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Enhancing the Safety of Vulnerable Road Users: Messaging Protocols for V2X Communication

Silas Lobo, Andreas Festag, Christian Facchi
CARISSMA Institute for Electric, COnnected, and Secure Mobility (C-ECOS)
Technische Hochschule Ingolstadt, Ingolstadt, Germany
{ SilasCorreia.Lobo | Andreas.Festag | Christian.Facchi } @carissma.eu

***Abstract*—The protection of vulnerable road users (VRUs) by means of V2X communication is increasingly considered for the next generation of cooperative safety systems. Two messaging protocols are being standardized: *(i)* With collective perception for sensor data sharing: VRUs can be passively perceived by the local sensors in vehicles and roadside units, which disseminate this information in dedicated messages carrying lists with VRU and other objects. *(ii)* VRUs can actively transmit messages in order to make other road users in their vicinity aware of their presence. This paper carries out a performance evaluation of a scenario with the two main messaging protocols and also their combined deployment, and compares them with two baseline approaches. Simulation results for a representative roundabout scenario with manifold interaction among vehicles and pedestrians indicate that the combination of sensor data sharing and active VRU transmissions performs best: It provides the highest VRU detection rate and the shortest VRU detection latency. This approach keeps the channel busy ratio below a critical threshold, which prevents the data congestion control of the V2X communication system from its activation.**

***Index Terms*—road safety, vulnerable road users, V2X communication, messaging, collective perception, CPM, VAM, VRU.**

I. Introduction

During the year 2020, a total number of 330 269 pedestrians, bicyclists and moped drivers got injured by road accidents in Germany, among them 855 fatalities [1]. In general, these Vulnerable Road Users (VRU) have a higher risk to be severely injured or even be killed by a traffic collision than other road participants, as they are mostly not protected by passive or active safety systems as modern vehicles.

Intending to provide a safer traffic environment for VRUs and to reduce the number of VRU accidents and their severity, research and development for sensor data sharing among vehicles and with the roadside infrastructure have emerged. The European Telecommunications Standards Institute (ETSI), has published an initial specification for a Vehicle-to-Everything (V2X)-based Collective Perception Service (CPS) [2]. CPS disseminates periodic Collective Perception Messages (CPMs) with lists of objects that have been perceived by vehicles or roadside units with their local sensors, such as cameras, RADAR or LiDAR. When a vehicle detects an object and classifies it as a VRU, this information will be included in the perceived objects and transmitted in the CPM. The receivers of a CPM become aware of the VRU even when their local sensors are not able to see the VRU, e.g., due to impaired perception of the local sensors.

Sensor data sharing is regarded as a next-generation V2X use case, also named "Day 2", that provides "sensing driving" [3] and extends the "Day 1" use cases with message types for highly aggregated information. The deployment roadmap for V2X communication systems also defines "Day 3+" use cases and adds VRU sensing by active advertisements. They allow VRUs to be part of the V2X network through VRU Awareness Message (VAM), where a VRU broadcasts a message carrying position and kinematic information [4]. CPMs and VAMs have similar objectives regarding VRU detection: both share information about VRUs. The CPM broadcasts VRU - and other - information based on its specified triggering conditions and object filtering procedures. However, the VRU detection is executed only by nearby vehicles or RSUs with their potentially limited sensor capacity, confidence, and range [4]. Enabling VRUs to be active in the V2X communication by sending V2X messages may result in a safer ambiance. The vehicles can receive information directly from VRUs that may have not been perceived by any other sensor. This perspective may also enlarge the perception of the vehicle's surroundings.

This work addresses VRU protection by dedicated V2X message types and assesses their impact on the VRU safety by simulation. It considers five approaches as summarized in Table I: The first approach provides an idealistic perception as a baseline, enumerating all VRUs presented in the vehicle's surroundings, even if they are not in line-of-sight or hidden by an obstacle. In the second approach, VRUs are detected by vehicle sensors only, excluding any message exchange via V2X communication. The third approach provides VRUs the capability to exchange VAMs, whereas in the fourth vehicles broadcast CPMs. The last approach combines the third and fourth: vehicles transmit CPMs and VRUs issue VAMs.

