Offloading Platooning Applications from 5.9 GHz V2X to Radar Communications: Effects on Safety and Efficiency

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***Abstract*—Vehicle to anything (V2X) communications are nowadays performed at 5.9 GHz spectrum, either using WiFi-based or Cellular technology. The channel capacity is limited, and congestion control regulates the number of messages that can enter the medium. With user rate growing, overloading becomes a factor that might affect road safety and traffic efficiency. The present paper evaluates the potential of using Radar-Based Communication (RadCom) for offloading the V2X spectrum. We consider a Heavy-Duty Vehicle (HDV) platooning scenario as a case of maneuver coordination where local messages are transmitted by means of RadCom at different penetration rates. Simulations show significant improvements in channel occupancy and network reliability. As a result, RadCom allows for shorter, safer, and more energy efficient inter-vehicle distances.**

***Index Terms*—Fuel Efficiency, Optimal distances, Platooning, Radar-based Communications.**

I. INTRODUCTION

Mobility with maximized road safety and traffic efficiency is a goal reflected in the United Nation's Social Development Goals [1], and in global initiatives such as Vision Zero [2], adopted by the European Commission. The road towards future mobility in Vision Zero is divided in stages called *Days*, which go from Day 1 (where we currently are) until Day 4, when Cooperative, Connected and Automated Mobility (CCAM) is expected to be present on all roads and at all times.

Efforts to arrive at the final stage of CCAM include two main fronts: automated mobility and Cooperative Intelligent Transport Systems (C-ITS). The latter uses vehicular communications, such as Vehicular ad hoc Networks (VANETs), that use access technologies such as 802.11p. For Day 1 services, aimed at increasing the awareness of road users, there are technologies such as the Cooperative Awareness (CA) [3] and Decentralized Environmental Notification (DEN) [4] basic services, which are used in the framework defined by the European Telecommunications Standards Institute (ETSI). These services rely on the exchange of messages that inform road users about each other's presence (through Cooperative Awareness Messages (CAMs)) or about risks on the road (using Decentralized Environmental Notification Messages (DENMs)). These messages are exchanged using access technologies such as ETSI ITS-G5 [5], which is based on 802.11p.

Subsequent Days are also expected to rely on messages. Day 2, when *cooperation* starts, uses Collective Perception Messages (CPMs) to exchange information about detected objects [6]. On Day 3, road users share their intentions (e.g., desired trajectories), and finally, on Day 4, vehicles coordinate their maneuvers. These features are expected to be performed by the Maneuver Coordination (MC) service, powered by Maneuver Coordination Messages (MCMs).

Early forms of maneuver coordination are Cooperative Adaptive Cruise Control (CACC) and platooning. These applications are also based on messages. For example, platooning uses CAMs and Platooning Awareness Messages (PAMs) to inform neighbors of the ability to form a platoon and negotiate its start (sent in broadcast mode), and Platooning Control Messages (PCMs) to maintain the platoon (sent in unicast between platoon members) [7].

This means that, from Day 1, the medium will be occupied by a myriad of messages to power services. Even for Day 1, the existence of traffic with different characteristics and priorities can cause problems in efficiency and effectiveness for safety applications [6], [8]. These issues stem from the capacity of the channel to accommodate a certain number of messages before reaching congestion [9], [10]. Thus, if more messages enter the system, e.g., MCMs, PCMs, the ability of the channel to accommodate them will be hindered.

This paper proposes the use of Radar-Based Communication (RadCom) as an alternative channel to offload future mobility use cases, such as platooning. We present a study of the potential saving in terms of medium usage (Channel Busy Ratio (CBR)), and whether such offloading allows reaching the goal of platooning and C-ITSs in general: minimizing risks of accidents (e.g., collisions between road users) and increasing efficiency.

The contributions of this work are:

1) A simulation-based study of the effect of offloading Vehicle-to-Vehicle (V2V) communications from the C-ITS medium to bumper-to-bumper RadCom.
2) An analysis of the effect of this offloading on minimizing safe inter-vehicle distances in a platoon.

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3) An analysis of the effect of these distances on traffic and in-vehicle efficiency.

The rest of the paper is organized as follows: in Section II, we explore the related work on platooning and its performance using VANETs; Section III presents our proposal for RadCom-enabled channel offloading; Section IV presents an experimental evaluation of the system; Section VI presents an analysis of our results and its effects on road safety and traffic efficiency; and, finally, Section VII presents the conclusions and our future lines of work.

II. PLATOONING

Platooning has been widely studied in the context of safety and efficiency. An early example of electronics-assisted platooning is the ”Electronic Tow Bar” resulting from the European project PROMOTE-CHAUFFEUR [11]. Further efforts from the industry and research communities are reflected in brand-specific projects SARTRE [12] and COMPANION [13], as well as multi-brand projects like ENSEMBLE [14]. These projects, however, rely mostly on sensing and adaptations in the infrastructure (e.g., lane markings), and use cloud services instead of vehicular communications. In this section, we describe network-enabled platooning, as expected by ETSI and as studied by the research community.

