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Cooperative Localization Enhancement through GNSS Raw Data in Vehicular Networks

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***Abstract*—The evolution and integration of communication networks and positioning technologies are evolving at a fast pace in the framework of vehicular systems. The mutual dependency of such two capabilities can enable several new cooperative paradigms, whose adoption is however slowed down by the lack of suitable open protocols, especially related to the positioning and navigation domain. In light of this, the paper introduces a novel vehicular message type, namely the Cooperative Enhancement Message (CEM), and an associated open protocol to enable the sharing of Global Navigation Satellite Systems (GNSS) raw measurements among connected vehicles. The proposed CEM aims at extending existent approaches such as Cooperative Awareness Messages (CAM) and Collective Perception Messages (CPM) by complementing their paradigms with a cooperative enhancement of the localization accuracy, precision, and integrity proposed by state-of-the-art solutions. Besides the definition of CEMs and a related protocol, a validation of the approach is proposed through a novel simulation framework. A preliminary analysis of the network performance is presented in the case where CEM and CAM transmissions coexist and are concurrently used to support cooperative vehicle applications.**

***Index Terms*—Global Navigation Satellite Systems, GNSS raw data, GNSS observables ETSI ITS-G5, automotive, cooperative awareness, cooperative positioning, V2X**

I. Introduction

The localization capabilities of modern navigation systems have enabled several successful paradigms in urban mobility. A growing number of integrated systems combine multiple sensors to guarantee positioning and navigation capabilities through information relative to nearby objects and agents. Besides, Global Navigation Satellite System (GNSS) receivers still handle the estimation of absolute timing and position with respect to conventional reference frames, thus feeding several Location Based Services (LBS) at the application layer. Such estimates are of prominent relevance in many modern services in which they are mistakenly given for granted and assumed to be reliable. Indeed, in the context of vehicular communications, typical simulation frameworks do not account for estimation uncertainties that detrimentally affect standalone GNSS and hybrid, integrated positioning and navigation units in harsh conditions (e.g., multipath, fading, occlusions).

To cope with the intrinsic limitations of current navigation systems, communication networks offer specific protocols for GNSS near-real-time corrections, thus implementing effective high-accuracy methods such as Real Time Kinematic (RTK). By relying on such accurate position estimates and additional data coming from sensors installed in vehicles, the Cooperative Awareness Messages (CAM) have already enabled a set of high-potential applications and use cases [1]. In line with the growing interest towards Cooperative Intelligent Transportation Systems (C-ITS) [2], vehicular communications are also expected to support novel paradigms in positioning and navigation technologies that are gathered in the literature under the name of Cooperative Positioning (CP) [3]. To meet this trend, additional GNSS measurements, other than the data transmitted via CAM, need to be exchanged among cooperating, connected network nodes. Concerning GNSSs indeed, the simplistic exchange of users' Position, Velocity and Time (PVT) estimates is not sufficient to enable novel approaches addressed by CP.

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Thus, in this paper we tackle the above issue and present:

- the design of a novel vehicular message type, named Cooperative Enhancement Message (CEM), along with a dedicated transmission protocol, i.e., the CEM protocol, to extend the European Telecommunication Standards Institute (ETSI) CAM and Collective Perception Messages (CPM) [4]–[6] capabilities and enable advanced cooperative applications for connected vehicles
- the analysis of the impact of the CEM traffic on the network performance through a proposed open-source simulation environment, i.e., a dedicated version of ms-van3t [7], [8], a modular and integrated Vehicle-to-Everything (V2X) simulation and emulation framework tailored to evaluate the impact of new communication protocols on Intelligent Transportation Systems (ITS) applications.

Contextually, ms-van3t has been enhanced with a set of real vehicular traces recorded through a highly accurate positioning and navigation unit. This data complements the framework for the evaluation not only of CP approaches relying on the proposed CEM protocol, but also for V2X applications in general.

II. Background

A. GNSS raw measurements and observables

Since the early steps of GNSS integration in vehicular navigation subsystems, positioning data has been considered as the main output of a GNSS receiver. However, the PVT inference comes with the preceding estimation of specific measurements, namely *raw GNSS data* or *observables*. Such quantities typically include distance estimates between the receiving antenna and the visible satellites, i.e., pseudorange measurements, along with their uncertainties, the variation rate of such distances (which relates to the Doppler shift), and the Carrier-to-Noise ratio of the received navigation signal (C/N_0). Since their disclosure in Android smartphones, raw GNSS measurements have been investigated for several applications of interest for the evolution of mobile devices as well as of transportation systems.

