Recent approaches that use sensitive information related to geographical trajectories and geospatial data for improving performance [41], are prone to benefit from a dedicated protocol, as well.

Cooperative integrity. The integrity of positioning and navigation data measures the level of trust that can be associated with the information provided by an on-board navigation system. To complement or extend the monitoring of standalone, local data, Receiver Autonomous Integrity Monitoring (RAIM), and more recent variants (e.g. ARAIM, RRAIM, ERAIM), have been proposed, together with new collaborative solutions. Among these, Cooperative Enhanced Receiver Integrity Monitoring (CERIM) has been proposed to exploit GNSS raw data shared among networked receivers, in order to perform Fault Detection and Exclusion (FED) [42]. Importantly, a Cooperative Integrity Monitoring (CIM) based on Kalman Filter (KF) can significantly improve detection sensitivity of faulty GNSS measurements, while also detecting faulty inter-nodes measurements. However, few recently proposed FED techniques allow for full, multi-sensor integrity [43, 44].

Time synchronization. Relying on an accurate estimation of their onboard clock bias, GNSS receivers provide distributed timing reference. The availability of in-orbit accurate clocks comes as a distributed timing source that can be exploited by many applications in ITS. Among these, road safety, communication channel scheduling, network interoperability and coordination, time-to-collision monitoring are posing remarkable synchronization constraints that may be not reached through conventional approaches, such as Network Time Protocol (NTP) and Precision Time Protocol (PTP). Given the high accuracy and the lower complexity of its timing estimation, GNSS-based timing is of large interest. Modern receivers can reach up to 30 ns accuracy time synchronization between two receivers, as demonstrated in urban environments [45]. Furthermore, GNSS time synchronization is characterized by almost 99.98% availability, while GNSS positioning solutions only by roughly 80%.

Authentication. The current usage of message authentication in vehicular networks [46, 47] can be further enhanced through the introduction in modern GNSS receivers of the Galileo Navigation Message Authentication (NMA) and Global Positioning System (GPS) CHIp-MEssage Robust Authentication (CHIMERA). GNSS message and signals

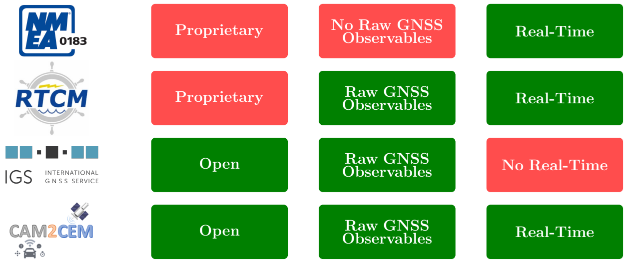


Figure 2: Comparison of the main features of existing protocols for the exchange of GNSS data.

authentications allow discriminating legitimate transmissions from illegitimate ones, thus introducing an independent and time-related source of authentication for network messages and communications at a large extent.

CP and navigation can be also supported by ML algorithms to enable specific applications in ITS that can be further complemented by the proposed protocol [48, 49]. The possibility to exchange lower-level information about localization sensors not only enables the aforementioned applications but also modern approaches such as soft information paradigms [50]. Peer-to-peer exchange of GNSS raw data is required to enable the aforementioned CP approaches. Such exchange can be pursued through general-purpose (e.g., 5G) or dedicated connectivity (either IEEE 802.11 Dedicated Short-Range Communication (DSRC) or Cellular-V2X). Given the multiplicity of applications addressed by the CP algorithms reviewed in this paper, an application-layer performance analysis falls outside the scope of the current study, which focuses instead on the CEM protocol and on its characteristics.

2.4. Network Exchange of Navigation Data

The concept of transmitting or broadcasting GNSS raw data between receivers and reference stations is not new. Currently, there are three main formats that support the transmission of position-related data among connected nodes, each with different kinds of limitations that do not allow the full applicability of the aforementioned CP paradigms. More in detail:

- National Marine Electronics Association (NMEA): NMEA 0183 is an American Standard Code for Information Interchange (ASCII) based serial communication protocol. It supports the so-called GGA strings that provide Time, Position and fix related data for a GPS receiver. NMEA standard is proprietary and does not support raw GNSS data.

- Radio Technical Commission for Maritime Services (RTCM): RTCM 10403 is a proprietary standard series that describes messages and techniques for supporting GPS and Globalnaya Navigazionnaya Sputnikovaya Sistema (GLONASS) operation with one reference station, or a network of reference stations. The Network Transport of RTCM via Internet Protocol (NTRIP) protocol can be used to transmit RTCM messages for differential corrections in RTK schemes. RTCM natively supports real-time-oriented exchange of raw GNSS measurements.

- Receiver Independent Exchange Format (RINEX): it is a data interchange file format for raw GNSS data popular in geodesy. RINEX files can contain observation data (i.e., raw measurements), navigation message data and atmospheric condition models as well. Despite the use of some compression schemes (i.e., Hatanaka file compression), RINEX files are not suitable for near real-time applications, and they are used mostly for post-processing and off-line investigation.

Considering the various limitations of these formats and protocols, *an open protocol for the exchange of raw navigation data between vehicles* is still missing, as well as a simulation/emulation framework for the experimental assessment of the impact on network performance of the transmission of GNSS data needed to enable cooperative navigation algorithms. Fig. 2 highlights the main differences of the proposed CEM protocol with respect to the other protocols available for the exchange of GNSS data.

It is also worth mentioning that ETSI has specified the RTCM Extended Messages (RTCMEM) in order to encapsulate RTCM data, along with its transmission from infrastructure nodes to vehicles, as part of a GNSS Positioning Correction (GPC) service [17]. Nonetheless, the proposed CEM have some significant differences from such messages, in paticular *i)* the main purpose of RTCMEMs is to enable a V2I differential positioning scheme, rather than to directly enable peer-to-peer CP approaches, *ii)* they encapsulate RTCM data which, as just mentioned, is encoded using a proprietary and closed-source protocol, *iii)* no optimization approach is employed to reduce usage of network resources (i.e., there is no exploitation of differential data, differently to CEMs, as detailed in Sec. 3).

2.5. Cooperative Awareness, Perception, and Information Enhancement

The position-related information present in CAMs is only able to support passive awareness of the surrounding environment. The received information can be taken advantage of locally in ADAS and enables the great majority of V2X use cases, but it does not actively contribute to enhancing absolute and relative localization capabilities. In particular, the transmission rate of CAMs can variate between 1 Hz and 10 Hz, depending on the vehicle dynamics [15], and comprises minimal information about positioning and navigation states. As a matter of fact, these messages are used to broadcast final output data of navigation filters, such as position, speed and heading values, which are not suitable to implement most of the CP applications described in Sec. 2.3.

To overcome these limitations, ETSI has recently proposed the so-called Cooperative Positioning Service (CPS) [51]. Such service, exploiting the CPMs, has the goal of improving the awareness of ITS nodes by exchanging measurement about the surrounding environment. The perception of objects around the nodes can be obtained thanks to vehicle on-board sensors. Therefore, CPSs provide an enhanced awareness of the surroundings, but they still do not allow any improvement based on exchanged GNSS information. Starting from such prior art, this work introduces the key idea of Cooperative Enhancement (CE), adopting the incorporation of raw measurements data to support the GNSS-based cooperative paradigms described in Sec. 2.3.

3. Cooperative Enhancement Messages (CEM) for Raw GNSS Data Sharing

This section describes the CEM protocol, a dedicated solution for the exchange of raw GNSS data in vehicular networks. Furthermore, it introduces the CEMs, which are used to encoded and transmit GNSS data among the network nodes. Although CEMs are meant to complement the information provided by CAMs, the CEM protocol can also be easily adapted to be employed as stand-alone. It is indeed worth highlighting how CEMs can be used both in stand-alone fashion as well as in parallel with other kinds of messages such as RTCMEMs, if needed by the overlying V2X applications. Furthermore, even if the main purpose of CEMs is to be exchanged between vehicles, e.g., by V2V communications (as depicted in Fig. 3), they can also be exchanged between moving nodes and network infrastructure.

Fig. 4 depicts the general structure of a CEM message. As can be seen, each CEM includes an ITS Packet Data Unit (PDU) Header, as in CAMs [15] and in DENMs [16]. This header is composed by a mandatory *station ID*, as an identifier of the transmitting vehicle, the *protocol version*, which should be currently set to 1 (future versions of the CEM protocol will foresee increasing numbers as protocol versions), and the *message ID*, which corresponds to *200* for CEMs (while it should be set equal to *2* for CAMs). Then, CEMs include the following network and GNSS data and observables:

1. τ: accurate timestamp of when the observables where measured;
2. TR ID: identifier of the transmitting node;
3. CB ID: identifier of the constellation and signal frequency;
4. PRN: identifier of the satellite from which observables are measured. Receiver can infer the satellite since each one transmits a unique pseudo-random code;
5. Pseudorange ρ: a value in meters of the distance between satellite and receiver (it also accounts for the time difference between transmitter and receiver clocks);
6. Carrier-phase ϕ: also a value of distance expressed between satellite and receiver, but instead expressed in terms of number of phase cycles of the carrier frequency;
7. Doppler Δf: shift in received frequency caused by the relative velocity between satellite and receiver;
8. Variance σ: a value of the measurements uncertainty that can be estimated by receivers (one value is associated with each observable ρ, ϕ, and Δf);
9. $\frac{C}{N_0}$: Carrier-to-noise ratio.

After the ITS PDU header, each CEM message consists of a CEM header and a sequence of *satellite containers* (in principle one for each received GNSS signal). The header of each CEM includes a single timestamp. It can be used

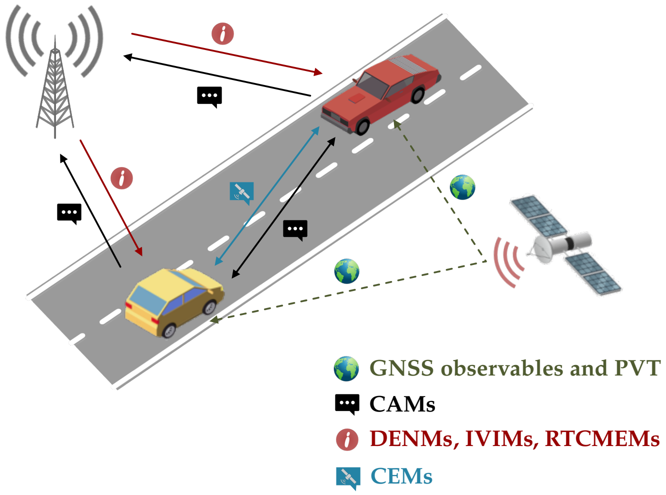


Figure 3: Scheme of a road segment showing two vehicles and one infrastructure node transmitting and receiving different ETSI standard-compliant messages, alongside the proposed CEMs for the exchange of raw GNSS data. In this scenario, vehicles are equipped with both V2X technologies for wireless communication and accurate GNSS receivers.

to synchronize measurements from different nodes, all of which in principle work independently from one another and take measurements at different time instants (and possibly different rates as well). The synchronization step is fundamental in order to enable most cooperative applications.

