A Critical Assessment of C-V2X Resource Allocation Scheme for Platooning Applications

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***Abstract*—V2X stands for vehicular to everything communications, but its definition is so vast that it does not even encompass a specific transmission technology. Up to a few years ago the only standardized technology for V2X was 802.11p and the protocol suites built on top of it like DSRC and ITS-G5. In recent years, however, Cellular-V2X defined both for LTE and for the upcoming 5G New Radio interfaces is drawing a lot of attention and seems to have a broad support. C-V2X standardization however, has been slow, but most of all lacks the elegant simplicity of 802.11p, so that performance analysis of automotive applications on top of C-V2X are still limited. This work presents initial results for platooning applications, highlighting the presence of severe impairments in the resource allocation schemes of C-V2X Out of Coverage modes that, if not corrected in future releases of the standards may hamper the development of this promising technology.**

I. Introduction

The advent of 5th Generation (5G) New Radio (NR) standards is expected to open another chapter for the evolution of vehicular networks, especially for cooperative driving applications, hopefully leaving behind the long discussion (fight?) Direct Short Range Communications (DSRC) vs. Cellular V2X (C-V2X) with a modern communication system allowing at the same time, direct inter-vehicular communications and tethering to the infrastructure. The 5th Generation Cellular V2X (5G-V2X) is not intended to entirely replace the services offered by the 4th Generation (4G) C-V2X, or LTE-V2X, but it is expected to have many enhancements with respect to it, both at the physical level and in protocols and scheduling algorithms. 5G-V2X will support unicast and groupcast sidelink communications, fundamental for cooperative driving as described in the support and requirements document [1]. This addition is linked with the introduction of sidelink Hybrid Automatic Repeat reQuest (HARQ) feedback. Furthermore it will support higher order modulation, sidelink Channel State Information (CSI), bigger subcarriers, different modulation schemes, and many other features [2]. As in LTE-V2X two different modes are defined for in-coverage and out-of-coverage scenarios; in 5G-V2X they are named Mode 1 and Mode 2, instead of Mode 3 and Mode 4, respectively.

Even if the standardization process still lacks details, these novel technologies should be properly evaluated within the environment that defines their natural "vertical:" vehicular networks. We are specifically interested in the applications that will characterize autonomous and smart mobility solutions, where cooperation among all actors (from vehicles to infrastructure element, and most notably VRUs[1]) is fundamental to achieve the goals and transportation efficiency of these applications. Cooperative driving, with all its flavors and declination, is definitely one of the potentially more promising applications and one where communication patterns and needs are understood in more detail, while interaction and communications with, and between, VRUs, albeit fundamental in urban scenario, is still less investigated.

Acronym	Meaning and explanation
eNB / gNB	4G/5G) Base Station
PC5	Radio interface for D2D communications both OoC and IC
PSSCH	Physical Sidelink Control Channel: D2D signaling channel
PSSCH	Physical Sidelink Shared Channel: D2D data channel
RB	Resource Block: The minimum amount of addressable resources (see Fig. 2)
RE	Resource Element: A single modulated sub-carrier in a symbol
RSRP	Reference Signals Received Power: A measurement of the received power level
RRI	Resource Reservation Interval: the constant interval between successive transmission schedules after resources are selected
RSI	Resource Selection Interval: a random interval between 0.5 and 1.5 s that defines how long resources are kept before re-selection
SBSPS	Sensing-Based Semi-Persistent Scheduling
SC-FDMA	Single Carrier-Frequency Division Multiple Access
Sidelink	Any channel for D2D communications, i.e., between User Equipments (UEs)
S-RSSI	Side Link Received Signal Strength Indicator; threshold to consider a resource occupied
TB	Transport Block: a block of user's data at the physical layer, it can be an entire packet or a part of it
VRU	Vulnerable Road Users: Pedestrians, Cyclists and so on
Uu	Radio interface between UEs and eNB / gNB

Table I: Acronyms and 3GPP specific terminology

This work is based the the MSc Thesis of Piermaria Arvani discussed in March 2020 at the University of Trento, Italy

[1]VRUs are all road users that are more vulnerable than vehicle passengers, from pedestrian to bikers and e-scooters [3]

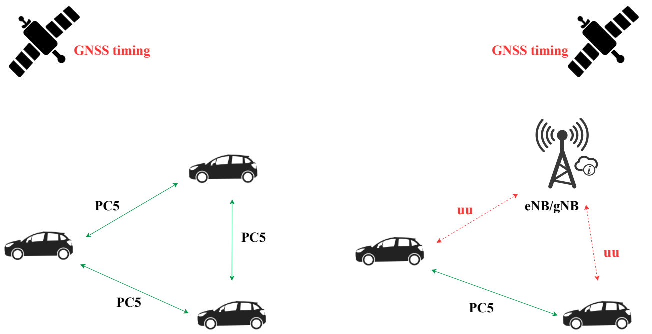


Figure 1: Out of Coverage (OoC) (left) vs. In Coverage (IC) (right) V2X communications, in OoC modes the sidelink interfaces PC5 are used also to communicate with RSUs.