B. GNSS-based Cooperative Applications

A remarkable number of cooperative applications aims at improving the accuracy, integrity, and reliability of positioning information by exploiting raw GNSS data concurrently available at different locations [9]. In parallel, they provide an augmentation framework for those network paradigms and services that leverage positioning data. By targeting such goals, cooperation among vehicles was indeed identified as a promising trend in [10] and later refreshed in [11]. In the context of CP and in the following, any network node (e.g., vehicle) that is equipped with a positioning and navigation system is referred to as *agent* or *node*, according to the related literature. Among the many valuable examples of CP, recent research works have identified five main cooperative applications enabled by vehicular networks:

a) GNSS-based ranging: These techniques leverage GNSS observables to estimate inter-nodes distances in non Line-of-Sight (nLOS) conditions. For instance, differential techniques, a.k.a. Differential GNSS (DGNSS), allow for near-real-time ranging with a low computational effort [12].

b) Multi-agent cooperative navigation: Few contributions proposed tight integration schemes to merge asynchronous, non-independent, non-stationary inter-agent distances [13]. Bayesian estimators such as Extended Kalman Filter (EKF) and Particle Filter (PF) are exploited to fuse ranging measurements and GNSS legacy observables to improve estimation accuracy in harsh environments [14], [15].

c) Cooperative integrity: The integrity of the positioning data aims at guarantying the correctness of information supplied by the on-board navigation systems. While Receiver Autonomous Integrity Monitoring (RAIM) and its variants only use the information of a standalone receiver, Cooperative Enhanced Receiver Integrity Monitoring (CERIM) has been proposed to exploit GNSS raw data exchanged among networked receivers [16].

d) Time Synchronization: Several applications in ITS can benefit from GNSS-based distributed timing. Network interoperability and coordination, scheduling of channels, road safety, network security, and time-to-collision monitoring [17] are only a few among a bunch of possibilities. Modern receivers indeed can reach 30 ns accuracy in time synchronization between two receivers, as proved in urban environments [17].

e) Authentication: The recent introduction of Navigation Message Authentication (NMA) and CHIp-MEssage Robust Authentication (CHIMERA) in GNSSs could greatly enhance message authentication in vehicular networks [18], [19]. GNSS message and signals authentication allows discriminating legitimate and illegitimate transmissions.

All the above CP approaches require a peer-to-peer exchange of GNSS raw data through general-purpose (e.g., 5G) or dedicated connectivity (either IEEE 802.11-based, such as Direct Short-Range Communication (DSRC), or cellular-based, such as Cellular-V2X). CP algorithms hence address several different aims; therefore, their performance assessment falls outside the scope of this paper and is left to the specific works referred to in the bibliography.

C. Network Exchange of Navigation Data

GNSS raw data is not new to the need of being transmitted or broadcasted between receivers and reference stations. Three main formats currently support the transmission of position-related data among connected nodes, with some limitations for the applicability to the aforementioned CP paradigms. In particular: (i) National Marine Electronics Association (NMEA) is a serial communication protocol used to output PVT data and it does not support raw measurements; (ii) Network Transport of RTCM via Internet Protocol (NTRIP) 10410.0 allows instead for the streaming of raw data but it is proprietary of Radio Technical Commission for Maritime Services (RTCM); (iii) Receiver Independent Exchange Format (RINEX) files store observation data (i.e., raw measurements), navigation message data and meteorological data for post-processing, thus being not suitable for real-time applications. Given the 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 framework to test the impact of cooperative navigation algorithms on the network performance.

It is worth mentioning that ETSI has specified the RTCM Extended Messages (RTCMEM) for the encapsulation of RTCM data and its transmission from infrastructure nodes to vehicles, as part of a GNSS Positioning Correction (GPC) service [20]. However, such messages are significantly different from the proposed CEM messages, since i) RTCM Extended Message (RTCMEM)s have been conceived for a Vehicle-to-Infrastructure (V2I) differential positioning scheme, and not to directly enable peer-to-peer CP approaches, ii) they encapsulate RTCM data, which is encoded using a proprietary and closed-source protocol, iii) no network usage optimization approach is considered (i.e., there is no transmission of differential data, as opposed to CEMs, as detailed in Sec. III).