A TR ID can optionally be included in the header, with a value ranging from 0 to 255 (8 bits). This identifier can be used to define any ad-hoc strategy for the identification of the nodes involved in a CP approach. If not specified, the CEM protocol will use the standard ETSI *station ID*. The usage of identifiers (either ad-hoc or based on the station ID) is needed when including sensor containers from other ranging sensors, as described in Section 4.

Future developments of the protocol foresee the possibility of including application-specific flags and other general purpose information in the header. It should be pointed out that in any case, the inclusion of such fields in the header should not contribute to a large increase of the packets size, and, hence, should not heavily influence the network performance.

All the other fields are encapsulated into the satellite containers. Every container can include one value of the measurement uncertainty σ for each of the three types of GNSS observables present in the message. The protocol specifies a maximum of 10 containers that an agent can include inside a CEM message. In case more than 10 satellites are visible, the transmitter has the freedom to choose which ones to include in the packet (e.g., the ones with highest $\frac{C}{N_0}$).

Finally, it is worth mentioning how CEMs can be potentially encapsulated into any transport and network layer, such as UDP over IP, or the ETSI ITS-G5 Transport and Networking layers [19, 20], depending on the user needs. As mentioned in Section 2.1, the latter normally represents the stack of choice for the dissemination of vehicular messages in Europe, and CEMs are thus designed to fully support their encapsulation inside BTP and GeoNetworking. In particular, CEMs should use the BTP-B header when being encapsulated inside BTP, as this kind of header is normally used for broadcast messages. The standard also defines a BTP port number for each vehicular message type (e.g., 2001 for CAMs, 2002 for DENMs) [52]. We thus define a new port number for the CEM protocol, which is set to 2200, being currently an unused value by ETSI. Furthermore, among the GeoNetworking addressing schemes, CAMs rely on a Single Hop topologically-scoped Broadcast (SHB), being broadcasted only to the nearest first hop. In a similar way, CEMs are designed to be broadcasted as SHB messages [20].

3.1. CEM Encoding

To reduce the load on the communication network, CEMs are designed to employ a low-complexity differential encoding. Thus, the protocol encompasses two types of CEMs:

1. An *Intra-message (I)* which contains the full value of measurements of both high and low frequency data;

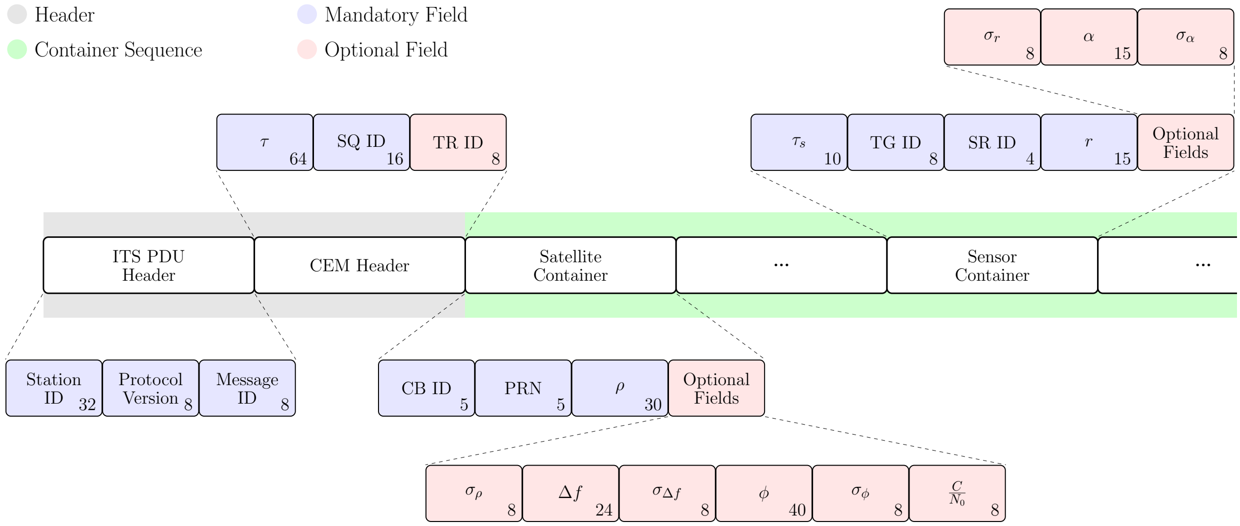


Figure 4: Diagram of a CEM *I* frame. Field size (bit) is indicated by a value in the bottom corner of each field . *D* frames contain an additional sequence identifier in their CEM header.

2. A *Differential message (D)* which contains a differential values. More precisely, this is the difference between the current measurements and the ones sent in the most recent *I*. Only high frequency data is included.

*I*s are transmitted at a fixed interval of 1 s. Spaced out between *I* are instead the *D*s, with a basic interval of 100 ms, so that at most 9 can fit between two consecutive *I*s. It is up to the transmitting node to adjust its rate of *D*s depending for example on the which target application need to be enabled or on the congestion of the network. The specific strategies for the adjustment of the transmission rate are outside the scope of this paper, and will be considered for future developments of the protocol. Fig. 5 provides and example of the flow of CEMs within two successive *I*s. The choice of such time intervals between frames has been done taking into consideration common vehicle dynamics in urban environment and the common rate of solution of GNSS receivers. These values are also in line with the rate intervals specified by CAM. It is worth mentioning that higher rates might facilitate time synchronization between received and local measurements. However, recent studies on time calibration between GNSS and Ultra-Wide Band (UWB) measurements show that time misalignment between multi-sensor range measurements can be compensated through measurement integration algorithms [53, 54]. Thus, higher rate would bring little benefit while significantly increasing the load of wireless channel and CP algorithms (i.e., navigation filters) may become congested.

The header of *I*s contains a unique sequence identifier (SQ ID). The mandatory data in a satellite container of a *I* frame consists of both CBID and PRN identifiers, along with the pseudorange measurements. As a consequence, all the other fields are optional. It should be added that if the transmitter decides to include optional data, it is not forced to send all of it, but can instead choose whatever sub-set of fields to include, depending on what is available or needed by the application. Considering instead the *D*s, two sequence identifiers need to be included. The first is its own unique message identifier and the second is the one of last *I*s. The addition of these sequence identifiers allow an easy sequence reconstruction by the receiver if needed. Within every *D*s satellite container, only the GNSS observables are sent, and only differential pseudorange is mandatory. Other data that does not need to be updated often, such as the variances and $\frac{C}{N_0}$ (low frequency data) is therefore not included, and can be averaged by the transmitter in case of severe fluctuations. Since measurements from different signals appear in the same order as in the last *I* frame, CBID and PRN can be easily inferred and therefore are not repeated in *D*s. To avoid redundancy, fields that are already present in CAMs have been omitted in the current implementation of CEMs, but it is foreseen to add an optional container encapsulating such fields which can be used in scenarios in which CAMs are not present.

3.2. Ranges of Values

The ranges of values that GNSS observables can take for the two kinds of messages described above are summarized in Table 1 and Table 2, respectively. The last column shows an approximate amount of bits that is needed to represent the ranges with the corresponding accuracy in order to provide a rough idea of the amount of data needed. These ranges

Table 1
GNSS observables - CEM Intraframe (I)

Description	Symbol	Min. Value	Max. Value	Precision	Units	Bits
Code pseudorange measurements	ρ	$1.9 \cdot 10^{10}$	$2.4 \cdot 10^{10}$	10^{-2}	m	30
Carrier phase measurements	ϕ	$0.7 \cdot 10^{8}$	$1.6 \cdot 10^{8}$	10^{-3}	Cycles	40
Doppler frequency shift	Δf	$-5.0 \cdot 10^{3}$	$5.0 \cdot 10^{3}$	10^{-3}	Hz	24
Carrier-to-Noise Density Ratio	C/N_0	20	70	0.25	dB Hz^{-1}	8

Table 2
GNSS observables - CEM differential frame (D)

Description	Symbol	Min. Value	Max. Value	Precision	Units	Bits
Code pseudorange measurements	ρ	$-1.0 \cdot 10^{3}$	$1.0 \cdot 10^{3}$	10^{-2}	m	18
Carrier phase measurements	ϕ	$-5.5 \cdot 10^{3}$	$5.5 \cdot 10^{3}$	10^{-3}	Cycles	24
Carrier-to-Noise Density Ratio	Δf	$-3.0 \cdot 10^{1}$	$3.0 \cdot 10^{1}$	10^{-3}	Hz	16

Table 3
Constellations and Signal Bands (identifiers in round brackets are compliant with RINEX standard)

Constellation	SB #1	SB #2	SB#3	SB #4	SB #5
GPS	L1 (1)	L2 (2)	L5(3)	-	-
GLONASS	G1 (6)	G2 (7)	G3 (8)	-	-
Galileo	E1 (11)	E2 (12)	E5a (13)	E5b (14)	E6 (15)
BeiDou	B1 (18)	B2 (19)	B3 (20)	-	-

have been defined considering the minimum and maximum values obtained from real GNSS datasets. In the case of Ds, these ranges are defined based on the largest possible variation of observables over a time span of 0.9 s, which is the maximum distance in time between a D and the latest I. All the uncertainties, as well as the $\frac{C}{N_0}$, are represented with a value from 0 to 200 (corresponding to roughly 8 bits). The protocol does not specify any specific combinations of ranges and precision, so that any implementation has the flexibility to map these values as preferred. Since information regarding the quality of signals is mainly exploited to obtain weighted estimates, its accuracy is not as crucial as for the measurements, and can be represented with only a few bits.

The timestamp is defined as the number of nanoseconds from 2004-01-01T00:00:00.000Z (i.e., January 1st 2004, at midnight Coordinated Universal Time), represented over 64 bits. The format is compliant with the ETSI standards, as it is the same format of timestamps stored inside CAMs [55]. Given the number of signals and constellations currently enabled by the protocol, the CBID is represented over 5 bits (32 values). The PRN for the satellites are also represented over 5 bits.

Table 3 provides a summary of the constellations and signal bands currently included and defined in the CEM protocol. The CBID field is defined for a range of 32 values (equivalent to 5 bits). The ID numbers which are not currently used can be reserved for a possible future addition of either new signals from the already included constellations or for other constellations (e.g., SBAS, QZSS, IRNSS). For every type of information, there is an additional value always reserved to communicate the case in which the information is outside the defined bounds or not available at all. This could for example occur if a satellite is no longer visible, or if the receiver is unable to compute a certain data. In the first case, the container for that satellite will still be included (with unavailable data) in the following Ds until the next I. The value reserved for unavailable data is always defined as the maximum value plus one time the corresponding precision, and it is therefore set to 201 for the uncertainties and $\frac{C}{N_0}$.