As evaluation metrics, VRU perception rate, VRU detection time, channel busy ratio, channel capacity, and V2X message size are applied. The simulation was carried out with the coupled simulators SUMO [5] using a representative roundabout in the Ingolstadt traffic scenario *InTAS* [6] and the V2X simulation framework Artery [7], which has been extended by VRU Awareness Service as specified in [4].[1]

The remainder of this paper is organized as follows: Related

[1]The simulator enhancements for the present paper are available as open source at https://github.com/silaslobo/artery-VRU.

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TABLE I
APPROACHES FOR VRU PROTECTION CONSIDERED IN THE PAPER

#	Name	Description	Reference
1	Idealistic	Perfect perception	NA
2	No-V2X	Sensor perception only	NA
3	VAM	VRUs broadcast VRU Awareness Messages (VAM)	[4]
4	CPM	Vehicles broadcast Collective Perception Messages (CPMs)	[2]
5	CPM & VAM	Vehicles and VRU broadcast CPM and VAM, respectively	[2], [4]

work is analyzed in Section II. After describing the simulation environment in Section III, Section IV presents and discusses the simulation results. Section V concludes the paper and gives an outlook to future work.

II. Related Work

In recent years, various research work have addressed VRU safety and investigated both passive and active safety systems. Also, for VRU safety with V2X communication, as a specific direction of active safety, various publications exist, see e.g. the survey in [8]. Considering the standardization of V2X communication, research on sensor data sharing and collective perception, optimizing functions and parameters to include VRU data on the CPM, enlarging the VRU safety without overloading the communication channel [9]–[12]. Some publications have presented novel approaches to implement V2X services for VRUs [13], [14], allowing them to be active on the network.

Compared to the existing approaches that study VRU safety based on V2X communication, the present paper assesses the messaging protocols in V2X communication systems by simulation in a realistic scenario and compares the proposed standards concerning their effectiveness in improving VRU safety.

A. Collective Perception Message (CPM)

Collective perception enhances the local perception of vehicles and roadside equipment by V2X communications. The collective perception standard. which is being developed by ETSI (see ETSI TR 103 562 [2] relies on a model where vehicles interact with each other through V2X, informing nearby vehicles of detected and classified objects, such as cyclists, pedestrians, and other vehicles [15]. As part of the standard, CPM has been introduced as a dedicated message to exchange the sensors' information. The message format consists of a Intelligent Transport Systems (ITS) Protocol Data Unit Header (ITS PDU Header) and CPM parameters [2]. The payload is composed of containers; the CPM's main containers are *Management Container*, *Station Data Container*, *Sensor Information Container*, and *Perceived Object Container*.The *Management Container* and *Station Data Container* provide information related to the type of the sender station, i.e. vehicle or a Road-Side-Unit (RSU), actual position, orientation angles, vehicle's dynamic, and heading. The *Sensor Information Container* inserts information about the sensors attached to the sender, e.g. LIDAR, radar, camera, and their characteristics, such as ranging, opening angle, and location where a specific sensor is placed. The *Perceived Object Container* carries a list of detected objects, detailing their dimensions, relative position, speed, and acceleration. According to the CPM generation frequency management, the message shall be transmitted with a minimum frequency of 1 Hz and a maximum frequency of 10 Hz, depending on the trigger conditions.

B. VRU Awareness Message (VAM)

The VRU Awareness Basic Service (VBS) is specified in ETSI TS 103 300-3 [4]. It enables the transmission and reception of VAM in order to enhance VRU's safety on the roads. The VBS allows the VRUs being active in the V2X communication and to send their message to the other V2X network participants. This service might raise the safety of VRUs that could not be detected by on-board sensors. The containers included in the VAM are: *(i)* ITS PDU Header, *(ii)* Generation Delta Time, *(iii)* Basic Container, *(iv)* High Frequency Container, *(v)* Low Frequency Container, *(vi)* Cluster Information Container, *(vii)* Cluster Operation Container, and *(viii)* Motion Prediction Container. Among these containers, the *(v)*, *(vi)*, *(vii)*, and *(viii)*, are optional in the message, whereas others are mandatory and included in every VAM. In comparison with the preexisting V2X message types specified by ETSI, the cluster container in the VAM is a novel approach, which intends to optimize spectrum resources. This operation groups VRUs with a homogeneous behavior [16], in a cluster. The cluster has a leader, who will transmit the VAM. The dissemination rules for VAM determine the frequency at which a VAM shall be transmitted. The minimal frequency is 1 Hz and the maximum is 5 Hz.