The contribution of this paper lies in a thorough analysis of the scheduling framework that is shared between LTE-V2X Mode 4 and 5G-V2X Mode 2, its implementation within PLEXE [4], and the assessment of the impact of some architectural choices on platooning, in light of the loss-burst patterns induced by these choices. Changes to make 5G-V2X Mode 2 really suitable for cooperative driving are possible, but they should be standardized as soon as possible and carefully crafted in light of the application needs and mode of operation. Even advanced predictive HARQ techniques like [5] may prove useless in broadcast communications, and the impossibility to receive during transmission actually reduces the amount of resources that can be effectively used in some applications.

II. C-V2X Out of Coverage Mode Essentials

Regardless of the access interface, Long Term Evolution (LTE) or 5G, mobile V2X share a few key architectural features that characterize the system. As already mentioned we are particularly interested in Mode 4 (LTE-V2X) and Mode 2 (5G-V2X), i.e., Out of Coverage (OoC) mode, which is the only one that can guarantee inter-vehicle communications in any scenario and location, and it is also the one that can more easily be adapted to work when mobile devices have a different network operator. The connections are called sidelinks, and have an organization similar to the normal uplinks in the IC modes. Fig. 1 sketches the difference in V2X communications between the OoC and IC modes. The direct interface for direct UE-to-UE communications is called PC5, a UE is any device not part of the network infrastructure.

The resources on PC5 are organized following the SC-FDMA scheme and are subdivided in frames of 10 ms. Each frame breaks down in subframes of 1 ms, which are further divided in 2 slots of N_{sym} SC-FDMA symbols. In the frequency domain resources are split into subcarriers with 15 kHz spacing. A single subcarrier in a symbol is called a RE, while the minimum amount of resources that can be addressed is RB and consists of 1 slot over N_{sc} subcarriers, i.e., $N_{\text{sym}} \times N_{\text{sc}}$ REs; the allocation of resources to a station is a multiple integer of RBs, and in general it is not possible to allocate a single RB, as any allocation requires at least 3 RBs for signaling purposes. Finally,

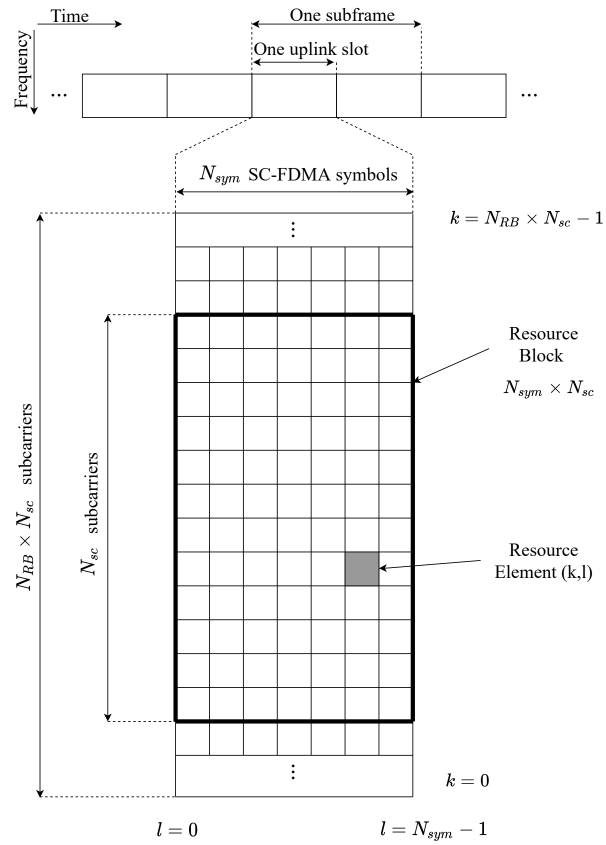


Figure 2: Sidelink resource organization, the terminology is simplifies w.r.t. the standard for the sake of clarity.

Paper symbol	3GPP symbol	Meaning and current value in the standard
N_{sym}	N^{SL}_{symbol}	Number SC-FDMA symbols in a slot, currently 7 or 6 when using an extended cyclic prefix
N_{sc}	N^{RB}_{sc}	Number of subcarriers per RB, currently 12
N_{RB}	N^{SL}_{RB}	Number of RBs in the RG
P_{RK}	$prob$ $Resource$ $Keep$	Probability of Resource Keeping, i.e., the probability of not changing the resource selection at the end of an RSI

Table II: Mapping between the terminology of this paper and the terminology used in the 3GPP standards.

resources are organized into a Resource Grid (RG) of N_{RB} RBs. These numbers may change as 5G NR evolves, however the overall organization is not supposed to change significantly. Fig. 2 describes this organization with the terminology reported in Tab. II, simplified compared to the 3GPP standards for the sake of clarity.

The scheduling of resources in PC5 is based on SBSPS, and it is based on the subdivision of the resources between a signaling channel (Physical Sidelink Control Channel (PSCCH)) and a user channel (PSSCH). Without entering in too many details, resources on PSCCH and PSSCH are always paired, even if the actual multiplexing of the two can follow many different schemes; moreover the allocation on the PSCCH is always exactly 3 RBs for every TB (i.e., a "user packet") allocated on the PSSCH, so that, for the sake of clarity, we can assume that every allocation of resources on PC5 consists of $A_{\text{C}} = A_{\text{TB}} + 3$ RBs, where A_{TB} is the number of RBs required by the TB to be transmitted.