As we defined CEMs to be fully ETSI-compliant, the description language ASN.1 was used to define the content of each I and D frame. Indeed, ASN.1 is the same kind of language used by ETSI to define the content of all vehicular messages [15]. Importantly, it is possible to leverage ASN.1 files to automatically generate the source code of encoding and decoding functions, thanks to tools like *asn1c* [56]. After defining the content of a message with ASN.1, several

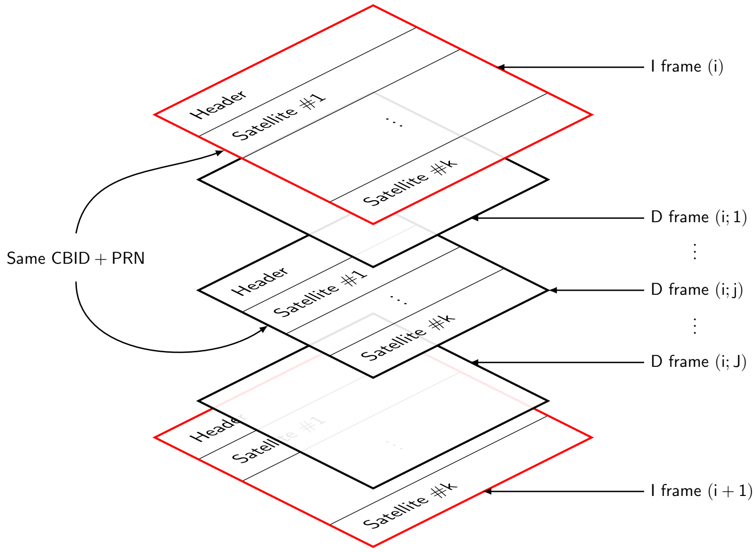


Figure 5: Example of a stream of CEMs. The agent sends J differential messages within two Intra-messages. Each message contains information related to k satellite signals.

encoding rules are then made available to the user, which define how the message will be encoded and provide different advantages and disadvantages in terms of processing speed and message compactness (which in turn translates into a reduced load on the wireless channel) [57]. When defining a new type of vehicular message it is thus crucial to agree on a proper encoding option. All ETSI standard-compliant messages, such as CAMs, make use of UPER (Unaligned Packed Encoding Rules), guaranteeing small message sizes [15]. We have therefore designed our CEMs to be encoded with the same rule.

4. CEM for Other Ranging Sensors

Considering harsh scenarios such as urban canyons, the visibility of GNSS satellites can be reduced and the quality of the received signal is degraded. In such cases, agents might want to rely on other measurements from on-board sensors to improve their positioning capabilities. In order to enable agents to share such measurements between each other, we now discuss the addition of a dedicated *sensor container* for the transmission of range data from other sensors. In addition to the GNSS data, the CEM protocol also enables the exchange of range data obtained from other on-board sensors such as radar, LiDAR, cameras, or UWB interfaces. Although this study was conducted mainly based on the characteristics of such sensors, the additional sensor container has been designed so that it can contain ranging data from any other type of sensor that could be used to obtain range measurements between agents. In this way, the CEM protocol is flexible enough to be tailored, with small modifications, according to the specific implementation of cooperation among vehicles, or to the use of new types of sensors in the future. The addition of this container for ranging data beyond GNSS enables a wide range of implementations of the applications mentioned in Sec. 2.3 that combine both GNSS data and other ranging measurements to further enhance the positioning performance. The containers for GNSS data shown in Fig. 5 can be therefore replaced with the newly designed container. Indeed, for each container slot in the CEM packet, it is up to the transmitter to choose whether to send container data for GNSS signals or for other sensors.

4.1. Cooperative Data from Other Sensors

The container for the additional cooperative information from other sensors has been defined in order to include the following data:

1. τ_s: accurate time difference between GNSS and sensor measurements;
2. Target ID (TG ID): identifier of target vehicles w.r.t. which the measurements are taken;
3. Sensor ID (SR ID): identifier of the type of sensor or signal used to obtain the measurement;

4. Range r: a measurement in meters of the distance between the transmitting (ego) vehicle and the target one;
5. Angle α: angle of the target vehicle with respect to a common reference frame;
6. Variance σ: an estimate of the measurements uncertainty (associated to r and α).

As mentioned earlier, an ID of the transmitting vehicle is included in the CEM header when one or more cooperative satellite or sensor containers are present in the CEM packet. Thanks to the presence of this identifier, each of the sensor containers can include a TG ID (of 8 bits) to uniquely identify the target vehicle with respect to which the measurements are taken. In this way, transmitting and receiving vehicles can all unambiguously identify each other, and properly associate and collect all measurement regarding each vehicle. The SR ID is included so that any agent can integrate the received cooperative measurement using an error model based on the type of sensor from which the measurement was obtained. The protocol can define up to 16 different types of ranging sensors.

An additional scalar value, τ_s, is included in the sensor container to represent the difference between the header timestamp and the time at which the measurements are obtained from the sensor. Indeed, other sensors may work asynchronously with respect to the GNSS on-board unit, and collect measurements with different rates. To reduce as much as possible the amount of data transmitted, this quantity is expressed as a differential scalar value τ_s, which is the time difference between the most recent measurement obtained from the sensor and the timestamp τ provided in the message header. The field hosts values in the range [0,100] ms with a granularity of 0.1 ms, leading to 1,024 values, which can be represented using 10 bits. Sensors measurements are expected to be always less fresher than GNSS data carried by CEM. Note that the minimum time resolution has been set based on current studies and investigations on GNSS and asynchronous sensors integration.

Finally, it is worth mentioning how sensor containers are designed to be inserted in CEMs after all available satellite containers. This, thanks to the UPER encoding rules, enables an easy message decoding at the receiver side, without the need for including a dedicated field carrying the type of each container.

4.2. Management of Vehicle IDs

As described in Section 3, each CEM may contain an optional TR ID, when not relying on the ETSI *station ID* as vehicle identifier. The latter can indeed be fixed on a per-vehicle basis, or anonymized with different strategies [58], and its management according to the ETSI standards may not be suitable for all the CP approaches. We thus consider two possible scenarios for an ad-hoc assignment of TR IDs: *(i)* In case of a platoon of vehicles that move together, IDs can be fixed and assigned a-priori; *(ii)* Otherwise, if vehicles are continuously moving in and out of range of each other, a dynamic allocation of IDs is needed, such that two vehicles in range of each other cannot have the same ID. In any of the two cases, the specific strategies for the assignment of IDs is beyond the scope of our work. Another issue that arises in the transmission of the cooperative measurements is the data association problem. When the ego vehicle is measuring a distance with respect to a target vehicle using on-board sensors, it needs to know which vehicle it is, so that the corresponding ID can be associated to the measurement and included in the sensor container of the CEM. This task is also out of the scope of this work, but we would like to highlight its importance. A proper management of the IDs is anyway crucial for the correct utilization of the cooperative measurements.

4.3. Ranges of Values

Based on the types of sensors considered for this work, common vehicles dynamics in urban environments, and the broadcasting range of the communication technology, we defined a maximum value for the inter-vehicle range r and we set it to 300 m. This value is also the only mandatory measurement for this sensor container, while every other field is optional. For angle measurements, instead, all values α are possible, as in general vehicles could be anywhere around each other. For both these quantities, variances are also included, as done for the GNSS data, to enable weighted estimation techniques. These uncertainties are represented with a value from 0 to 200, exactly as for the GNSS container. Given the usual rate at which sensors obtain measurements and the basic rate of the CEM protocol, the maximum value of τ_s has been set to 100 ms. A summary of all the considered ranges is provided in Table 4, with a rough amount of bits needed to represent the given range and corresponding precision.

As for the differential values in D, given the possibility of fast changing vehicles dynamics in an urban environment, all differential values of the angle α are still possible at any time, especially when the cooperating vehicles are in proximity of each other. Therefore, the full value of α is transmitted again at every D. On the other hand, considering realistic vehicle speeds, the maximum value of the differential range has been set to 80 m. To provide an extreme case as a reference, considering that a D can be generated at most 0.9 s after the original I, if two vehicles were to travel at a speed of $120\,\mathrm{km\,s^{-1}}$ in opposite directions, then their distance would change of at most 60 m in that time span.

Table 4
Sensor data - CEM Intraframe.

Description	Symbol	Min. Value	Max. Value	Precision	Units	Bits
Range measurements	r	0	300	10^{-2}	m	15
Angle measurements	α	0	360	10^{-2}	Degree	15
Differential time stamps w.r.t. GNSS time	τ_s	0	100	10^{-1}	ms	10

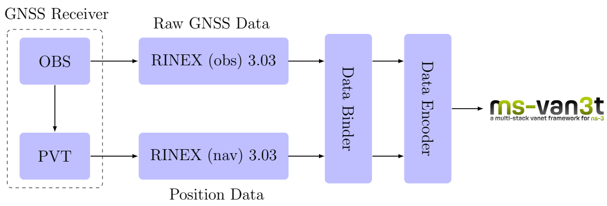


Figure 6: Block diagram of the simulation steps.

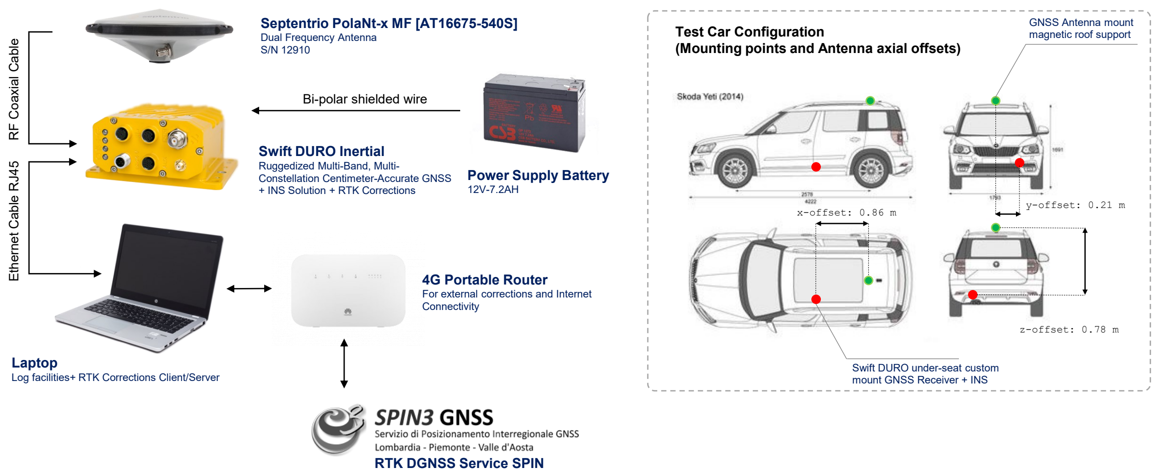


Figure 7: Scheme of the car-mounted, GNSS data acquisition subsystem for the creation of the SAMARCANDA dataset.

5. Simulation Framework with Real GNSS Data

In this section, we first introduce the dataset we use to perform our analysis. Subsequently, we describe the new simulation tool that we developed, starting from the existing ms-van3t simulator.

5.1. SAMARCANDA Dataset

For our study, we build a novel, open dataset named Synthetic Accurate Multi-Agent RealistiC Assisted-gNss DatAset (SAMARCANDA). The dataset has been conceived to support applied research on navigation and positioning technologies in the area of ITS, vehicular mobility, and related technologies. It consists of a collection of accurate GNSS PVT estimates and RINEX files obtained from 19 distinct vehicular tracks collected through a multi-band, multi-constellation Swift Piksi Multi GNSS/INS/RTK, high-accuracy receiver mounted on a car[3].