III. Simulation Environment

A macro view of the simulation environment presents the traffic scenario and the V2X simulator. The traffic scenario developed for this work was only one and it was implemented for five approaches. Among the approaches, three have implemented a V2X environment, intending to analyze the behavior of the V2X messages. The first approach considers only the VRU broadcasting VAMs. The second approach considers only the vehicles sending CPMs. The third V2X approach considers the VRU sending VAMs and the vehicles sending CPMs.

The approaches have been evaluated by simulation in a realistic scenario with detailed modeling of vehicles and VRUs mobility as well as the V2X communication system. The simulation environment is composed of the traffic scenario, the wireless network, and the V2X protocols. SUMO has been used as simulation framework for microscopic traffic generator [5]. The wireless network is simulated by the discrete-event simulator *OMNeT++*[2] combined with the INET[3] framework

[2]https://omnetpp.org
[3]https://inet.omnetpp.org

for PHY and MAC layers. The V2X networking is handled by *Vanetza*[4], and the messaging protocols are simulated by *Artery* [7]. As *Artery* and *Vanetza* did not support the VAM, this work has developed and implemented the new message type with its triggering conditions and message containers according to [4].

A. Traffic Scenario

InTAS [6] has been chosen as SUMO traffic scenario. It models a realistic traffic scenario of Ingolstadt, Germany, validated with real traffic numbers and also simulates pedestrians. A Region of Interest (ROI) was selected from the *InTAS* scenario, which reproduces a roundabout. Figure 1 shows the ROI, highlighted and delimited by the red circle. The roundabout scenario has been chosen based on the iteration and risks among vehicles and VRUs on this road topology. The ROI is the InTAS largest roundabout, according to the number of vehicles driving through it during the day, and their speed, which is higher than for others, i.e., vehicles can drive up to 50 *km/h*.

The simulation starts in the afternoon traffic peak at 16:47 and runs for 100 s, comprising 22 s for the simulation warm-up. The duration of the simukation gives the ego vehicle to enter the simulation area, approach the roundabout, and leave the simulation. A total of 109 vehicles have been simulated during this period, and 166 pedestrians represent the VRUs. The ROI has a high concentration of VRU, as it is nearby a shopping center and has multiple bus lines serving this area.

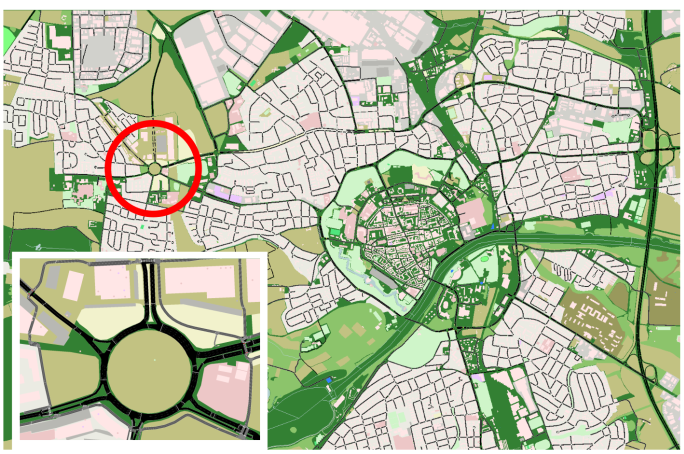

Fig. 1. Roundabout from the InTAS traffic scenario

B. V2X Simulator

Artery is an open-source simulation framework that gathers the simulation stacks, i.e. *SUMO*, *Vanetza*, and *Omnet++*, simulating a V2X interconnection among all of them. The communication is according to the ETSI ITS-G5 protocol standard. *Artery* allows users to develop new V2X services, e.g. the VRU Awareness Service, and promotes an environment to develop novel V2X applications on higher layers. Moreover, *Artery* deploys an environment model, allowing obstacles to be detected and creates shadow areas for the sensors. The detection is based on radar sensors, that can be integrated into the vehicles and Road-Side-Units (RSU), creating a detection area, according to the sensor's range and Field of View (FoV).