Fig. 3 sketches the fundamental operation of SBSPS. PC5 is a single radio, half duplex channel interface, and in this respect it is very similar to 802.11, but the physical organization of the channel is very different as discussed above, and this reflects on the resources access and contention schemes. Since OoC PC5 is exactly the same as IC PC5 the problem of resources allocation and reservation is of the utmost importance: in IC the allocation is centralized and can be based on algorithms working on the complete knowledge of transmission requests, in OoC a distributed allocation algorithms must be implemented. The physical layer implementation does not lend itself to a simple Carrier-Sense Multiple Access (CSMA) solution, because there is no provision to run a contention; however in the absence of a centralized solution carrier sensing remains essential. In SBSPS sensing is based on a sliding Sensing Window extending for $1\,\text{s}$ before the current subframe, called n in the figure. When a UE needs transmission resources, selects them based on those sensed free in the Sensing Window that allows the allocation based on these two criteria:

- They fall in the Selection Window $[n + T_1, n + T_2]$;
- They are free also in all repetitions at constant intervals called RRI within the RSI.

T_1 and T_2 are two guard intervals that define how fast (T_1) and aggressive (T_2) the device performing the access can be. In cooperative driving applications, we can assume $T_1 = 0$, which means an efficient device, and $T_2 = 100\,\text{ms}$ even if this second setting means that most probably sending periodic information can have a fairly large access delay. RRI defines the resource repetition interval in ms, it can be 20, 50, 100 or larger. The value of RRI also defines how many scheduling repetitions the resources are maintained, and this is a uniform random number that in practice correspond to RSI comprised between $0.5\,\text{s}$ to $1.5\,\text{s}$ independent of RRI because the random number support changes with RRI itself. When RSI expires, the UE maintains the same resources with a probability $0 \leq P_{\text{RK}} \leq 0.8$ (P_{RK} is a tuning parameter) extracting a new RSI, and re-selects them with the procedure described above otherwise.

How a resource is defined free is rather complex and depends on the load on the channel. Fig. 4 defines the logical flow of free resources selection used in SBSPS. Let's call RS_{th} a signal strength threshold. This threshold is initialized at S-RSSI; the standard does not specify a value for this threshold, but 3GPP documents indicate a value of $-107\,\text{dBm}$/RB. The algorithm makes use of two sets $\mathcal{S}_A$ and $\mathcal{S}_B$ to select "free" resources. Initially, $\mathcal{S}_A$ contains all the resources that are defined free because the sensed signal energy is below RS_{th} and $\mathcal{S}_B$ is empty. If the resources in $\mathcal{S}_A$ are less than 20% of all the resources available in the Selection Window then RS_{th} is raised by $3\,\text{dBm}$ and the procedure is repeated until $\mathcal{S}_A$ is above 20%. Then the 20% of resources (w.r.t. the Selection Window) in $\mathcal{S}_A$ with the lowest average S-RSSI are moved to $\mathcal{S}_B$, and $\mathcal{S}_B$ is reported to the MAC layer that randomly selects the resources to be used in $\mathcal{S}_B$.

Clearly, this resource selection procedure is "blind," and if two UEs select overlapping resources there will be a burst of collisions. Worse than this, a UE is not able to receive any information during its transmissions, so that all the transmission by other UEs during the time slots where resources are selected will not be received by the UE, resulting in lost information.

III. Related Work

The recent decision[2] of the Federal Communications Commission (FCC) to deallocate the $5.9\,\text{GHz}$ band reserved for DSRC in favor of Wi-Fi ($45\,\text{MHz}$) and C-V2X ($30\,\text{MHz}$), raises the expectations of C-V2X for automotive safety even further. However, it is still unclear whether C-V2X will be capable of supporting highly demanding cooperative driving applications, especially when considering the OoC mode. There are several works highlighting severe weaknesses of the OoC mode, not much with respect to Packet Delivery Ratio (PDR) but rather on severe error bursts, causing large update delays (a.k.a. packet inter-reception times, depending on the paper).

In general, the works analyzing the performance of C-V2X in OoC mode do so considering only network metrics. Some works focus on PDR alone, and show that at small inter-vehicle distances (up to $200\,\text{m}$), the PDR is above $90\,\%$. In [6], this is shown analytically, while in [7] this is shown by means of simulations. In particular, [7] analyzes the performance of C-V2X when considering different types of automotive safety messages, i.e., Cooperative Awareness Messages (CAMs) (periodic) and Decentralized Environmental Messages (DENMs) (event-driven).

The PDR alone, however, does not tell the whole story. Indeed, even if the PDR is very high, errors might be distributed in bursts which, for cooperative driving, can be devastating. As an example, the work in [8] shows that in a highway scenario, while the PDR is above $90\,\%$, C-V2X OoC can lead to update delays in the order of several seconds. This result is confirmed by other works [9]–[12]. The work in [11] shows that the update delay heavily depends on the value of the probability of resource keeping P_{RK} (the higher the probability, the higher the maximum update delay), but update delays around $1.2\,\text{s}$ can occur regardless of the choice of such probability.