The equipment shown in Fig. 7 was used to perform the data collection. A high-end Septentrio PolaNt-x MF antenna was installed on top of the car as indicated by the green dot in the Test Car Configuration. The antenna axial offsets were set in the receiver configuration for accurate RTK solutions. In order to limit the roll and pitch vibration angles affecting the on-board INS measurements, the GNSS receiver was installed below the driver seat (as shown

[3]Swift DURO, https://www.swiftnav.com/duro

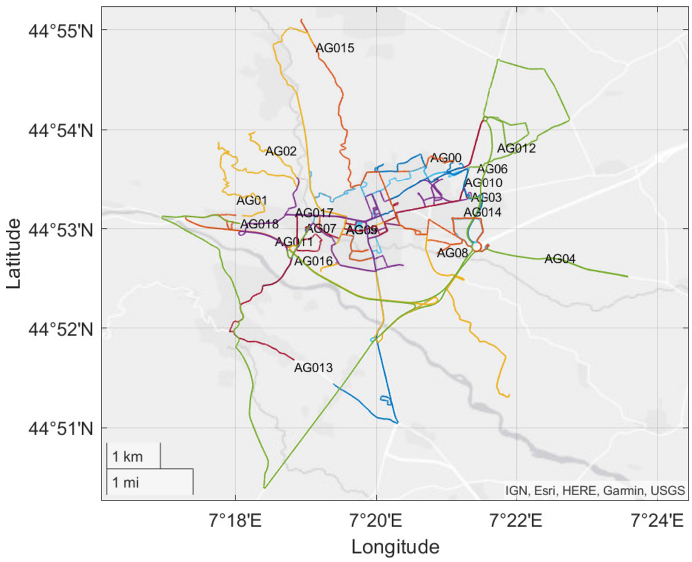


Figure 8: Map of real vehicular trajectories of the SAMARCANDA dataset. Labels and colours identify the different emulated agents.

by the red dot). The receiver was supplied by a 12V battery, while a laptop was used to check its operational activity and to provide Differential corrections. A 4G portable router was also installed to exchange data between the GNSS receiver and the RTK DGNSS Service of the SPIN3 regional network.

The dataset emulates a fleet of vehicles travelling across a urban area of approximately 50.34 km^2, nearby the city of Turin, Italy. The trajectories of the recorded tracks are shown in Fig. 8. This provides a realistic source of data that is typically hard to be synthetically generated with such simulation frameworks as SUMO (Simulation of Urban MObility). The trajectories acquired asynchronously are expected to be reproduced according to a synchronous scheduling in the ms-van3t simulation framework. A demo version of the SAMARCANDA dataset will be made available as part of the main ms-van3t repository [5], to enable the testing and performance evaluation of standard V2X applications when fed with real GNSS data. It is worth stressing that, thanks to such dataset, ms-van3t can account for real positioning errors, unlike conventional traffic simulators such as SUMO.

5.2. Simulation Framework

ms-van3t is an open source framework for the evaluation and simulation of ETSI-compliant V2X applications, which includes several state-of-the-art models, enabling the simulation of different access technologies. These include IEEE 802.11p [10], C-V2X Mode 4 [11] and LTE.

It already provides several sample applications, which can be used as a base to build and simulate more complex scenarios, both with V2V and V2I communications [4]. As it is aimed at providing a fully ETSI-compliant simulation and emulation framework, it includes a complete ETSI ITS-G5 stack, including: *(i)* the BTP Layer [19], *(ii)* the GeoNetworking Layer [20], *(iii)* The Facilities Layer for CAMs and DENMs [15, 16]. The latter includes both the Cooperative Awareness (CA) Basic Service, to manage the reception and transmission of CAM messages, and the Decentralized Environmental Notification (DEN) Basic Service, controlling the exchange of the ETSI Decentralized Environmental Notification Message (DENM)s. All the V2X messages can be encapsulated inside BTP and GeoNetworking, as foreseen by the ETSI standards.

With the aim of extensively evaluating the CEM protocol, leveraging at the same time an open source tool, we have developed a dedicated version of ms-van3t. This version, named *ms-van3t-CAM2CEM*, comes with several enhancements with respect to the original framework.

Specifically, the ms-van3t framework has been enhanced as follows:

- We have generated the encoding and decoding functions for the CEM messages, thanks to the *asn1c* tool [56]. *asn1c* enables the automatic generation of C/C++ message handling functions starting from any ASN.1 data structure. In our case, we fed the tool with the latest version of the CEM specifications, and integrated the resulting code into ms-van3t.
- We have implemented and integrated a novel CE basic service managing the CEM protocol, including *(i)* the management of the differential enconding scheme and of the optional containers and fields, *(ii)* the transmission of CEM messages at the proper frequency, *(iii)* the reception of CEM messages and the extraction of the relevant data, which is then made available to the V2X applications; this service provides an easy-to-use interface to the ms-van3t user thanks to callbacks;
- We have adapted the ETSI BTP implementation to support CEMs, by coding a new port number, as defined in Section 3.
- We have developed a set of dedicated examples, which can be used as a starting point to simulate the exchange of CEMs in urban scenarios, leveraging different access technologies;
- We have integrated the SAMARCANDA dataset, thanks to a full-fledged CSV version which includes pre-processed vehicle dynamic data, including greographical positions, speed, acceleration and heading of the different vehicles. ms-van3t can leverage our real-world dataset thanks to the `gps-tc` module, which can be used as mobility simulator instead of relying on the SUMO tool, representing the default mobility manager in ms-van3t;
- We have implemented and integrated a special module, called `gps-raw-tc`, which is able to read raw GNSS traces (i.e., files containing raw GNSS observables coming from pre-recorded vehicular traces) and provide them as input to the CE basic service for the generation of CEMs. The newly created module can work in conjunction with SUMO, when sample raw GNSS traces are assigned to simulated vehicles (i.e., traces with exactly the same data types and ranges as real traces, but without application-layer informative content) for the evaluation of network-related parameters. It can also work with `gps-tc`, to simulate a real scenario, where vehicles are generating CEMs with actual application-layer content, for the evaluation of full-fledged CP approaches;
- Finally, we integrated a sample raw GNSS trace from the SAMARCANDA dataset, with the aim of simulating the transmission and reception of GNSS observables and evaluate the network performance when CEMs are being transmitted besides other standard-complaiant messages (mainly, CAMs).

ms-van3t-CAM2CEM is specifically designed for the evaluation of CP approaches. We have made it available on GitHub with an open source license [59]. A scheme of the simulation steps, from the dataset to the framework, is provided in Fig. 6. Our enhanced framework also includes a module, called *PRR supervisor*, which is able to report latency and Packet Reception Ratio (PRR) in an automatic and transparent way with respect to the underlying access technology. The PRR, in particular, provides a quantitative measurement on the network reliability, showing how many packets are lost under different scenarios and access technology settings. A PRR of 100% means that no packets are lost, and represents an ideal condition, while a theoretical PRR of 0% would mean that no communication is possible. This module has been used to gather the results presented in the next section, which validate the CEM approach from a networking point of view.

6. Results and Discussion

This section presents the most relevant results coming from an extensive simulation campaign, performed to validate the CEM protocol, when vehicles exchange both CAMs and CEMs in a realistic urban scenario. After an initial set of tests performed using the SAMARCANDA dataset, we present a detailed scalability analysis, in order to assess the network behaviour when the number of connected vehicles grows large. To do so, a dedicated simulation scenario has been set up on the ms-van3t-CAM2CEM framework, which in turn leverages SUMO to represent the vehicles' mobility. In particular, since our main goal is to thoroughly evaluate the network performance when CP approaches are enabled by the CEM protocol, we have leveraged SUMO to simulate the vehicles trajectories, instead of directly relying on the SAMARCANDA dataset. This choice was led by the possibility of increasing the number of vehicles in SUMO without any hard limit (other than the one imposed by the hardware running ms-van3t-CAM2CEM),

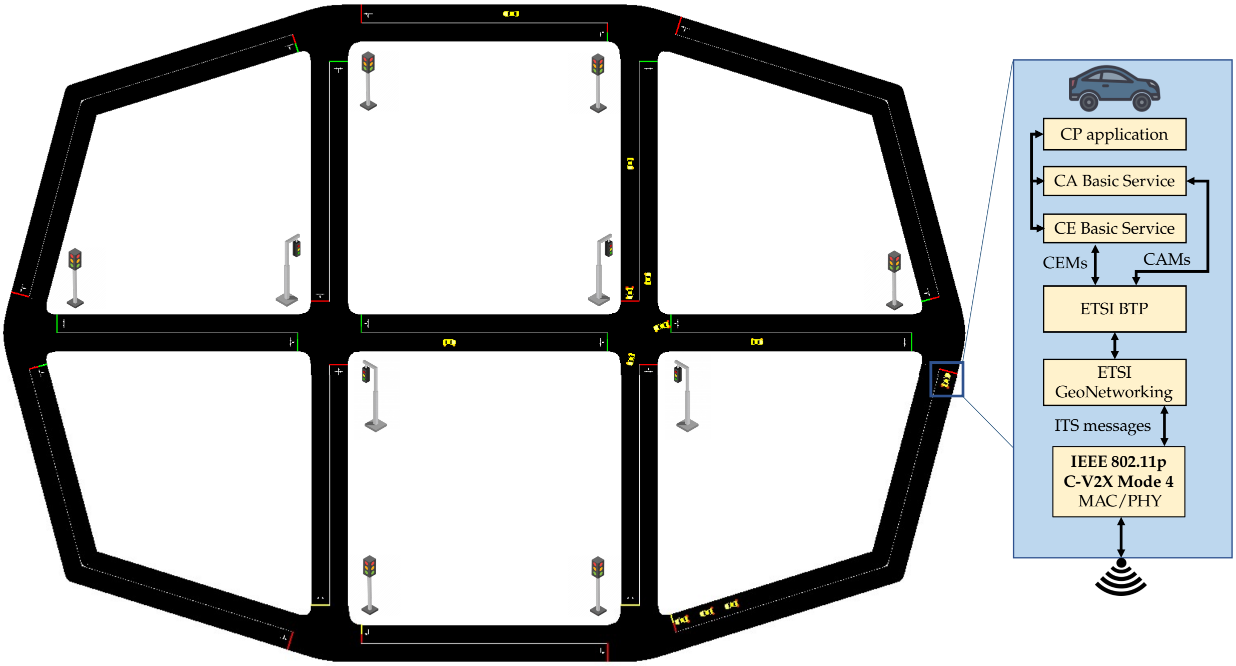


Figure 9: The simulated urban scenario of choice for the CEM evaluation from a network standpoint. It is composed of several intersections regulated by traffic lights, with two central intersections and an outer ring with one lane per direction of travel. The scheme also depicts the different modules which are deployed on each simulated vehicle.

and, hence, of analyzing the network behaviour with a higher number of vehicles than what would be available in SAMARCANDA.