The radar range and FoV are simulated as most sensors placed on the shelf, and also the objects detection sense capabilities from the modern vehicles, i.e., where the sensors are installed on the vehicles. The sensor parameters as simulated as listed in Table II, where two parameters for front radar detection are implemented, i.e., long-range and short-range. The front long rager radar is limited to a 200 m range, FoV of 18°, and two segments. The front short-range radar has a range of 100 m, FoV of 80°, and four segments. Each vehicle is equipped with one of the sensors types presented in Table II.

TABLE II
ON-BOARD SENSOR SPECIFICATION

Sensor	Range [*m*]	FoV [deg.]	# Segments	# Sensors
Long Range	200	18	2	1
Short Range	100	80	4	1

The radio medium is modeled according to the Geometry-based Efficient propagation Model for Vehicle-to-Vehicle (GEMV2) [17], which better represents path loss due to obstacle interference, and limits the distance for the communication by 500 m. Table III lists all the simulation parameters implemented in this paper.

TABLE III
SIMULATION PARAMETERS

Parameter	Value
PHY and MAC	INET
Access Layer	ITS-G5
Antenna Power	200 [*mW*]
Path Loss Model	GEMV2
DCC Model	Limeric
Obstacle Interference	yes

Simulation deterministic behavior on the traffic simulation has been ensured in *SUMO*, applying only one thread for the simulation. On the communication simulator *OMNeT++*, one hundred seeds for random number generation have been used for all the developed approaches. Each approach was run one time with each seed, i.e., each approach has been run one hundred times. The seeds implemented are known, which make it possible to reproduce the results.

1) Baseline Approach: A baseline approach has been developed to provide the VRU ground truth, i.e., to identify all the VRUs surrounding the ego-vehicle at a distance of 500 m. In this scenario, none of the traffic participants are equipped with V2X devices. They will not interact among them over V2X. For each simulation step, the number of VRUs inside of the 500 m range has been counted. This is an unrealistic behavior, due to the lack of line of sight

[4]https://www.vanetza.org

among VRUs and the ego vehicle, particularly when it is behind a building. However, the baseline approach provides the comparison foundation for further analysis. The radius distance of 500 m represents the maximum distance coverage by V2X communication on GEMV2. To achieve this result, the `SeeThrough` radar model in *Artery* has been implemented.

2) Radar Approach: The ego vehicle has been equipped only with radar-sensors, as presented by Table II. All the detected objects by the ego have sensors as a source.

3) VAM Approach: The VA Service has been developed on the Facilities Layer to cover the VAM approach. All VRUs were equipped with V2X devices, where this service runs. Moreover, the ego-vehicle was equipped with V2X device able to parse and decode the received VAMs. Other vehicles in the simulation were not considering receiving or sending any V2X messages. In this approach the ego vehicle has been also equipped with radar-sensor as described in Table II.

4) CPM Approach: The third approach has implemented the CPS as defined by ETSI TR 103 562 [2]. The CPS was enabled on every vehicle running in the simulation, i.e., equipment rate is 100 %. Moreover, all the vehicles are equipped with radar-sensors according to Table II.

5) VAM & CPM Approach: The last approach has gathered the VA Service and CPS in the same scenario. In this approach, VRUs transmit VAMs and all vehicles broadcast CPMs. Similar to the previous approach, the ego-vehicle and all other vehicles are equipped with the sensor set-up. The VRUs detection is based on V2X and the radar sensors.

IV. Evaluation

This work applies the following metrics for evaluation: VRU Perception Rate (VPR), VRU Detection Time (VDT), Channel Busy Ratio (CBR), channel capacity, and V2X message size. All the metrics assesses the communication based on the approaches base-line (BL), RADAR, VAM, CPM, and a the combination VAM and CPM (VAM & CPM).

A. VRU Perception Rate (VPR)

VPR calculates the rate a VRU is detected by the ego vehicle in every simulation step. It is defined as the rate of VRUs detected by the ego vehicle in relation to the number of VRUs in the 500 *m* by the ego evhcile, according to:

$$VPR = \frac{\sum x_{d,t}}{\sum x_{r,t}} \tag{1}$$

where, $x_{d,t}$ represents all the detected VRUs by the ego vehicle at the simulation time t, and $x_{r,t}$ is the number of VRUs in the 500 *m* radius among the same simulation time t.