In [13], the authors name this problem in C-V2X OoC as "wireless blind spot", which clearly indicates the fact that vehicles can become totally unaware of the presence of each other due to long "silence" periods. The wireless blind spot problem is caused by the fact that the communication is broadcast-like (thus with no feedback), so that the chosen resource might be kept for long time periods even when it leads to information loss. To overcome this problem, the work in [14] propose the use of full-duplex radios. The solution dramatically improves the performance but, as full-duplex radio

[2]https://docs.fcc.gov/public/attachments/DOC-368228A1.pdf, visited Dec. 14, 2020.

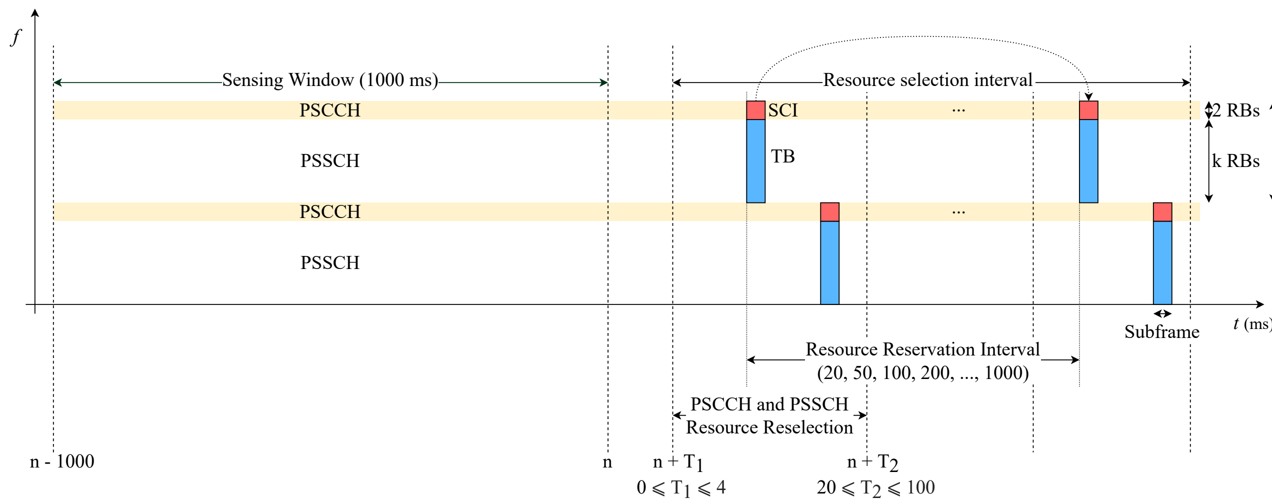


Figure 3: UEs autonomous sensing and resource selection.

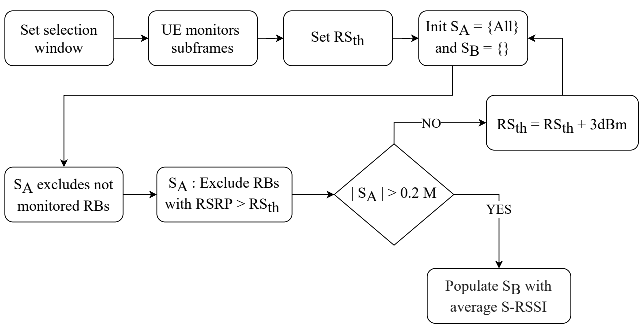


Figure 4: UEs resource selection procedure. At least 20% of the resources monitored are passed to the MAC for scheduling. M is the total amount of available resources; not monitored RBs include, for instance, those that fall in the transmission intervals of the station, which cannot listen to the channel while transmitting.

technology is still in its infancy [15], it might take a lot of time before becoming commercially available.

Other works exist on the topic like [16] that propose enhanced and improved scheduling for C-V2X Mode 3 (under coverage), or [17] that compare 802.11p and LTE-V2X Mode 3 and Mode 4. This latter work recognizes the problem of persistent and resource re-selection collisions, but leaves it open for future research without delving deep in their consequences.

While the body of literature clearly highlights the problem in term of network metrics (large update delays), no work measures the impact on an actual cooperative driving application. The probability distribution of update delays might be misleading, hinting that such issues might never manifest. As we show in the remainder of the paper, this issue can occur even with a very small number of vehicles, and the impact on a cooperative driving application can be substantial.

IV. Implementation in Plexe/Veins

In this section we briefly describe the simulation framework we used for the performance evaluation, which is fundamental for understanding and reproducing our results. The structure of the simulation framework is highlighted in Fig. 5. We make use of different simulation software in a federated configuration. The framework is composed by two main components: mobility and networking.

Mobility is managed by the Simulation of Urban MObility (SUMO) simulator [18] (v1.5.0). SUMO embeds the cooperative driving control algorithms and vehicle dynamics developed within Plexe [4], enabling the realistic analysis of the impact of network on vehicles' behavior. In particular, it includes several Cooperative Adaptive Cruise Control (CACC) algorithms for platooning control. These algorithms exploit wireless communication and sensor measurements to drive vehicles in a platoon configuration, maintaining small inter-vehicle distances without sacrificing safety. In this work we consider two of these CACCs, namely the PATH [19] and the Ploeg [20] controllers.