Following this approach, each vehicle is assigned a sample raw GNSS trace from the SAMARCANDA dataset, as SUMO cannot provide such information. Even if the data is sample data, not directly related to the simulated positions in SUMO, this methodology allows us to simulate the exact range of values, data types, and data size that we would expect in real-world CEMs. The urban scenario we considered for this evaluation campaign is depicted in Fig. 9. As can be seen, each vehicle is equipped with *(i)* a CA Basic Service, for the exchange of CAMs, *(ii)* a CE Basic Service, for the exchange of CEMs, *(iii)* a sample CP application receiving data from both Basic Services and storing it locally, *(iv)* an ETSI ITS-G5 stack with the GeoNetworking and BTP layers, and *(v)* a radio interface (including the MAC and physical layers) either based on IEEE 802.11p or on C-V2X Mode 4. All the CAMs and CEMs are broadcasted after being encapsulated into the BTP and GeoNetworking layers, following the rules defined in Section 3.

Indeed, to evaluate our proposed protocol in different operational conditions, we consider two access technologies for V2X communications: *i)* IEEE 802.11p, based on Wi-Fi and well-established for V2I and V2V communications, and *ii)* C-V2X, which has emerged since a few years ago as a very promising cellular-based alternative. The two protocols are different in all layers of the communication stack, and their pros and cons have long been under discussion in the scientific community [60, 61, 62]. Both technologies are fully supported by ms-van3t-CAM2CEM, through state-of-the-art models. Further, C-V2X supports two main modes of operation: Mode 3, with infrastructure support, and Mode 4, for direct communication without infrastructure support. In our analysis, we focus on the latter, as it is supported in ms-van3t and allows us to obtain a direct comparison against IEEE 802.11p while exchanging CEMs in V2V scenarios.

The performance metrics that we investigate are: *(i)* the total transmission rate, expressed as the number of bytes per second transmitted in the wireless medium by vehicles as their density grows larger, *(ii)* the average one-way latency between a transmitting vehicle and all the vehicles receiving the message (we recall that both CAMs and CEMs are normally broadcasted), and *(iii)* the Packet Delivery Ratio (PDR), also called Packet Reception Ratio (PRR) by 3GPP [63] (in the following we will use PRR to refer to such metric). The latter represents a measure of network reliability,

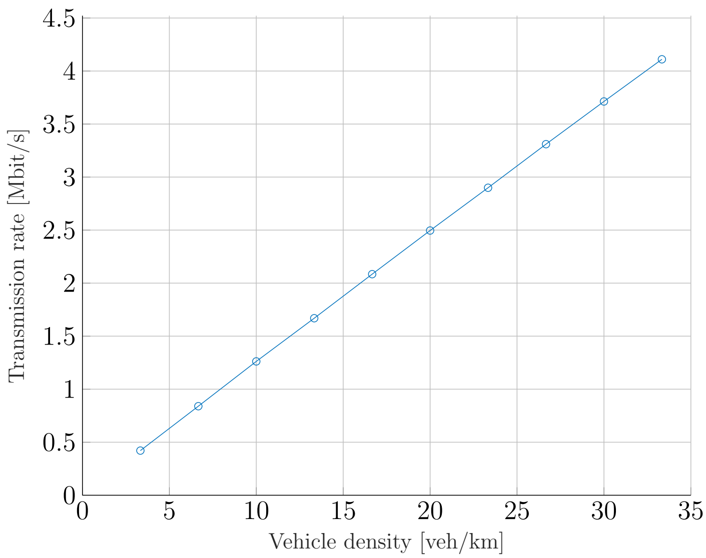


Figure 10: Total transmission rate, representing the amount of bytes transmitted per second as a function of the vehicle density, when both CAMs and CEMs are being actively transmitted by vehicles [9].

as it accounts for the number of packets that are lost due to channel collisions, interference, or harsh propagation conditions. The PRR has been computed following the 3GPP TR 36.885 specifications [63], which report a way to compute the packet loss, or better, the overall PRR, when packets are broadcasted.

Given a baseline distance, which we vary from 100 m to 200 m, the PRR for each message is calculated as the ratio between the number of vehicles, X, that within the baseline distance successfully receive the message, and the total number of nearby vehicles, Y, within the same distance. We then average the per-message PRR over all the message transmissions, (n_{tx}), to compute the average PRR, given a certain value of baseline distance; i.e.,

$$PRR_i = \frac{X_i}{Y_i},\ i = 1, ..., n_{tx} \quad (1)$$

The results are presented in Fig. 12, for an increasing number of vehicles, up to a density of about 33 veh/km, and a varying baseline distance and transmission power. Specifically, two transmission power levels are considered: 23 dBm, as it represents a typical value for the exchange of vehicular messages [64], and 33 dBm. For each access technology and scenario, results are averaged over 10 different experiments, each corresponding to a randomly selected traffic pattern. Each plot also reports the 95% confidence intervals.

The first set of results is related to the total transmission rate as the vehicle density increases. These results do not depend upon the actual access technology and show how much the wireless medium is potentially used when transmitting both CAMs and CEMs in an urban scenario. The obtained values are depicted in Fig. 10, in which the y axis represents the total transmission rate, in Mbit/s, computed over all vehicles in the considered scenario.

The first important outcome is the almost linear proportionality with respect to the vehicle density, which shows how the communication complexity of the proposed protocol is relatively low. Indeed, the system scales almost linearly with the vehicle density, and thus also with the number of nodes participating in the CP process. This is due to CEMs being mainly designed to be broadcasted by vehicles. A second relevant outcome is represented by the maximum transmission rate that is achieved under very high vehicle density, namely, 4.1 Mbit/s. As this is a fairly low value, this figure confirms that the proposed solution can work well even when the network is congested and the available throughput is limited.

The latency results are instead depicted in Fig. 11. Notice that these results do not depend on the value of baseline distance, which is a parameter for the computation of the PRR only. As can be seen, IEEE 802.11p can provide an overall average latency which is significantly lower than the one provided by C-V2X, even for a relatively large vehicle density. In particular, the IEEE-based access technology can provide a latency of around 0.4 ms when only CAMs

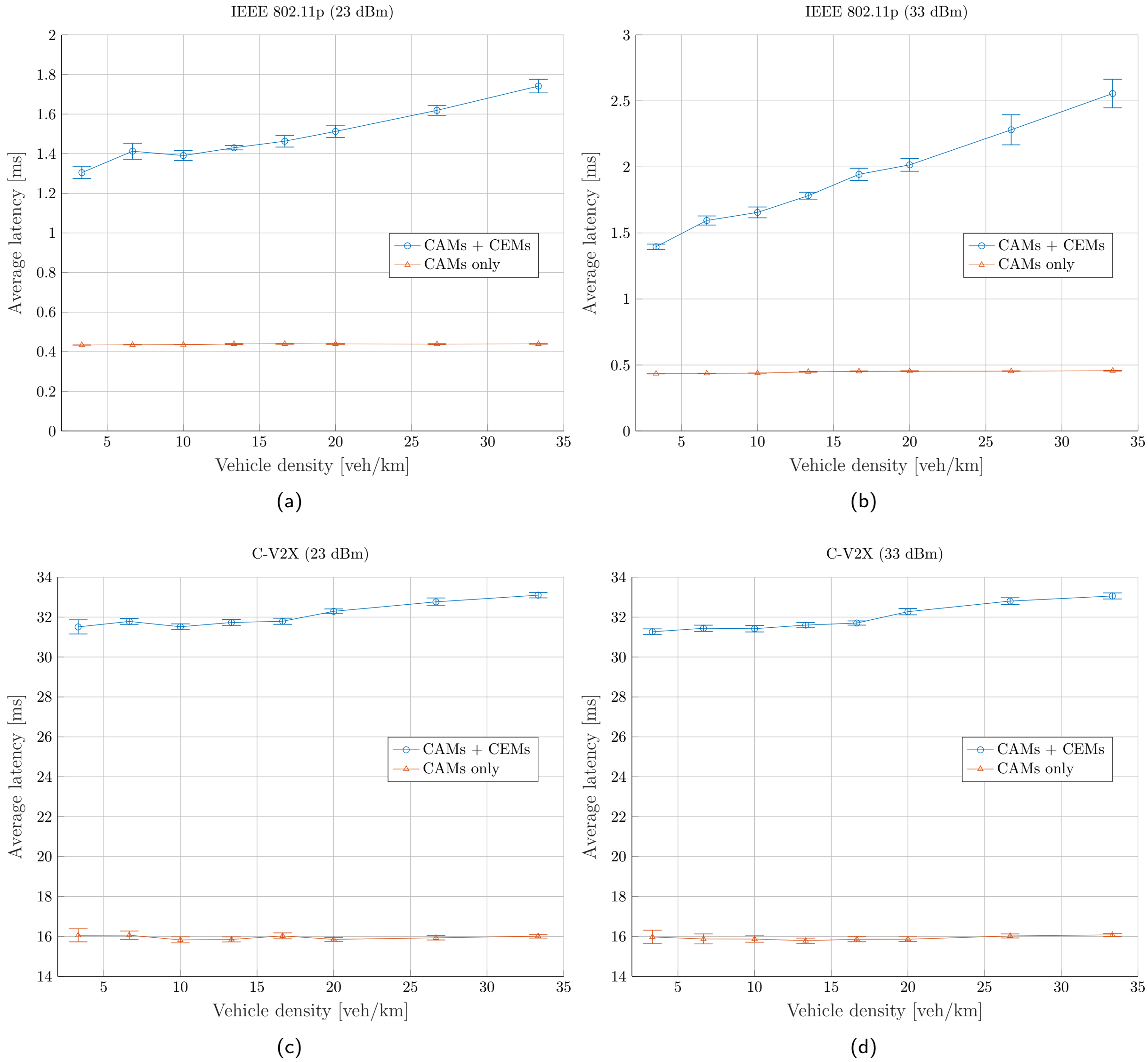


Figure 11: Average one-way latency with respect to vehicle density. (a) IEEE 802.11p at 23 dBm (b) IEEE 802.11p at 33 dBm (c) C-V2X at 23 dBm (d) C-V2X at 33 dBm

are transmitted, which increases to, on average, 1.3-2.5 ms (depending upon the vehicle density) when both CAMs and CEMs are used. This is due to the larger size of CEMs, compared to the one of standard CAMs. Indeed, in our simulation, the size of the CEMs can range from 496 B (smallest *D* frames) to 860 B (largest *I* frames), while CAMs reach up to a maximum of 121 B. However, despite the increased latency, the delays remain very low and compatible with all the safety critical applications which may require, according to ETSI, a maximum end-to-end latency between 50 and 300 ms (depending on the specific application) [65, 66, 67]. The latency observed under C-V2X is instead higher, with values around 16 ms for the transmission of CAMs only, and 32 ms in the case of concurrent transmission of CAMs and CEMs. Such increase in latency is again due to the larger size of the CEM messages. As the amount of data required to exchange raw GNSS information is higher than what is normally transmitted within CAMs, this latency increase also shows the importance of adopting a differential encoding to reduce as much as possible the impact of the transfer of GNSS raw data on the underlying network.