A. Network-enabled platooning

Platooning is an C-ITS application contemplated in the ETSI ITS framework [7]. As it is for Day 1 applications, it relies on the exchange of messages: CAMs inform about a vehicle’s capability to platoon, PAMs are used to negotiate platoon creation, and PCMs are sent between the leader and members (in unicast) to maintain the platoon.

The platoon leader exchanges information with the rest of the members and with other road users. This enables functionalities for platoon safety and efficiency, such as negotiating inter-vehicle distances to enable safe braking in emergency situations [15], or exchanging information on attributes and capabilities (e.g., acceleration/deceleration capability).

While the platoon is enabled, the rest of Vehicle-to-anything (V2X) communications are still used, so there is a possibility that PCMs use a channel different from the main V2X channel (e.g., CCH for ETSI ITS-G5), which is used by other safety-critical applications. However, even if a different channel is used, they are likely to suffer from access layer phenomena, as we explore in Section II-B.

B. Access phenomena affecting platooning

There are several Access layer phenomena that affect V2X-enabled platooning. Some of these phenomena are inherent to the nature of WiFi-based protocols such as ETSI ITS-G5, such as hidden and exposed nodes; and others are related to channel congestion and how different frameworks deal with it. Figure 1 summarizes the hidden and exposed node phenomena. A and D are hidden nodes for C and B, respectively, and messages they send to each other (A and C) could collide with messages coming from the hidden nodes. Similarly, if A and B want to communicate with each other, communication between C and D can prevent them from accessing the medium. This is the exposed node phenomenon. While there are mechanisms, e.g., back-off procedures in WiFi networks, to counter hidden and exposed nodes, there are access protocols in C-ITS that only use them when unicast communication takes place (e.g., ETSI ITS-G5 does not use exponential back-off for single-hop broadcast traffic, but does so for unicast) [16].

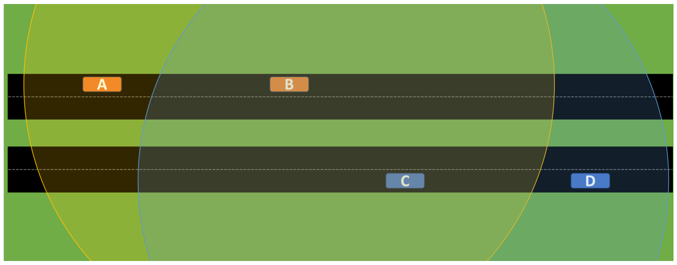


Fig. 1. Hidden and exposed node phenomena in V2X scenarios.

An analysis of CAM-based platooning is performed in [17]. Here, authors present an evaluation of the CA basic service as an enabler for platooning and identify a problem with message synchronization. While CAM synchronization is solved with kinematic generation, PCMs are generated at high, periodic rates [7], and are thus susceptible to collisions due to synchronization.

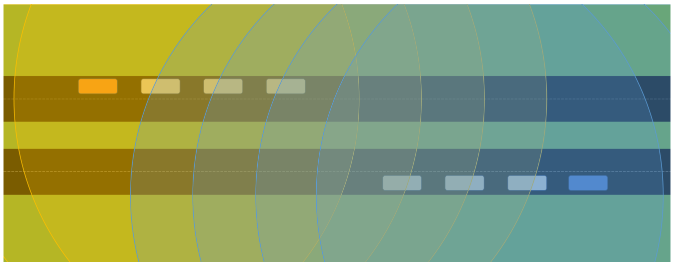
Furthermore, even if PCMs are sent in unicast mode (as opposed to CAMs and DENMs, which are broadcast), neighbors can overhear these exchanges (i.e., sense the medium as occupied). In moderate to high density scenarios, these exchanges add to the existing channel occupancy and create congestion. The work in [18] analyzes the performance of ETSI DCC in multi-lane platooning scenarios, and proposes the use of congestion control techniques different to adapting message rates (e.g., controlling transmission power).

There is a need for ”intra-platoon” communications to occur without interfering with other applications sharing the medium. The use of millimiter wave (mmWave) communications for platooning applications is explored in [19]. The authors use mmWave to rely sensor information using multi-hop dissemination. The difference with our proposal is that, while they consider a generic mmWave antenna, we analyze the possibility of piggy-backing communications specifically on radars with specific attributes and capabilities.

III. RADCOM-ENABLED PLATOONING

Figure 2 summarizes our proposal to offload intra-platoon communications to RadCom. The top part of the figure (2a) shows the foreseeable status of network-enabled platooning. After negotiating the start of a platoon using CAMs and PAMs, the platoon leaders (dark nodes) start communicating with the members (light nodes) exchaning PCMs in unicast mode. The arches express a conservative range for the wireless signals from each node (yellow for the platoon on the left and blue for the one on the right). These ranges are typically measured above 300 m, but are sometimes greater [20].