Figure 2 shows the VPR for each of the approaches, representing them on the traces, where x axis is the simulation time, and y axis is the VPR value. The values are comprised among simulation time 22 s and 100 s, due to the time that the ego vehicle enters in the simulation and starts receiving V2X messages. The ego vehicle is inserted in the simulation at time 20 s, but only at the time 22 s the simulation starts recording the simulation results.

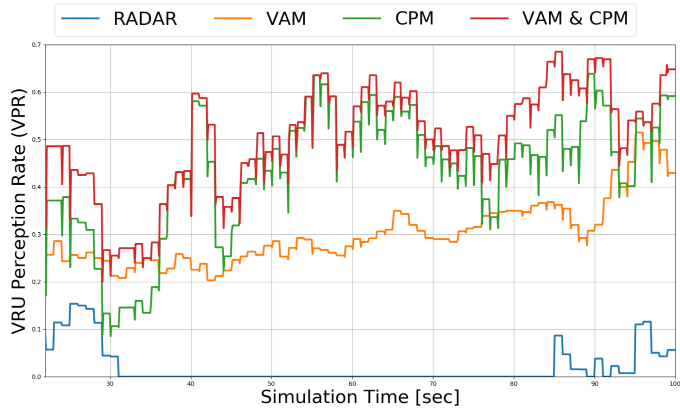

Fig. 2. VRU Perception Rate (VPR)

The RADAR approach is represented by the blue line, where the maximum value is approximately 0.15, and the minimum value is zero. The value zero means that none of the VRUs have been detected by the ego vehicle, when it was equipped only with the radar-sensor. According to Figure 2, it is possible to observe that between simulation time 31.07 s and 84.9 s, no VRUs was detected. That means that during circa 53.9 s, VRU detection was not able to give any feedback to the ego vehicle. The mean VPR for the Radar approach is 0.02 with a standard deviation (σ) of 0.04.

The VAM is shown by the orange line, where the maximum rate value was observed at simulation time 95 s, and it has a rate of approximately 0.51. The lower rate for the VAM approach was detected at the time 43 s with a rate of 0.20. Moreover, this approach has a mean VPR equal to 0.30, and σ is 0.07. Comparing VAM with RADAR, it is possible to infer that using only VAMs increase the VPR by about 0.28.

The results of the CPM approach are shown in green color, where a higher perception rate is observed during most periods of the simulation time, when comparing with the VAM approach. For the CPM approach the maximum rate is 0.64, the minimum is 0.08, the average is 0.44, and σ is 0.13.

When CPM and VAM are broadcasted by the traffic elements, the VPR rises a better result, i.e. more VRUs are detected by the Ego. This combination scenario yields a maximum value of 0.68, a minimum value of 0.20, a mean value of 0.50, and σ is 0.11.

Table IV resumes the statistically relevant values observed for the traces in Fig. 2.

TABLE IV
VPR Results

Approach	Min	Max	Mean	Std. dev.
Radar	0.00	0.15	0.02	0.04
VAM	0.20	0.51	0.30	0.07
CPM	0.08	0.64	0.44	0.13
VAM & CPM	0.20	0.68	0.50	0.11

According to these results, it is possible to infer, that VAMs alone on a V2X environment, does not provide as much safety for the VRU as CPM does. This assumption is based on the VPR analysis, where the CPM approach has a VPR average rate 0.14 higher. However, for simulation time between 28 s and 36 s, a clearly higher number of VRUs were detected by VAMs instead of CPMs. This behavior can be understood by the low number of vehicles nearby the ego vehicle at that moment. Lower number of vehicles surrounding the ego vehicle represents less CPMs received, and it implicates a lower VPR. This behavior explains that in traffic situations with low number of vehicles broadcasting CPMs, the VRU safety can be increased based on VAMs.

In an ideal environment where VAMs and CPMs are broadcast by the traffic participants, the average VPR rises 0.06, when compared with only-CPM. This approach not only brings more perception rate to the ego-vehicle, but also has a lower standard deviation, i.e. a more reliable data.