Given the focus of the paper, we do not detail the control formulas, but we simply describe the main difference between the two, which resides in the inter-vehicle spacing policy. The PATH controller exploits information received from the leading and the preceding vehicles and uses a constant-gap spacing policy, meaning that the inter-vehicle distance is fixed regardless of the cruising speed. The Ploeg controller, instead, exploits preceding vehicle information only, and employs a time headway spacing policy. With this policy, the inter-vehicle gap depends on the cruising speed and the actual distance is computed as $h \cdot v$, where h is the headway time in seconds and v the cruising speed in meters per second.

With respect to communications, we exploit the Veins vehicular networking simulation framework [21] (v5.0) coupled with SimuLTE [22] (v1.0.1) and OpenCV2X [23] (v1.3.0). Veins couples SUMO with the network simulator, so that nodes in the network move according to the vehicle they are associated with; OpenCV2X extends the SimuLTE framework to enable C-V2X communication using OoC mode.

Finally, Plexe [4] (v3.0a2) provides cooperative driving features, including communication protocols specific to platoon-

	Parameter	Value
mobility	Leader's average speed	$100\,\mathrm{km/h}$
	Oscillation frequency	$0.2\,\mathrm{Hz}$
	Oscillation amplitude	$\simeq 95$ to $105\,\mathrm{km/h}$
	Platoon size	8 cars
	Simulation sampling rate	$100\,\mathrm{Hz}$
	PATH CACC target distance	$5\,\mathrm{m}$
	Ploeg CACC time headway	$0.5\,\mathrm{s}$ ($15.89\,\mathrm{m}$ at $100\,\mathrm{km/h}$)
C-V2X	Number of subchannels N_{sc}	3
	Subchannel size	16 RBs
	UE Tx power	$23\,\mathrm{dBm}$
	Prob. resource keep P_{RK}	0, 0.1, 0.2, …, 0.8
	Max. allowed latency	$25\,\mathrm{ms}$, $50\,\mathrm{ms}$, and $100\,\mathrm{ms}$

Table III: Network and road traffic simulation parameters.

ing, as well as means to obtain/pass data from/to the control algorithms inside SUMO.

A. Scenario under Investigation

We consider a single-platoon highway scenario where a platoon of 8 vehicles travel with an average speed of $100\,\mathrm{km/h}$. The leader of the platoon changes its speed profile in a sinusoidal fashion, oscillating between roughly $95\,\mathrm{km/h}$ to $105\,\mathrm{km/h}$ once every $5\,\mathrm{s}$ (oscillation frequency of $0.2\,\mathrm{Hz}$). The aim is to show the huge impact the design of the OoC mode has on the application. We test the performance for the two aforementioned CACCs. We set a fixed inter-vehicle gap of $5\,\mathrm{m}$ for the PATH controller and a $0.5\,\mathrm{s}$ time headway for Ploeg (corresponding to $15.89\,\mathrm{m}$ driving at $100\,\mathrm{km/h}$, including an additional stand-still gap of $2\,\mathrm{m}$).

With respect to the network, we test three different configurations. The first one considers perfect network conditions, i.e., no packets are being lost. The second one simulates non-bursty, independent Bernoullian losses to simulate a $90\,\%$ packet delivery ratio. The third one uses C-V2X OoC mode. The goal is to show the performance of CACC algorithms in perfect conditions and the robustness of such algorithms to uncorrelated losses, highlighting how the semi-persistent scheduling mechanism of C-V2X OoC can harm the safety of such applications. Tab. III summarizes the simulation parameters, including radio configurations for the C-V2X model. We set missing configuration parameters according to the default values of SimuLTE and OpenCV2X.

V. Scheduling Issues and Initial Results

As discussed in Sect. III, several works already hinted to possible flaws in the scheduling mechanisms of OoC C-V2X; however, the impact of such flaws of applications has not been investigated yet, thus we start right from this point, exploring the performance of PATH and Ploeg longitudinal controllers. Next, we analyze the network behavior in detail to single out the reason of the performance.

Fig. 6 sets the benchmark for comparison, showing the performance, in terms of deviation of the target inter-vehicle distance, of the two platooning algorithms in case of no losses (top plot) and of an average 10% Bernoullian loss rate (bottom plot). We consider a single platoon of 8 vehicles, labeled $0, \ldots, 7$ and the plots show the distance from the vehicle in front for vehicles 1–7. The platoon leader continuously changes the speed following a sinusoid to test the controller performance. The most relevant simulation parameters are listed in Tab. III, and the simulation code and configuration files will be available through the Plexe web site[3] for validation and further research. As the 8-cars platoon is in isolation there are no further sources