D. Cooperative Awareness, Perception, and Enhancement

CAMs carry position-related information to support passive awareness of the surroundings. The data received through CAMs are locally exploited in Advanced Driver-Assistance Systems (ADAS) and enable the great majority of V2X use cases but they do not actively contribute to enhance absolute and relative localization capabilities. Indeed, CAMs broadcasting occurs at a variable rate between 1 Hz and 10 Hz, according to the vehicle dynamics [21], and foresees minimal information about positioning and navigation states. As a matter of fact, they are used to transmit final output data, such as latitude, longitude, speed and acceleration values, which are not enough to enable many of the CP applications described in Sec. II-B.

To overcome the CAM limitations, ETSI has recently proposed the so-called Cooperative Positioning Service (CPS) [22]. Such a service, leveraging the CPMs, aims at increasing awareness between the ITS components by mutually contributing information about the perceived objects. As these objects can be perceived through the vehicle on-board sensors, CPSs extend the environment sensing but they still do not foresee any enhancement leveraging shared GNSS information. We draw on such prior art and introduce the key idea of Cooperative Enhancement (CE) embracing the combination of raw measurements data to support the GNSS-based cooperative paradigms described in Sec. II-B.

III. Cooperative Enhancement Messages (CEM)

This section describes the CEM protocol, a solution for the exchange of raw GNSS data in vehicular networks. Contextually, CEM messages are defined, through which such data is encoded and transmitted among the network nodes. It is worth underlining how the CEM messages can be used either alone or in combination with other messages such as RTCMEMs, if required by the overlying V2X applications. Furthermore, even if they are thought to be exchanged between moving entities, e.g., by Vehicle-to-Vehicle (V2V) communications (as depicted in Fig. 1), they can also be exchanged between vehicles and network infrastructure. The CEM messages include the following data and GNSS observables:

1) Timestamp τ: accurate time at which the measurements were taken;
2) CBID: Identifier of constellation and signal frequency/band;
3) PRN: Identifier of the unique pseudo-random code transmitted by a given satellite;
4) Pseudoranges ρ: a measurement of the distance in meter between satellite and receiver;
5) Carrier-phase ϕ: satellite-to-receiver distance expressed in terms of number of phase cycles;
6) Doppler Δf: shift in received frequency due to the relative velocity between satellite and receiver;
7) Variance σ: an estimate of the measurements uncertainty associated to ρ, ϕ, and Δf;
8) $\frac{C}{N_0}$: Carrier-to-noise ratio.

A single timestamp is included in the header of each CEM. All the other fields are encapsulated into specific subsets of data (i.e., *signal containers*) obtained for each given satellite signal and therefore contained multiple times inside each CEM. The measurement uncertainty can be included up to three times, one for each of the three types of GNSS observables described above. An agent can send data related to up to 10 satellite signals inside the same CEM. The addition of application-specific flags or other fields in the header of the message is foreseen for future developments of the CEM protocol.

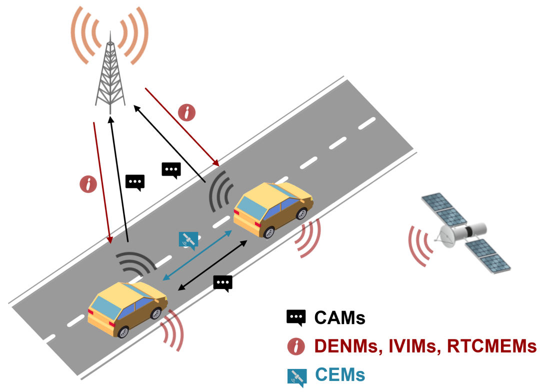

Fig. 1. Scheme representing the exchange of various cooperative messages including CEM, in a scenario with both V2X-connected and GNSS-equipped vehicles.

A. CEM Encoding

To reduce the load on the network, CEMs employ a low-complexity differential encoding. The protocol encompasses two types of CEMs:

1) An *Intra-message (I)* containing full-precision measurements and both high and low frequency data;
2) A *Differential message (D)* that contains the difference between current measurements and those sent in the last I; only high frequency data is sent.