B. VRU Detection Time (VDT)

As the VRU detection time is also an important metric – it indicates the duration after which a given VRU were perceived by the vehicle – it has also been considered in the present work. The earlier the VRU is perceived and the shorter the VRU detection time is, the better the driver can take decisions and avoid an accident. The evaluation on this topic follow the same approaches presented on Section IV-A: RADAR, VAM, CPM, and VAM & CPM.

The first analysis of the VDT determines the number of VRUs detected by each approach. In the RADAR approach, the ego vehicle detected 48 VRUs during the simulation time. Running the VAM approach a total number of 124 VRUs were perceived. In the CPM approach, 144 VRUs were detected, and in the VAM & CPM, a total of 150 VRUs were perceived by the ego vehicle. In this comparison, it is observed that VAM & CPM approach provides a better VRU perception.

To deepen this result singular comparisons among the approaches was developed. As the number of perceived VRUs is not the same, the comparison was done only between VRUs that integrate both approaches. The statistic values implemented in the analysis are average values from one hundred simulation runs with different seeds.

In the RADAR approach, only 48 VRUs were perceived by the ego vehicle. The comparison between the RADAR approach and the other, only considered the 48 VRUs detected by the RADAR.

The analysis between the RADAR and the VAM approach shows that all the 48 VRUs were perceived 3.92 s beforehand in the VAM approach. Evaluating RADAR and CPM, it is observed that all the VRUs were detected before by the CPM, and 21.20 s beforehand. In the analysis among RADAR and VAM & CPM, again all the VRUs were perceived by V2X messages, with a time of 25.13 s in advance.

Considering VAM as an analysis base, the comparison among VAM and CPM considers 124 VRUs. In this evaluation, eleven VRUs were perceived beforehand by the VAM, with an average time of 9.05 s. The CPM approach has detected beforehand 113 VRUs, and 17.19 s before. Extending the VAM analysis, the comparison with VAM & CPM was deployed. This analysis brought that six VRUs were detected beforehand in the VAM, and 24 ms before. On the other hand, 118 VRUs were perceived by VAM & CPM beforehand, with a mean time of 17.51 s before.

At the end, CPM and VAM & CPM are compared. In the CPM approach no VRU was perceived beforehand VAM & CPM. However, 129 VRUs had the same detection time, and 15 VRUs were perceived 3.75 s before on VAM & CPM.

C. Channel Busy Ratio (CBR)

The CBR represents, from a given radio, the rate in a fraction of time that the radio channel is busy [18], according to:

$$CBR = \frac{t_{oc}}{\Delta t_s} \tag{2}$$

where, t_{ocb} represents the time that the channel is occupied by an ongoing transmission, and Δt_s is the period of time under evaluation. Intending to evaluate the CBR, and the communication costs by exchanging VAMs, this section analyses the maximum CBR faced by each communication node. Figure 3 shows the results for all approaches presented in previous sections. The nodes in the VAM approach encountered a maximum CBR of 0.04, a minimum rate of 0.01 and an average rate of 0.03. When only vehicles exchange CPMs, the maximum CBR is 0.15, and the minimum rate is 0.01, with an average rate of 0.09. In the last V2X scenario, where VAMs and CPMs are exchanged, we observed that the maximum CBR is 0.18, the minimum is 0.01, and the average rises to 0.11.

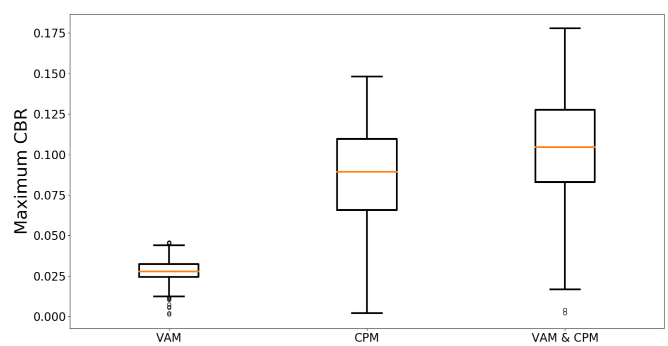

Fig. 3. Maximum CBR for V2X Approaches

The values presented in Figure 3 depict, for this specific traffic scenario, that the CBR does not play a crucial role in VRU safety in any of the V2X approaches. This assumption is based on the CBR value, which is under 30%, that means a "Relaxed State" classification in the Decentralized Congestion Control (DCC) [18], has no restrictions for the packet rate.