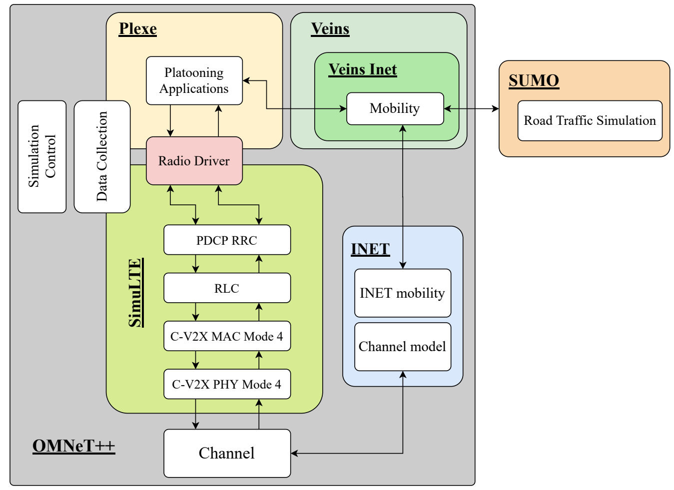
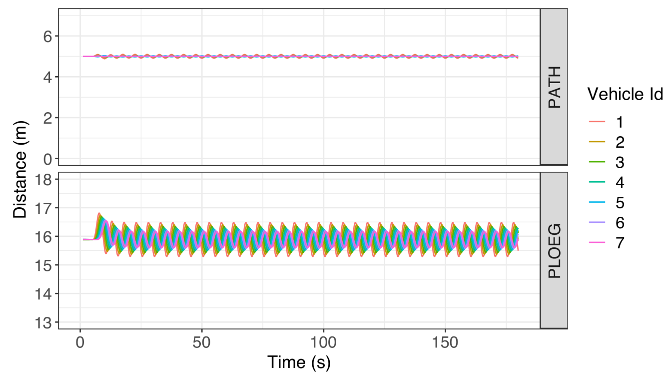
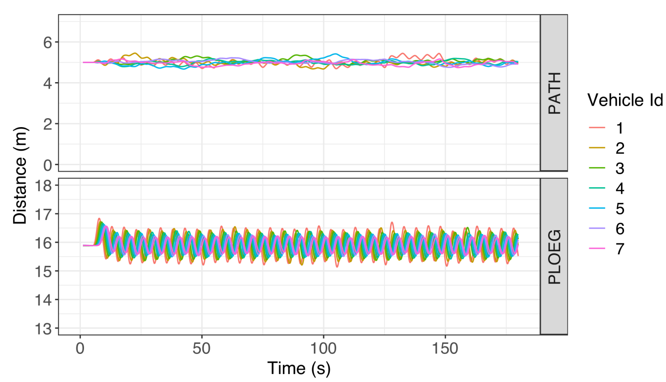


Figure 5: Architecture of the C-V2X simulation framework integrated with Veins and Plexe.



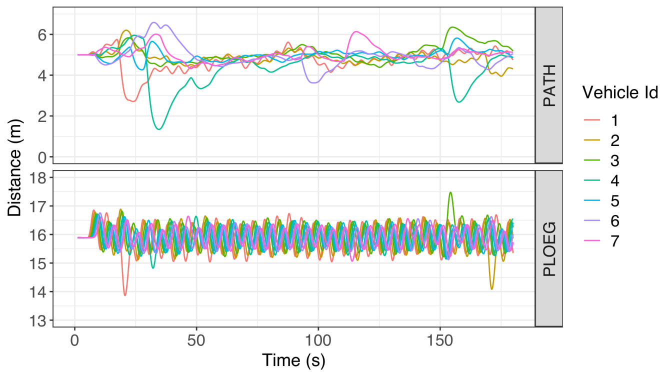
(a) $100\,\%$ PDR



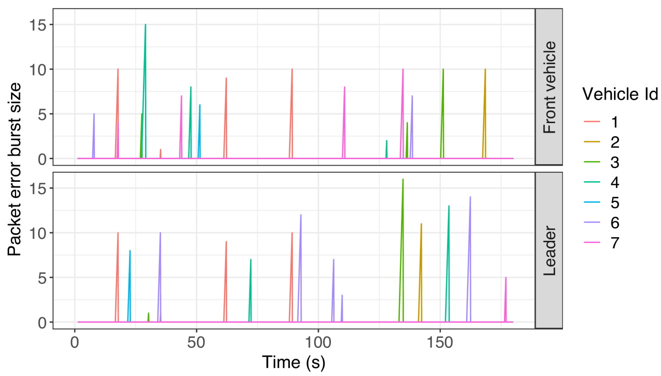
(b) $90\,\%$ PDR

Figure 6: Performance of the PATH and Ploeg CACCs subject to perfect network conditions and to a non-bursty $90\,\%$ PDR.

[3] See http://plexe.car2x.org/



(a) Distance between a vehicle and the one in front



(b) Packet error burst sizes of leader and front vehicle beacons for each vehicle.

Figure 7: Comparison of a simulation in which a crash occurred using PATH controller and the same using Ploeg's CACC. Parameters: $P_{\text{RK}} = 0.5$, Number of Subchannels = 3, Subchannel size = 16 RBs, Max latency = $100\,\text{ms}$.

of interference, and the distance between the vehicles is such that losses due to random channel errors are negligible. The PATH controller tries to achieve a fixed $5\,\text{m}$ distance between vehicles, while the Ploeg one ties to achieve a fixed headtime of $0.5\,\text{s}$, which translates into an average of slightly less than $16\,\text{m}$ at the selected speed. It is clear that both controllers work as intended both in the ideal, no losses, case and when the loss rate is 10%. In these latter case the distances are slightly disturbed, but remains within a clear "comfort zone" of a few centimeters variation that is most probably not even detected by passengers.