Is are sent once every second, while Ds have a rate multiple of $100\,\mathrm{ms}$, so that at most 9 can fit in between two subsequent Is. The agent can adjust the rate of Ds depending on the target applications and on the congestion of the network. Fig. 2 exemplifies the flow of CEMs within two successive Is. Inside the header, Is have a unique sequence identifier. The signal containers of Is must contain both the CBID and PRN signal identifiers, as well as the pseudorange measurements. All the other information is optional. The agent can also choose to send only a portion of the optional information depending upon what is available or required. Concerning the Ds, the header contains both a unique message identifier as well as the one of the last Is, thus enabling an easy sequence reconstruction at the received side if needed. Within each signal container, only the GNSS observables are sent, and only differential pseudoranges are mandatory. Variances and $\frac{C}{N_0}$ are not present, as they do not need to be updated often (low frequency data) and they can be averaged in case of severe fluctuations. CBID and PRN are also not repeated in Ds since measurements from different signals appear in the same order as in the last Is. To avoid redundancy, fields that are already present in CAMs have been omitted in the definition of CEMs, but an additional, optional container encapsulating such fields can be defined and enabled in situations in which CAMs are not available.

B. Ranges of Values

Table I and Table II summarize, for the two types of messages introduced above, the ranges of values that GNSS

TABLE I
GNSS OBSERVABLES - CEM INTRAFRAME.

Symbol	Min. Value	Max. Value	Precision	Units	Bits
ρ	$1.9 \cdot 10^{10}$	$2.4 \cdot 10^{10}$	10^{-2}	m	30
ϕ	$0.7 \cdot 10^{8}$	$1.6 \cdot 10^{8}$	10^{-3}	Cycles	40
Δf	$-5.0 \cdot 10^{3}$	$5.0 \cdot 10^{3}$	10^{-3}	Hz	24

TABLE II
GNSS OBSERVABLES - CEM DIFFERENTIAL FRAME

Symbol	Min. Value	Max. Value	Precision	Units	Bits
ρ	$-1.0 \cdot 10^{3}$	$1.0 \cdot 10^{3}$	10^{-2}	m	18
ϕ	$-5.5 \cdot 10^{3}$	$5.5 \cdot 10^{3}$	10^{-3}	Cycles	24
Δf	$-3.0 \cdot 10^{1}$	$3.0 \cdot 10^{1}$	10^{-3}	Hz	16

observables can assume. The last column provides the approximate amount of bits that is needed to represent the ranges with the corresponding accuracy. These ranges have been defined using the minimum and maximum values that were measured from real GNSS datasets. In the case of *D*s, the ranges refer to the largest variation of the observables over 0.9 s, which is the farthest in time a *D* can be from the original *I*. All the uncertainties, as well as the $\frac{C}{N_0}$, are represented on a scale from 0 to 200 (8 bits) that can be mapped into different combinations of ranges and precision. Since this information is used to obtained weighted estimates, it does not need to be as accurate as the other measurements, and can be represented with fewer bits. The timestamp is defined as the number of nanoseconds from 2004-01-01T00:00:00.000Z, represented over 64 bits. It is used to synchronize measurements from different agents. The format is compliant with the ETSI standards, which foresees the same format for the timestamps stored inside CAMs [23]. Both CBID and PRN are represented over 5 bits (32 values). A summary of the constellations and signal bands currently included in the CEM protocol is provided in Table III. The ID numbers which are not used, are reserved for either possible new signals from the already included constellations or for other constellations (e.g., SBAS, QZSS, IRNSS). For all the fields, an additional value is reserved in case the information is not available (e.g., when a satellite is not visible any longer). This value is always defined as the maximum plus one times the corresponding precision, and it is set to 201 for the uncertainties and $\frac{C}{N_0}$. As CEMs are defined so as to be fully ETSI-compliant, we leveraged the ASN.1 description language, i.e., the same kind of file used by ETSI to define the content of all vehicular messages [21]. The ASN.1 files created can then be used to automatically generate the source code of encoding and decoding functions, thanks to tools like *asn1c* [24].

TABLE III
CONSTELLATIONS AND SIGNAL BANDS (IDENTIFIERS IN ROUND BRACKETS)