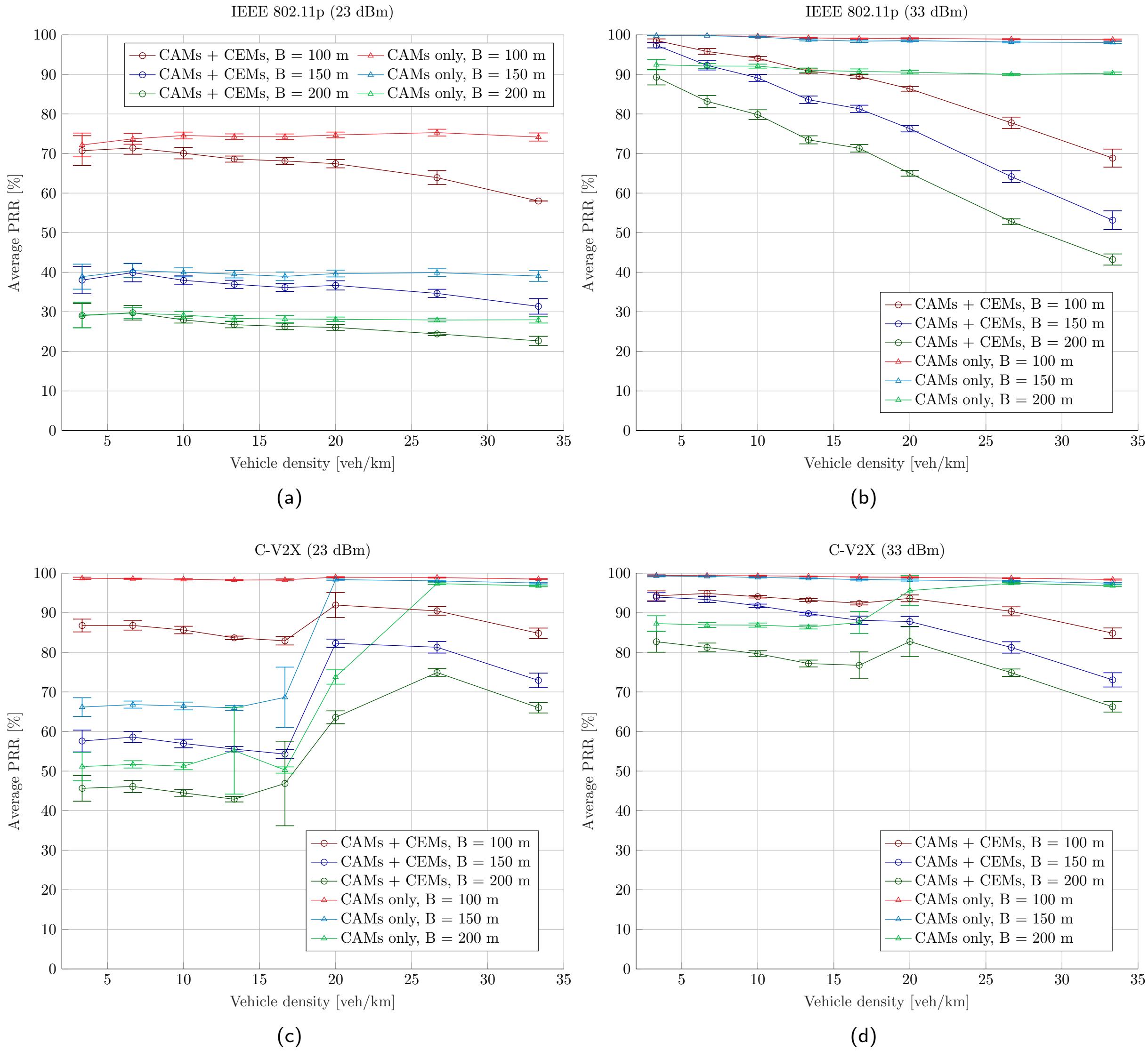
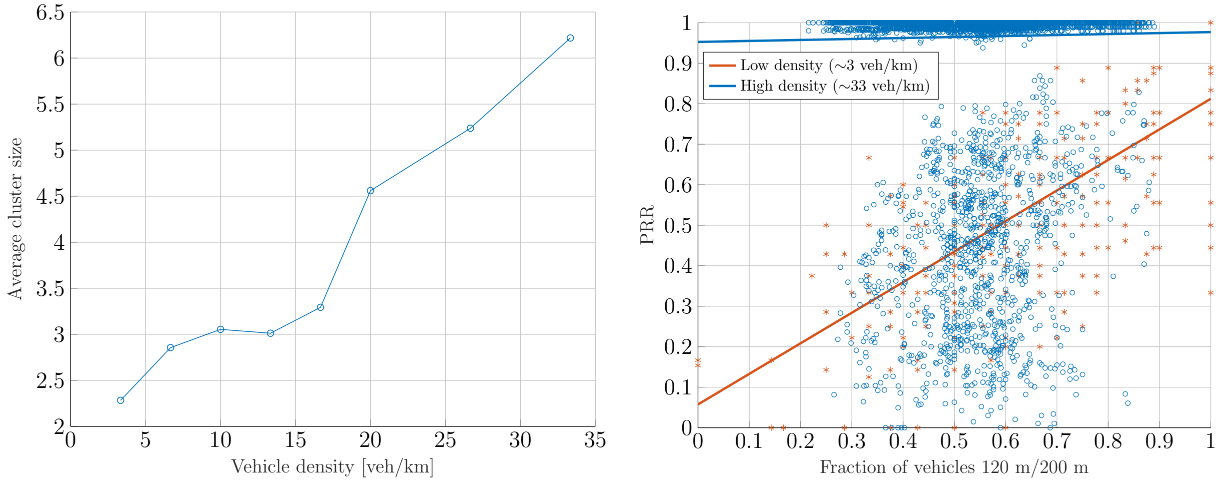


Figure 12: Packet Reception Ratio, in percentage as a function of vehicle density, for three different values of baseline distance, i.e., 100 m, 150 m and 200 m. (a) IEEE 802.11p at 23 dBm (b) IEEE 802.11p at 33 dBm (c) C-V2X at 23 dBm (d) C-V2X at 33 dBm.

These results are also in line with past simulation studies comparing the performance of C-V2X and IEEE 802.11p [60]. It is also worth noticing that increasing the transmission power does not lead to changes in the order of magnitude of the measured values, but it makes the IEEE 802.11p latency increase more as the vehicle density grows, due to higher interference levels. This effect is not observed in the case of C-V2X, which suffers less severely from highly congested network conditions. Thus, when transmitting CEMs over C-V2X, the latency remains almost constant, regardless of the selected transmission power level. This suggests that, when leveraging C-V2X and transmitting both CAMs and CEMs, a higher transmission power would be desirable, as it has a minimal impact on latency, while guaranteeing a higher PRR, as described below.

Next, Fig. 12 shows the PRR results. Each plot depicts the average PRR as the vehicle density grows from low values (around 3.4 vehicle/km) to a very high traffic scenario (with 33.4 vehicle/km). The lines corresponding to the transmission of CAMs only are marked by triangles, while those corresponding to the concurrent transmission of CAMs and CEMs are marked by circles. Each color corresponds to a different baseline value, i.e., 100 m, 150 m and 200 m.



(a) (b)

Figure 13: Analysis of the C-V2X Mode 4 PRR behaviour, taking as reference one of the traffic patterns in the urban scenario depicted in Fig. 9, a transmission power of 23 dBm and a baseline of 200 m. (a) Mean vehicle cluster size (b) PRR, for each transmitted packet, as a function of the fraction of vehicles within 120 m, with respect to the total amount within the 200 m baseline; the straight lines show a linear interpolation of the single PRR values.

The first interesting result comes from the trend of the PRR as the vehicle density grows larger, as different access technologies exhibit different behaviours for highly congested scenarios. Indeed, IEEE 802.11p experiences a monotonically reduced PRR when the vehicle density increases, which is especially evident when transmitting both CAMs and CEMs. This is due to the contention-based channel access, which suffers from increased collisions and backoff times when a large number of vehicles try to access the same shared wireless medium. Interestingly, C-V2X Mode 4 experiences instead a slight reduction until 16.67 vehicle/km, followed by a sudden increase for higher vehicle densities, when a lower transmission power (e.g., 23 dBm) is used. Taking the baseline of 200 m as a reference, for the 23 dBm case, the *CAMs + CEMs* PRR increases from 46.86% with 16.67 veh/km to 63.58% with 20 veh/km. Such effect is less evident when increasing the value of transmission power.

The observed trend is mainly due to the resilience of C-V2X when there is a large number of communicating nodes. Simulating the same scenarios but using a very high transmission power (i.e., 42 dBm, which is not shown here as it would represent an unrealistically high value) led, in both the *CAM only* and *CAMs + CEMs* scenarios, to PRR values always around 100%. The behaviour of the PRR when the vehicle density increases is thus mainly due to the selected level of transmission power, which may not be sufficient to reach all the vehicles within the desired baseline. This fact also explains why high transmission power levels (i.e., 33 dBm), or, equivalently, smaller baseline values (i.e., 100 m), make this effect much less noticeable.

Taking this into account, we were able to evaluate how in urban scenarios, like the one considered here, vehicles tend to form clusters. This occurs especially in correspondence of regulated intersections. Fig. 13a depicts the mean cluster size as a function of the vehicle density, taking as reference one of the ten traffic patterns used to gather the PRR results. A cluster is defined here as a group of vehicles with a reciprocal distance lower than 20 m. As can be seen, the mean cluster size almost doubles between 3 veh/km and 33 veh/km, making the number of vehicles within the baseline that can be reached by C-V2X Mode 4 grow larger.

Fig. 13b shows instead the relationship between the obtained PRR values and the ratio between the number of vehicles within 120 m and the total number within a 200 m baseline. As a reference, a transmission power of 23 dBm is considered, as the C-V2X PRR increase is much more evident for low transmission power levels. The dependence between the PRR values and the fraction of vehicles is significantly less when high density scenarios are considered, with higher values of PRR becoming more likely even when the fraction of vehicles is relatively low.

Next, we look at the comparison between the PRR values obtained with a 23 dBm transmission power and those achieved at 33 dBm. A transmission power higher than 23 dBm is always desirable, as it provides higher values of PRR in all cases and under any of the selected technologies. Indeed, a transmission power of 23 dBm is not always sufficient to reach a transmission range greater than 100 m, thus leading to low packet reception ratios for both the baseline values of 150 m and 200 m. Even though a range of 100 m may be enough for enabling several CP approaches, it can be important to take this into account, especially when targeting use cases which may require larger single-hop ranges. It can also be observed that the C-V2X technology provides, overall, better PRR results than IEEE 802.11p, especially when the vehicle density grows, hence more devices try to access the shared wireless channel. C-V2X with 33 dBm-transmission power can indeed provide a PRR which is always higher than 77%, for a vehicle density up to 16.67 veh/km (which already represents a quite congested scenario for most CP approaches), no matter the selected baseline distance. Further, the same transmission power level can guarantee an average PRR higher than 66%, even for a density of 33.4 veh/km and a large baseline of 200 m.