Consider now the top plot of Fig. 7, that reports a simulation where communications are through LTE-V2X with typical parameters. The average PDR is above 99% so one should expect a fairly good performance given that a random loss with 90% PDR still yields a tight control of vehicles; instead it is clear that both controllers suffer significantly, and the inter-vehicle distance when PATH is used drops below 2 meters in one case, which is scary for passengers to say the least. Indeed, in some simulations with different parameters we even observed collisions within the platoon, indicating that, without countermeasures, the system is still not ready to support a cooperative driving vertical. The reason of this surprisingly poor performance is reported in the lower plot of Fig. 7 that

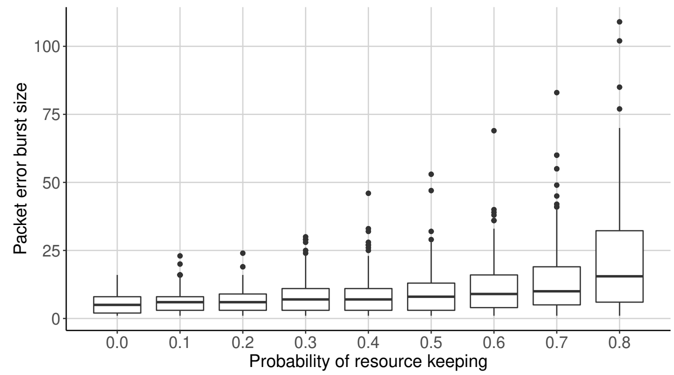
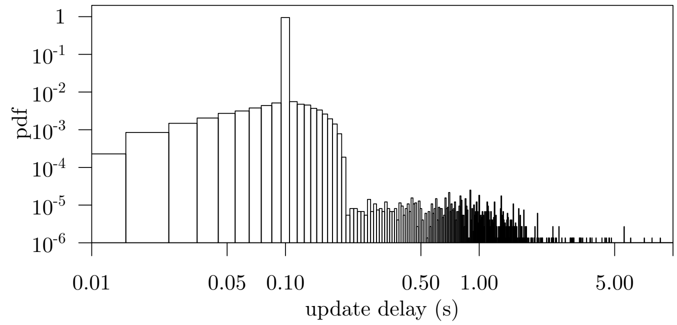


Figure 8: Packet error burst sizes comparison varying P_{RK}. Boxplots report the average and the 25th and 75th percentiles, the whiskers are at 1.5 the interquartile range (or the minimum/maximum in the dataset), while isolated dots are all the samples that falls outside these bounds.

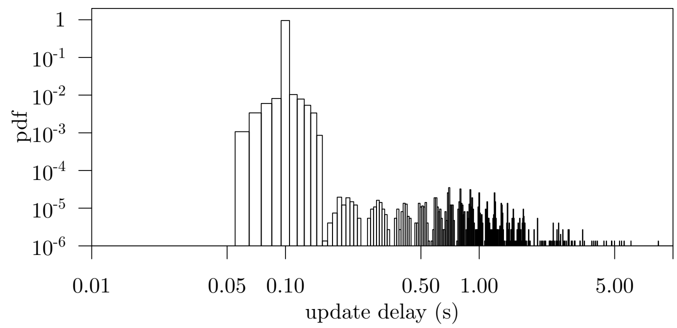
highlights that packet losses are not uniformly distributed, but happen in long bursts that can reach and exceed 15 packets in a row. This plot reports, for each vehicle in the platoon excluding the leader, the size of bursts of missing packets from the vehicle in front (upper row) and the leader of the platoon (lower row). Missing packets from other vehicles should have a minor impact on the controllers, because only the information from these vehicles is used by the CACCs selected. The correlation between large bursts and controllers instabilities is evident.

Since there are no additional interference sources, it is clear that the reason of the burst losses must lie in the scheduling process, as already observed in several of the works we discussed in Sect. III. Indeed, it is not difficult to observe that the scheduling scheme is purely feed-forward and UEs do not have any feedback on the quality of their selection. In particular, a UE is completely deaf while transmitting, thus not only there are losses when there is a collision in resource selection, but all the packets that are scheduled during the same slots are mutually lost for all UEs that are transmitting in that slot, even if on different frequency resources, showing that SBSPS as it is now specified in the standard does not map well with the transmission of broadcast messages. Indeed, this behavior may have an even larger impact on CACCs based on different control principles like consensus [24], on worst case analysis [25], as well as on maneuvers [26], [27].

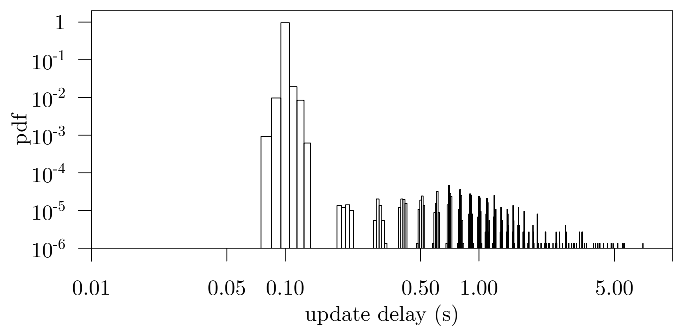
Let's now analyze the performance at the network level in more detail. Fig. 8 reports a comparison of the packet error burst size as a function of the probability of maintaining the same scheduling resources, P_{RK} with the standard value of the maximum latency, i.e., $100\,\text{ms}$. We let P_{RK} go from 0, meaning that resources are deterministically reallocated whenever RSI expires, to 0.8. Obviously the burst size increases with P_{RK}, but even with deterministic reallocation burst sizes are fairly large, in practice corresponding to the number of scheduled resources within an RSI. Fig. 7 is obtained for $P_{\text{RK}} = 0.5$, and we can imagine that for $P_{\text{RK}} = 0$ the performance can be slightly, maybe even significantly better; however, the experiment is with a single platoon of 8 cars, thus the channel is lightly