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)	-	-

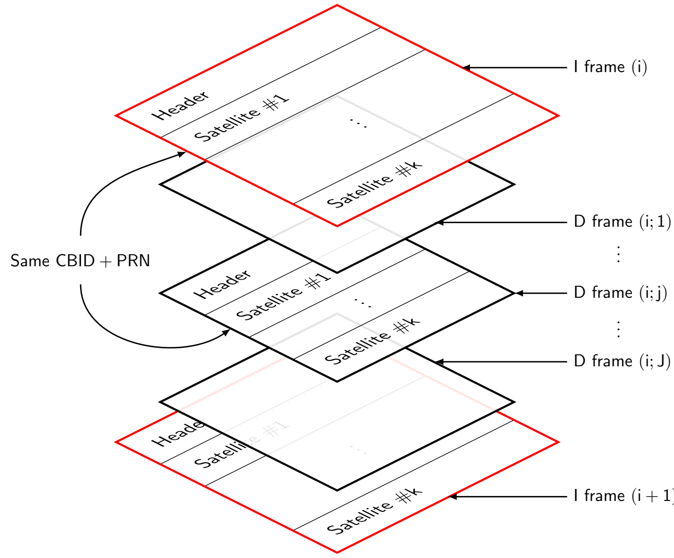

Fig. 2. Example of a stream of CEMs. The agent sends J differential messages within two Intra-messages. Each message contains information of k satellite signals.

IV. SIMULATION FRAMEWORK WITH REAL GNSS DATA

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

A. SAMARCANDA Dataset

In our study, we use a novel open dataset, named Synthetic Accurate Multi-Agent RealistiC Assisted-gNss DatAset (SAMARCANDA). SAMARCANDA collects accurate GNSS PVT estimates and RINEX files obtained from 19 distinct vehicular tracks through a multi-band, multi-constellation Swift Piksi Multi GNSS/Inertial Navigation Sytem (INS)/RTK, high-accuracy receiver installed in a car[1]. The dataset emulates a fleet of vehicles travelling across an urban area of approximately $50.34\,\text{km}^2$, nearby the city of Turin, Italy. A demo version of the SAMARCANDA dataset is made available as part of the main ms-van3t repository [8], to enable the testing and performance evaluation of standard V2X applications when fed with real GNSS data. Thanks to such dataset, ms-van3t can account for real positioning errors, unlike conventional traffic simulators such as SUMO.

B. Simulation Framework

To reliably evaluate the proposed CEM protocol with open source tools, a dedicated version of the ms-van3t framework

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

has been developed. Among the modules enabling the simulation and emulation of V2X scenarios, ms-van3t, already integrates an implementation of (i) the Cooperative Awareness (CA) basic service, in charge of managing the transmission and reception of CAMs and (ii) the Decentralized Environmental Notification (DEN) basic service, managing instead the transmission and reception of the so-called ETSI Decentralized Environmental Notification Message (DENM)s. The ms-van3t framework has been enhanced as follows:

- Generation of the encoding and decoding functions for the CEMs, starting from the CEM ASN.1 definition, thanks to the *asn1c* tool [24];
- Implementation of a CE basic service, implementing the CEM protocol and managing the transmission and reception of CEMs, including the management of Is and Ds;
- Integration of the SAMARCANDA dataset (CSV version with already processed positioning data, such as latitude, longitude, speed, heading and acceleration of different vehicles);
- Integration of a sample raw GNSS trace, to simulate the transmission of realistic raw observables via CEM;
- Implementation of an additional `gps-raw-tc` module which acts as data provider for the CE basic service, starting from raw GNSS traces. This module can work both with sample traces (i.e., traces containing exactly the same data types and ranges as real traces, but with no application-layer informative content) and with real traces, such as the ones included in the SAMARCANDA dataset.

This version of ms-van3t, named "ms-van3t-CAM2CEM", is specifically designed for the basic evaluation of CP approaches. It is available on GitHub with an open source license[2].