Looking instead at the comparison between the case where both CAMs and CEMs are transmitted and the one where only CAMs are used, one can notice how the use of CEMs slightly reduces the overall PRR, due to the larger size of our messages and of their more frequent transmission. This reduction is, however, limited, especially in the presence of mid-to-low connected vehicle densities, and does not significantly impact several relevant CP use cases enabled by our protocol. In particular, a range of 100 m with a PRR higher than 90% can enable the development and testing of different cooperative approaches for high-precision localisation. Furthermore, focusing on the highest level of transmission power level (i.e., 33 dBm) and on the exchange of both CAMs and CEMs, IEEE 802.11p showcases a PRR which is much lower than the one of C-V2X, when the number of connected vehicles increases. As an example, for 16.67-veh/km density and a 100-m baseline distance, we observe a reduction on the PRR, with respect to the transmission of CAMs only, by 9.67% for IEEE 802.11p and 6.71% for C-V2X. Once again, this is due to the contention-based nature of the IEEE 802.11p access technology, which suffers from increased collisions and longer backoff procedures as more vehicles try to access the shared medium.

Interestingly, the PRR results also provide useful insights on how the CEM protocol specifications can be improved in the near future. In particular, a future version of the CEM protocol should include:

- The possibility of transmitting the I and D frames at varying periodicity, depending on the actual GNSS raw data, which may help to improve the overall PRR, as less D frames would be transmitted when the deviation from the preceding I frame is not big enough; this would also help to reduce the likelihood of concurrent CAMs and/or CEMs transmissions from different vehicles;
- The possibility of dynamically reducing the number of D frames in case of detected channel congestion;
- A Decentralized Congestion Control (DCC) mechanism to automatically reduce, or increase, the transmission power depending on the real-time PRR performance and on the channel congestion, thus leading to an optimal setting of the transmission power. The same mechanism could be realized in an agnostic way with respect to the underlying access technology (i.e., either IEEE 802.11p or C-V2X), which would just need to tune the maximum transmission power depending on the inputs from a CEM DCC module.

Take-away messages. To conclude, our results highlight how the CEM protocol is an effective way of exchanging raw GNSS data between connected vehicles, using a fully open protocol. Further, the CEM protocol showed to be well-suited to work with both the IEEE 802.11p and C-V2X technologies, depending on the latency and reliability requirements of the overlying CP application. We have also demonstrated that, in order to reach all vehicles within a range of at least 100 m with a reliable PRR, a transmission power of 23 dBm may not be sufficient. On the contrary, 33 dBm can guarantee a PRR higher than 90% at a 100 m-distance, for up to 16.67 veh/km, which represents an already congested value for most CP approaches. We have also provided an insight on how IEEE 802.11p yields a better latency, when it is used to transmit CEMs to nearby vehicles, while C-V2X showed to be more resilient to channel congestion. Finally, the obtained results highlighted which enhancements would be utmost beneficial to further improve the performance of a protocol for GNSS raw data transfer.

7. Conclusions and Future Work

We presented a novel approach for the exchange of raw GNSS data between vehicles in a V2X network. The proposed protocol leverages a new type of vehicular message, named CEM, which we defined to efficiently carry all the information needed to enable CP applications for connected vehicles. Importantly, the CEM protocol can seamlessly inter-operate with the other vehicular services foreseen by ETSI, and, to foster its use, we have released the protocol with open specifications. CEMs are also designed to be encapsulated into any lower layer protocol, with full support for the the ETSI BTP [19] and GeoNetworking [20] layers, being the Transport and Networking layer of choice for the majority of ETSI standard-compliant messages.

Furthermore, we presented an open source tool for the simulation of CP applications, namely, a dedicated version of the ms-van3t framework, including a full implementation of the CEM protocol and an open source dataset containing both raw GNSS data and high-accuracy vehicle tracks. Using this framework, we validated our protocol, and we assessed the impact of the CEMs on the performance of both a C-V2X Mode 4 and an IEEE 802.11p communication network. Our results show that, provided that a sufficiently high value of transmission power is used, CEMs can enable a wide range of CP applications. Indeed, all the vehicles within a range of 100 m from a transmitter can be reached with a PRR larger that 90% up to around 15-veh/km density, without significantly affecting the network performance. This work may contribute to ongoing standardization efforts in ETSI ITS-G5, where the exchange of raw GNSS data could be leveraged as a fundamental enabler for next-generation cooperative positioning applications.

Future research could enhance the CEM protocol by integrating a DCC mechanism, to automatically adjust the value of transmission power depending on the context and the channel load. This would allow the CEM protocol to provide even larger values of PRRs, especially under high channel load. We are also planning to implement a multi-hop feature for CEMs (moving from GeoNetworking SHB packets to multi-hop topologically-scoped ones), which would allow each vehicle to extend the raw GNSS data dissemination range. This, however, may cause an increased impact on the overall network performance, facing additional challenges in the management of I and D frames. It will be thus necessary to thoroughly evaluate this new approach, to understand which benefits may bring to our protocol. Furthermore, future work includes the investigation of techniques for the assignment and management of vehicles IDs, as they play a crucial role in the implementation of numerous CP algorithms.

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CRediT authorship contribution statement

F. Raviglione: Protocol definition and software simulation, writing. **S. Zocca:** Conceptualization, requirements definition, writing. **A. Minetto:** Conceptualization, data curation, writing. **M. Malinverno:** Protocol definition and software simulation. **C. Casetti:** Supervision, coordination, review of the original draft. **C. F. Chiasserini:** Supervision, coordination, review of the original draft. **F. Dovis:** Supervision, coordination, review of the original draft.

References

[1] G. Thandavarayan, M. Sepulcre, J. Gozalvez, Generation of cooperative perception messages for connected and automated vehicles, IEEE Transactions on Vehicular Technology 69 (2020) 16336–16341.

[2] F. A. Schiegg, N. Brahmi, I. Llatser, Analytical performance evaluation of the collective perception service in C-V2X mode 4 networks, in: 2019 IEEE Intelligent Transportation Systems Conference (ITSC), 2019, pp. 181–188. doi:10.1109/ITSC.2019.8917214.

[3] F. A. Schiegg, D. Bischoff, J. R. Krost, I. Llatser, Analytical performance evaluation of the collective perception service in IEEE 802.11p networks, in: 2020 IEEE Wireless Communications and Networking Conference (WCNC), 2020, pp. 1–6. doi:10.1109/WCNC45663.2020.9120490.

[4] M. Malinverno, F. Raviglione, C. Casetti, C.-F. Chiasserini, J. Mangues-Bafalluy, M. Requena-Esteso, A multi-stack simulation framework for vehicular applications testing, in: Proceedings of the 10th ACM Symposium on Design and Analysis of Intelligent Vehicular Networks and Applications, DIVANet '20, Association for Computing Machinery, New York, NY, USA, 2020, p. 17–24. URL: https://doi.org/10.1145/3416014.3424603. doi:10.1145/3416014.3424603.

[5] GitHub, ms-van3t [online], 2021. https://github.com/marcomali/ms-van3t.

[6] N. Lyamin, A. Vinel, M. Jonsson, B. Bellalta, Cooperative awareness in VANETs: On ETSI EN 302 637-2 performance, IEEE Transactions on Vehicular Technology 67 (2018) 17–28.

[7] N. Alam, A. Kealy, A. G. Dempster, Cooperative inertial navigation for GNSS-challenged vehicular environments, IEEE Transactions on Intelligent Transportation Systems 14 (2013) 1370–1379.

[8] C. Gao, G. Zhao, H. Fourati, Cooperative localization and navigation: theory, research, and Practice, CRC Press, 2019.

[9] A. Minetto, S. Zocca, F. Raviglione, M. Malinverno, C. E. Casetti, C. F. Chiasserini, F. Dovis, Cooperative localization enhancement through GNSS raw data in vehicular networks, in: 2021 IEEE Globecom Workshops (GC Wkshps), 2021, pp. 1–6. doi:10.1109/GCWkshps52748.2021.9682163.