(a) 100 ms



(b) 50 ms



(c) 25 ms

Figure 9: Distribution of delays between two consecutive received messages in case of C-V2X OoC for different values of the maximum allowed latency. Both axes are logaritmic. Number of subchannels = 3, subchannel size = 16 RBs.

loaded: experimenting with a realistic scenario where tens of platoons and hundreds of vehicles interact is not worth as performance would be disastrous.

SBSPS is a conceptually simple protocol, but it has many parameters, besides the amount of resources available for the side channel. Fig. 8 gives already a clear indication that packet bursts for broadcast traffic cannot be eliminated without major modifications to the protocol, but before drawing conclusions it is worth analyzing at least the impact of the maximum latency allowed by the protocol. Indeed, this value is fixed to 100 ms in the standard, but given the fact that CAMs and similar messages have a 10 Hz repetition frequency, it is interesting to explore if reducing this value changes the distribution of the inter-message delay, which is strictly related to the Age of Information (AoI) [28], [29], which is ultimately the key metric of interest in distributed control.

Fig. 9 reports the inter message delay distribution reducing the maximum latency from 100 ms to 50 and finally 25. In all cases that distribution is dominated by the message inter-generation time of 100 ms that is measured every time messages are correctly scheduled. Notice that this is not the AoI, as this latter should account also for the delay between the message generation and its transmission due to the schedule. Besides this obvious peak the distribution changes significantly reducing the maximum allowed latency. If the maximum allowed latency is reduced to 25 ms the distribution is dominated by the packet losses, with repetitive peaks spaced by 100 ms and some variability around them due to re-scheduling. These peaks tend to merge for a maximum latency of 50 ms, while they are completely overlapping for the standard value of 100 ms. Without entering in too many details, we highlight that platooning, and in general cooperative driving, is based on advanced control techniques that rely on the reliable and regular delivery of information that is fed to the controllers and actuators. All these techniques suffer not only from increased average AoI, but also from its variability, which normally translates either in additional delay introduced to smooth the process, or from less precise control and "rougher" system behavior, in platooning this is often a higher jerk, i.e., the annoying variation of the acceleration.

VI. Conclusions and Future Work

As cellular based vehicular networking is emerging as a really viable technology and a credible alternative to DSRC and 802.11p, the assessment of its performance becomes of the utmost importance. Indeed, what is urgent and fundamental is the analysis of the architectural choices and networking capabilities in light of the *applications* they are supposed to support. The standards, specifically those for 5G New Radio (NR), are still evolving and there are good chances that they can be improved if the scientific community gives evidence of impairments and solutions to them.

This paper provided a first evaluation of the impact of SBSPS, the scheduling algorithm for OoCs LTE-V2X, on platoon control, using well known and controllers accepted as standards by the scientific community. The initial results are far from exciting, showing that the already observed bursts of lost packets severely hampers the possibility of realizing cooperative driving solutions and, indeed, of most of the "smart" applications that are the reason of existence of V2X networks. Burst errors at every vehicle can be due to scheduling collisions on the channel or to half-duplex errors, i.e., messages scheduled on different sub-channels, but in the same timeslot. Hopefully, more research on these topics will allow significant improvements in scheduling for 5G-V2X.

Fortunately, however, these impairments are fairly easy to understand, and we can conjecture that they are also fairly easy to correct modifying in part the architecture and in part the access scheme to resources. Focusing on the access scheme, two different reasons emerge as dominant of this behavior:

1) The semi-persistent resource reservation implies that a 'wrong' choice of the resources causes a long sequence

of consecutive collisions and, with higher probability, the simple impossibility of hearing messages that are transmitted on different frequency resources but during the same time slots selected by the UE to transmit;
2) The lack of feedback for broadcast communications due to the purely feed-forward resource selection scheme, which listen to the channel for a period of time and then takes the decision for a future period without the possibility of collecting a feedback on how good the selection has been.

Both reasons are rooted in the fact that sidelink communication interfaces are derived from uplink ones, where resources are scheduled by a centralized controller that collects all requests and then assigns resources. SBSPS seems to have no knowledge of broadcast communications and replicate locally, in a distributed access scheme, the operation done by a centralized scheduler: assign resources that are free. The difference is that a centralized scheduler assigns resources globally based on requests that represent a model of the future behavior, while SBSPS does it assuming that the local observation of the past is a good predictor of the future, which our results tell is not really a safe assumption.

How to change PC5 and SBSPS to meet the requirements of cooperative driving, safety related applications, and smart environments in general is the exciting challenge cast on research.

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