D. Channel Capacity

The V2X simulation presented by this paper was deployed with the channel type G5CC, which corresponds to 180 in the IEEE channel numbering scheme. This channel has a center frequency of 5,9 *GHz*, and a maximal data rate of 6 *Mbit/s* [19]. The maximal data rate represents the channel capacity, and intending to evaluate the impact of the message sizes on the channel capacity, an evaluation method was implemented. This analysis presents the summed-up size of all messages transmitted in a time window of 1 *second*, referred to as timestamp. To collect the values, for all seeds the average for was computed for each timestamp. The evaluation was developed for all of the V2X approaches, i.e., VAM, CPM, and VAM&CPM. Figure 4 depicts the average accumulated number of bits injected into the communication channel, by the nodes, in each approach. The blue line represents the VAM&CPM approach, where the maximal accumulated message size is 864.12 *kbit*, and occurred at timestamp 92 *seconds*. The traces in orange color represents the average values for the CPM approach, where the maximum accumulated message size is also observed at timestamp 92 *seconds*, with a value of 845.49 *kbit*. The green line corresponds to the average message sizes for the VAM approach, showing a maximal value of 57.69 *kbit* at the timestamp 95 *seconds*. From Figure 4, it is also possible to infer, that at any timestamp, the maximal accumulated message size has extrapolated channel capacity, i.e., it is below 6 *Mbit/s* for the entire simulation time.

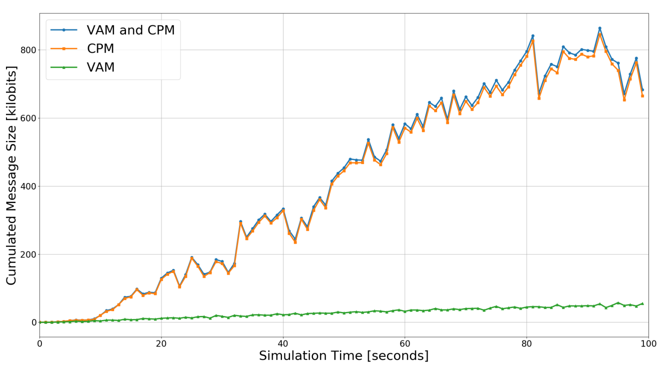

Fig. 4. Accumulated Message Size per Simulation Timestamp

E. Message Size

The ETSI standards define a segmentation threshold on V2X messages with a size over 1,100 bytes (excluding lower layer protocol headers) [2], i.e., it is the maximum message size expected to be transmitted by a station. Therefore, this evaluation metric seeks to appraise the message size and to compare the measured values with the segmentation threshold. Figure 5 presents the resulting analysis for each V2X approach. The results are based on the absolute size of all messages transmitted on the communication channel in each approach. The VAM approach shows that the message has a small size when compared with the segmentation threshold, or even the other approaches. The largest message broadcasted in this scenario has 116 bytes. On the other hand, the smallest message has 74 bytes. Moreover, this approach presented an average message size of 89.13 bytes. Examining the CPM approach the greatest message presented a size of 668 bytes, the smaller has also 74 bytes, and an average message size of 215.43 bytes. The last V2X approach, VAM&CPM, showed similar values to the previous ones. The greatest message in this approach has 668 bytes, the smaller has 74 bytes, and the average message size is 214.03 bytes. According to this analysis, it is possible to infer, that in any approach, the message size below the segmentation threshold, i.e. always remains 1,100 bytes.