V. Results

This section presents a preliminary evaluation of the CEM protocol, leveraging on the CAM2CEM version of ms-van3t described above. The study aims at investigating the network performance when both CAMs and CEMs are used. To this end, a specific simulation scenario has been set up, and we used SUMO to generate vehicle trajectories, instead of directly using the real traces from the SAMARCANDA dataset. Indeed, when evaluating only network-related metrics, SUMO has the advantage of allowing the number of vehicles to grow as needed. To simulate the transmission of realistic GNSS data, which SUMO cannot provide, each vehicle has been assigned a sample raw data collection from the SAMARCANDA dataset. So doing, it is possible to simulate the exact data types and ranges of values which would be present in real CEMs. As underlying access-layer technology, Cellular-V2X Mode 4 (i.e., the mode for direct communication without infrastructure support) was selected inside ms-van3t, as it represents a promising emerging technology for V2V communications [25]. Each simulation has been set to last for 100 s. The performance evaluation focuses on two main metrics: the Packet Delivery Ratio (PDR) with and without the transmission of CEMs (i.e., with the transmission of CAMs only), and the transmission rate as a function of the vehicle density, which was increased up to around 33 vehicles/km (reflecting a very congested scenario). The PDR results are plotted in Fig. 3. The effect of transmitting CEMs together with CAMs on the PDR is negligible up to around 15 vehicles/km. As the vehicle density starts to increase, the use of CEMs, which have larger size than CAMs, affects more and more the overall PDR, leading to a reduction of more than 20% with 33 vehicles/km. This effect is also due to the fact that often vehicles transmit CEMs at the same time instant (every 100 ms for Ds and every second for Is, at least in the default CEMs protocol settings), which increases the packet collision probability under congested traffic conditions. The results also show that: i) the CEMs protocol, as-is, works very well when involving less than 15 vehicles/km, which represents, in any case, a quite high density in most cases, ii) an evolution of the CEMs protocol should take synchronization effects into account, considering, e.g., the possibility of transmitting only some D frames, or none of them, in case of congestion, iii) the vehicles in the simulated scenario use high transmission power so that they can all communicate with each other. Thus, one could consider applying Decentralized Congestion Control (DCC) mechanisms, in order to better manage the transmission power and, hence, reduce the channel load [26].

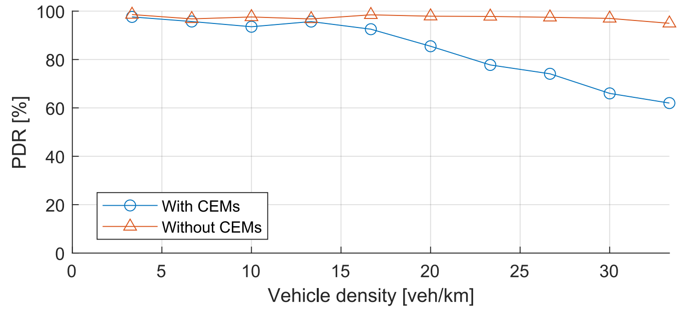

Fig. 3. PDR with and without transmission of CEMs, as a function of the vehicle density.

Fig. 4 depicts the total transmission rate as a function of vehicle densities (when both CAMs and CEMs are transmitted). The total value, in kbit/s, is calculated over all the vehicles travelling in the considered scenario. It is evident how the generated traffic is almost linearly proportional to the vehicle density. The most important result is represented, however, by the maximum transmission rate reached, which remains relatively limited (up to around 4.1 Mbit/s) even in a very congested scenario. This suggests that the proposed CEM protocol can work properly, even when a low value of throughput can be provided by the underlying access technology.

[2] https://github.com/francescoraves483/ms-van3t-CAM2CEM

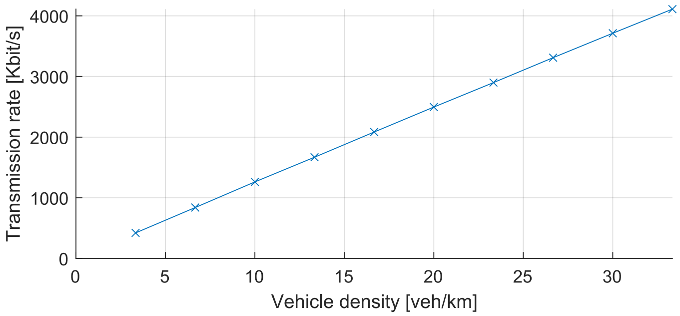

Fig. 4. Total transmission rate (considering all the vehicles) as a function of the vehicle density, when both CAMs and CEMs are transmitted.

VI. Conclusions and Future Work

The paper presented a novel approach for the exchange of raw GNSS data between vehicles in a V2X network. The proposed protocol leverages a new kind of vehicular message, named CEM, which has been designed to carry all the information needed to enable CP applications for connected vehicles. This CEM protocol is released with open specifications and to seamlessly inter-operate with the other vehicular services foreseen by ETSI. Furthermore, we presented an open source tool for the simulation of CP applications, namely, a dedicated version of the ms-van3t framework, including a first 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 provided a preliminary validation of our protocol as well as of the impact of the CEMs on the performance of a C-V2X communication network. Our results showed that CEMs can enable a wide range of CP applications, without significantly affecting the network PDR up to around 15 vehicles/km. Future work will aim at further improving the CEM protocol, and will extend the performance evaluation to consider different network scenarios and V2X communication technologies.

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