[10] IEEE standard for information technology–telecommunications and information exchange between systems - local and metropolitan area networks–specific requirements - part 11: Wireless lan medium access control (MAC) and physical layer (PHY) specifications, IEEE Std 802.11-2020 (Revision of IEEE Std 802.11-2016) (2021) 1–4379.
[11] R. Molina-Masegosa, J. Gozalvez, M. Sepulcre, Configuration of the C-V2X mode 4 sidelink PC5 interface for vehicular communication, in: 2018 14th International Conference on Mobile Ad-Hoc and Sensor Networks (MSN), 2018, pp. 43–48. doi:10.1109/MSN.2018.00014.
[12] SAE J3016 2021-04 - Surface Vehicle Recommended Practice - Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles, SAE J3016 2021-04 (Revision of SAE J3016 2018-06) (2021) 1–41.
[13] R. L. Thompson, Z. Hu, J. Cho, J. Stovall, M. Sartipi, Enhancing driver awareness using see-through technology, SAE Technical Paper Series 1 (2018).
[14] ETSI, ETSI EN 302 665 V1.1.1 (2010-09) - European Standard (Telecommunications series) Intelligent Transport Systems (ITS); Communications Architecture, Standard ETSI EN 302 665, European Telecommunications Standards Institute, 2010.
[15] ETSI, ETSI EN 302 637-2 V1.4.1 (2019-04) - Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service, Standard ETSI EN 302 637-2 V1.4.1, European Telecommunications Standards Institute, 2019.
[16] ETSI, ETSI EN 302 637-3 V1.3.1 (2019-04) - Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 3: Specifications of Decentralized Environmental Notification Basic Service, Standard ETSI EN 302 637-3 V1.3.1, European Telecommunications Standards Institute, 2019.
[17] ETSI, ETSI TS 103 301 V2.1.1 (2021-03) - Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Facilities layer protocols and communication requirements for infrastructure services; Release 2, Standard ETSI TS 103 301 V2.1.1, European Telecommunications Standards Institute, 2021.
[18] ETSI, ETSI EN 302 890-1 V1.2.1 (2019-07) - Intelligent Transport Systems (ITS); Facilities layer function; Part 1: Services Announcement (SA) specification, Standard ETSI EN 302 890-1 V1.2.1, European Telecommunications Standards Institute, 2019.
[19] ETSI, ETSI EN 302 636-5-1 V2.2.1 (2019-05) - Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 5: Transport Protocols; Sub-part 1: Basic Transport Protocol, Standard ETSI EN 302 636-5-1, European Telecommunications Standards Institute, 2019.
[20] ETSI, ETSI EN 302 636-4-1 V1.4.1 (2020-01) - Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 4: Geographical addressing and forwarding for point-to-point and point-to-multipoint communications; Sub-part 1: Media-Independent Functionality, Standard ETSI EN 302 636-4-1, European Telecommunications Standards Institute, 2020.
[21] ETSI, ETSI EN 303 613 V1.1.1 (2020-01) - Intelligent Transport Systems (ITS); LTE-V2X Access layer specification for Intelligent Transport Systems operating in the 5 GHz frequency band, Standard ETSI EN 303 613, European Telecommunications Standards Institute, 2020.
[22] J. Ferreira, J. Fonseca, D. Gomes, J. Barraca, B. Fernandes, J. Rufino, J. Almeida, R. Aguiar, Pasmo: An open living lab for cooperative its and smart regions, in: 2017 International Smart Cities Conference (ISC2), 2017, pp. 1–6. doi:10.1109/ISC2.2017.8090866.
[23] A. Minetto, F. Dovis, A. Vesco, M. Garcia-Fernandez, À. López-Cruces, J. L. Trigo, M. Molina, A. Pérez-Conesa, J. Gáñez-Fernández, G. Seco-Granados, et al., A testbed for GNSS-based positioning and navigation technologies in smart cities: The HANSEL project, Smart Cities 3 (2020) 1219–1241.
[24] A. Minetto, M. C. Bello, F. Dovis, DGNSS cooperative positioning in mobile smart devices: A proof of concept, IEEE Transactions on Vehicular Technology 71 (2022) 3480–3494.
[25] D. Wang, Y. Dong, Z. Li, Q. Li, J. Wu, Constrained MEMS-based GNSS/INS tightly coupled system with robust Kalman filter for accurate land vehicular navigation, IEEE Transactions on Instrumentation and Measurement 69 (2019) 5138–5148.
[26] O. Vouch, A. Minetto, G. Falco, F. Dovis, On the adaptivity of unscented particle filter for GNSS/INS tightly-integrated navigation unit in urban environment, IEEE Access 9 (2021) 144157–144170.
[27] E. Kaplan, J. Leva, D. Milbert, M. Pavloff, Fundamentals of Satellite Navigation, in: Understanding GPS: Principles and Applications, 2 ed., Artech House, 2017, pp. 21–63. URL: https://us.artechhouse.com/Understanding-GPSGNSS-Principles-and-Applications-Third-Edition-P1871.aspx.
[28] GSA working group, Using GNSS raw measurements on android devices, https://www.gsa.europa.eu/system/files/reports/gnss_raw_measurement_web_0.pdf, 2018.
[29] A. Privat, M. Pascaud, D. Laurichesse, Innovative smartphone applications for Precise Point Positioning, 2018. URL: https://arc.aiaa.org/doi/abs/10.2514/6.2018-2324. doi:10.2514/6.2018-2324. arXiv:https://arc.aiaa.org/doi/pdf/10.2514/6.2018-2324.
[30] X. Zhang, X. Tao, X. S. F. Zhu, F. Wang, Quality assessment of GNSS observations from an android N smartphone and positioning performance analysis using time-differenced filtering approach, GPS Solutions 22 (2018) 70.
[31] N. Chukhno, S. Trilles, J. Torres-Sospedra, A. Iera, G. Araniti, D2D-based cooperative positioning paradigm for future wireless systems: A survey, IEEE Sensors Journal (2021).
[32] I. Skog, P. Handel, In-car positioning and navigation technologies—a survey, IEEE Transactions on Intelligent Transportation Systems 10 (2009) 4–21.
[33] N. Alam, A. G. Dempster, Cooperative positioning for vehicular networks: Facts and future, IEEE Transactions on Intelligent Transportation Systems 14 (2013) 1708–1717.
[34] H. Bagheri, M. Noor-A-Rahim, Z. Liu, H. Lee, D. Pesch, K. Moessner, P. Xiao, 5G NR-V2X: Toward connected and cooperative autonomous driving, IEEE Communications Standards Magazine 5 (2021) 48–54.
[35] M. Tahir, S. S. Afzal, M. S. Chughtai, K. Ali, On the accuracy of inter-vehicular range measurements using GNSS observables in a cooperative framework, IEEE Transactions on Intelligent Transportation Systems 20 (2019) 682–691.
[36] A. Minetto, A. Gurrieri, F. Dovis, A cognitive particle filter for collaborative DGNSS positioning, IEEE Access 8 (2020) 194765–194779.

[37] S. Ma, H. Lee, Improving positioning accuracy based on self-organizing map (SOM) and inter-vehicular communication, Trans. Emerg. Telecommun. Technol. 30 (2019).
[38] A. Minetto, F. Dovis, On the information carried by correlated collaborative ranging measurements for hybrid positioning, IEEE Transactions on Vehicular Technology 69 (2020) 1419–1427.
[39] S. Zocca, A. Minetto, F. Dovis, Adaptive bayesian state estimation integrating non-stationary DGNSS inter-agent distances, in: 2021 IEEE 93rd Vehicular Technology Conference (VTC2021-Spring), 2021, pp. 1–7. doi:10.1109/VTC2021-Spring51267.2021.9448952.
[40] M. Rohani, D. Gingras, V. Vigneron, D. Gruyer, A new decentralized Bayesian approach for cooperative vehicle localization based on fusion of GPS and VANET based inter-vehicle distance measurement, IEEE Intelligent Transportation Systems Magazine 7 (2015) 85–95.
[41] F. Yin, Z. Lin, Q. Kong, Y. Xu, D. Li, S. Theodoridis, S. R. Cui, Fedloc: Federated learning framework for data-driven cooperative localization and location data processing, IEEE Open Journal of Signal Processing 1 (2020) 187–215.
[42] J. Xiong, J. W. Cheong, Z. Xiong, A. G. Dempster, S. Tian, R. Wang, Integrity for multi-sensor cooperative positioning, IEEE Transactions on Intelligent Transportation Systems 22 (2021) 792–807.
[43] S. Safavi, M. A. Safavi, H. Hamid, S. Fallah, Multi-sensor fault detection, identification, isolation and health forecasting for autonomous vehicles, Sensors 21 (2021).
[44] J. Gabela, A. Kealy, M. Hedley, B. Moran, Case study of Bayesian RAIM algorithm integrated with spatial feature constraint and fault detection and exclusion algorithms for multi-sensor positioning, NAVIGATION 68 (2021) 333–351.
[45] K. F. Hasan, Y. Feng, Y.-C. Tian, GNSS time synchronization in vehicular ad-hoc networks: Benefits and feasibility, IEEE Transactions on Intelligent Transportation Systems 19 (2018) 3915–3924.
[46] H. J. Jo, I. S. Kim, D. H. Lee, Reliable cooperative authentication for vehicular networks, IEEE Transactions on Intelligent Transportation Systems 19 (2018) 1065–1079.
[47] Y. Hao, Y. Cheng, C. Zhou, W. Song, A distributed key management framework with cooperative message authentication in VANETs, IEEE Journal on Selected Areas in Communications 29 (2011) 616–629.
[48] W. Hammedi, B. Brik, S. M. Senouci, Toward optimal MEC-based collision avoidance system for cooperative inland vessels: A federated deep learning approach, IEEE Transactions on Intelligent Transportation Systems (2022) 1–13.
[49] M. N. de Sousa, R. S. Thomä, Enhancement of localization systems in NLOS urban scenario with multipath ray tracing fingerprints and machine learning, Sensors 18 (2018).
[50] A. Conti, S. Mazuelas, S. Bartoletti, W. C. Lindsey, M. Z. Win, Soft information for localization-of-things, Proceedings of the IEEE 107 (2019) 2240–2264.
[51] K. Garlichs, H.-J. Günther, L. C. Wolf, Generation rules for the collective perception service, in: 2019 IEEE Vehicular Networking Conference (VNC), 2019, pp. 1–8. doi:10.1109/VNC48660.2019.9062827.
[52] ETSI, ETSI TS 103 248 V1.2.1 (2018-08) - Intelligent Transport Systems (ITS); GeoNetworking; Port Numbers for the Basic Transport Protocol (BTP), Standard ETSI TS 103 248 V1.2.1, European Telecommunications Standards Institute, 2018.
[53] M. Li, A. I. Mourikis, Online temporal calibration for camera–IMU systems: Theory and algorithms, Int. J. Rob. Res. 33 (2014) 947–964.
[54] yihan guo, O. VOUCH, S. Zocca, A. Minetto, F. Dovis, Enhanced EKF-based Time Calibration for GNSS/UWB Tight Integration (2022).
[55] ETSI, ETSI TS 102 894-2 V1.3.1 (2018-08) - Intelligent Transport Systems (ITS); Users and applications requirements; Part 2: Applications and facilities layer common data dictionary, Standard ETSI TS 102 894-2 V1.3.1, European Telecommunications Standards Institute, 2018.
[56] GitHub, asn1c [online], 2021. https://github.com/vlm/asn1c.
[57] D. Mundy, D. Chadwick, An XML alternative for performance and security: ASN.1, IT Professional 6 (2004) 30–36.
[58] ETSI, ETSI TR 103 415 V1.1.1 (2018-04) - Intelligent Transport Systems (ITS); Security; Pre-standardization study on pseudonym change management, Standard ETSI TR 103 415 V1.1.1, European Telecommunications Standards Institute, 2018.
[59] GitHub, ms-van3t-cam2cem [online], 2022. https://github.com/francescoraves483/ms-van3t-CAM2CEM.
[60] R. Molina-Masegosa, J. Gozalvez, M. Sepulcre, Comparison of IEEE 802.11p and LTE-V2X: An evaluation with periodic and aperiodic messages of constant and variable size, IEEE Access 8 (2020) 121526–121548.
[61] G. P. Wijesiri N.B.A., J. Haapola, T. Samarasinghe, A discrete-time Markov chain based comparison of the mac layer performance of C-V2X mode 4 and IEEE 802.11p, IEEE Transactions on Communications 69 (2021) 2505–2517.
[62] W. Anwar, N. Franchi, G. Fettweis, Physical layer evaluation of V2X communications technologies: 5G NR-V2X, LTE-V2X, IEEE 802.11bd, and IEEE 802.11p, in: 2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall), 2019, pp. 1–7. doi:10.1109/VTCFall.2019.8891313.
[63] 3GPP, Technical Specification Group Radio Access Network; Study on LTE-based V2X Services; Release 14, Technical Report (TR) 36.885, 3rd Generation Partnership Project (3GPP), 2015. Version 14.0.0.
[64] N. Lyamin, A. Vinel, D. Smely, B. Bellalta, ETSI DCC: Decentralized Congestion Control in C-ITS, IEEE Communications Magazine 56 (2018) 112–118.
[65] ETSI, ETSI TS 101 539-1 V1.1.1 (2013-08) - Intelligent Transport Systems (ITS); V2X Applications; Part 1: Road Hazard Signalling (RHS); application requirements specification, Standard ETSI TS 101 539-1 V1.1.1, European Telecommunications Standards Institute, 2013.
[66] ETSI, ETSI TS 101 539-2 V1.1.1 (2018-06) - Intelligent Transport Systems (ITS); V2X Applications; Part 2: Intersection Collision Risk Warning (ICRW); application requirements specification, Standard ETSI TS 101 539-2 V1.1.1, European Telecommunications Standards Institute, 2018.
[67] ETSI, ETSI TS 101 539-2 V1.1.1 (2013-11) - Intelligent Transport Systems (ITS); V2X Applications; Part 3: Longitudinal Collision Risk Warning (LCRW); application requirements specification, Standard ETSI TS 101 539-2 V1.1.1, European Telecommunications Standards Institute, 2013.

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