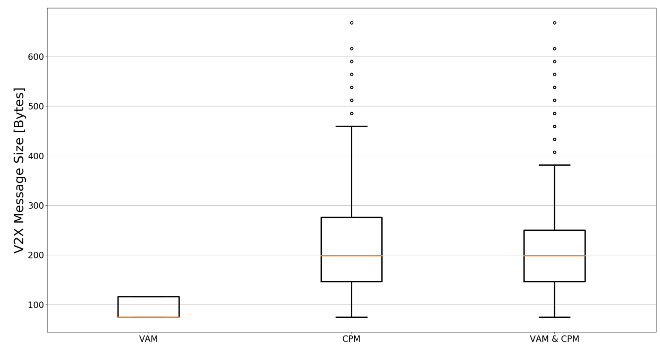

Fig. 5. V2X Message Size for V2X approaches

This analysis can be extended to evaluate the additional band needed on top of the upper bound, for each of the V2X approaches, intending to handle the communication. The additional upper bound was computed according to:

$$UB_t = (f_{m_v} \times N_{v_t} + f_{m_c} \times N_{c_t}) \times 1100 \qquad (3)$$

where, UB_t represents the upper bound value in bytes for the time t, f_{m_v} is the maximal frequency a VAM can be transmitted by a node, N_v is the number of VRUs running on the simulation on time t, f_{m_c} represents the maximal frequency a vehicle can broadcast a CPM, N_{c_t} is the number of vehicles driving on the simulation during the time t, and $1,100$ is the maximal size for a V2X message in bytes.

Figure 6 shows the needed additional band per second, in each V2X approach. The maximal needed value for the VAM approach is 0.79 Mbytes, for the CPM it is 0.65 Mbytes, and for the combined scenario it is 1.43 Mbytes. These values represent more than the channel capacity, which was discussed in Section IV-D. However, this behavior would be observed neither in the V2X simulation nor in the real world. Mechanisms implemented on the V2X would avoid a channel overload above the ETSI standards limits. The DCC, which was mentioned in Section IV-D is a mechanism example, limiting the channel load [18]. Thus, this behavior is unrealistic in the V2X communication environment.

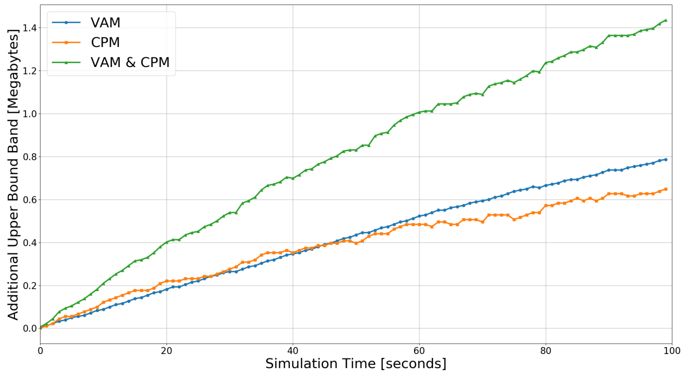

Fig. 6. V2X Message Size for V2X Approaches

V. Conclusion

This paper studied the impact of V2X messaging protocols on the safety of vulerable road users and simulated a roundabout traffic scenario in Ingolstadt. For this purpose, the VRU awareness service as proposed in the standardization process for V2X communications was implemented in the *Artery* simulation framework. The traffic scenario was evaluated for two message types that are currently being standardized: the VRU awareness and the Collective perception message, VAM and CPM. Also, the combined approach of VAM & CPM was considered. The performance of these three V2X approaches was compared with the two baseline approaches.The evaluation metrics were VRU Perception Rate, VRU Detection Time, and Channel Busy Ratio. In terms of perception rate, the combined approach of VAM & CPM provided the best results, where on average 6% more VRUs were detected compared to the second best approach CPM. This approach has also shown the shortest detection time, i.e., compared with the other approaches more VRUs have been detected earlier. For the CBR we observed that running two services simultaneously, the VRU awareness and the collective perception service, increases the maximum CBR by 18%. Still, the maximum CBR is kept under 30%, which corresponds to the relaxed state of decentralized congestion control (DCC) and does not result to restrictions in the message rate.

The simulation results indicate that the combination of VRU awareness and collective perception service maximizes the VRU safety in the roundabout traffic scenario. It not only provides a better perception of the environment to the ego-vehicle, but it also does not overload the wireless communication channel. Thus, to enhance the VRU safety it is beneficial that VRUs transmit VAMs while vehicles broadcast CPMs. However, the presented study chose a roundabout as a representative traffic scenario. Extending the scenario to a larger area or even a city will lead to more significant results. Furthermore, studying different rates of vehicles equipped with V2X devices will bring more realism.

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