(a) Network-enabled platooning. C-ITS spectrum



(b) Network-enabled platooning. C-ITS spectrum and RadCom

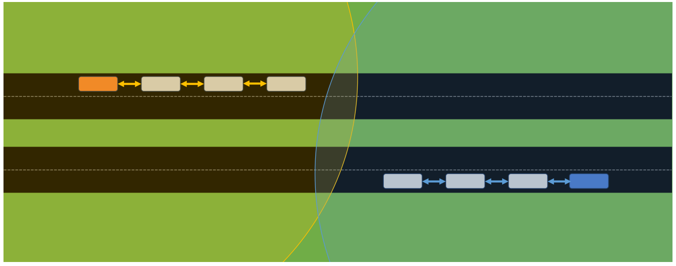


Fig. 2. Representation of offloading intra-platoon communications to RadCom. The yellow and blue shades represent the coverage area for the members of each platoon, yellow for the westbound and blue for the eastbound.

This means that, in scenarios like this, intra-platoon communications will not only interfere with other platoon members, but also with other platoons and even other vehicular communications. Figure 2a shows that the tails of both platoons are within the range of most of the nodes, and are likely to suffer from the exposed node phenomenon, as described in Section II-B.

Figure 2b shows how intra-platoon communications can be offloaded to V2V RadCom. On this example, the leaders can send commands, e.g., through PCMs, and receive feedback or other communications from platoon members through multi-hop RadCom (represented by arrows). Then, radio resources would be available for other applications, e.g., inter-platoon communications. At the very least, this offloading will avoid causing congestion in the C-ITS spectrum.

A. RadCom ability to support V2V communications

The bare minimum requirements for RadCom to support V2V communications are the specifications for the ETSI ITS-G5 medium [5]. These are:

1) **Data rate:** support 3 Mbit/s, 6 Mbit/s and 12 Mbit/s. The default rate in ETSI ITS-G5 is 6 Mbit/s.
2) **Message rate:** maximum 40 Hz and minimum 1 Hz.

The body of work on mmWave systems supporting vehicular applications shows that these requirements can be met by generic mmWave deployments. The work in [19] tests their proposed multi-hop system at Gbit/s rates when exchanging sensor information. The work in [21] assesses the capacity of generic mmWave when coding errors are present. OFDM waveforms has been proposed for automotive radar enabling wide bandwidth communication [22]. Communication networks may also be instrumental in avoiding interference between wide band radar sensors [23]–[25]. Their results show that, starting with bandwidths of a fraction of a GHz, rates in tens of Mbit/s are possible in line-of-sight scenarios. Thus, we can expect RadCom to be able to accommodate the requirements that are set for ETSI ITS-G5 and beyond.

IV. EVALUATION OF CHANNEL OCCUPANCY

We use Artery [26] as our simulation toolkit. It combines OMNET++ and Vanetza — a C++ implementation of the ETSI ITS protocol stack. Our setup uses Artery's integration with Veins [27] for the physical layer. Finally, SUMO [28] provides the mobility model for the road topology. Simulation parameters are specified in Table I.

TABLE I. SIMULATION PARAMETERS

Parameter	Values
Access Layer protocol	ITS-G5 (IEEE 802.11p)
Channel bandwidth	10 MHz at 5.9 GHz
Data rate	6 Mbit/s
Transmit power	20 mW
Path loss model	Simple Path-loss Model
Maximum transmission range	1500 m
CAM packet size	285 bytes
CAM Traffic Class	TC2
CAM generation frequency	Kinematic-based [3]
PCM packet size	301 bytes
PCM Traffic Class	TC1
PCM generation frequency	Periodic at 2 Hz
RadCom penetration rate	0, 50, 100%

A. Simulation Scenario

For our scenario, we simulate a 5 km long road with four lanes in each direction. Vehicles occupy the road with a density of 30 veh/km per lane and are running in a steady state, where we can consider them to have organized platoons of different lengths, and have different roles (platoon leader and platoon member). We take measurements for 30 s after a warm-up period of 120 s. Vehicles send CAMs (generated dynamically following ETSI rules [3]), and PCMs that work for controlling and maintaining the platoon (generated periodically every 500 ms). We send both messages on the same ETSI ITS-G5 channel, with PCMs having higher priority than CAM since we consider them to be more critical, although there is not a standardized priority for PCMs as of now [7].

A subset of platoons offload PCMs to bumper-to-bumper RadCom. This means that these vehicles stop sending PCMs on the ETSI ITS-G5 spectrum and perform platoon control and maintenance ”bumper-to-bumper”. We increase the number of RadCom platoons (i.e., penetration rate) until only the platoon leaders send messages on the ETSI ITS-G5 channel (i.e., 100% penetration rate).

We measure conditions in the ETSI ITS-G5 channel. The performance metrics we evaluate from the simulation are:

- **Packet-delivery Ratio (PDR)**: the number of successful message receptions divided by the total expected receptions.

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- **Smoothed Channel Busy Ratio (S-CBR)**: the smoothed average of CBR measurements which is used in the Decentralized Congestion Control (DCC) mechanism [29].

The results above allow the calculation of safety and efficiency metrics presented in Section V. We use the work in [15] to relate network performance to inter-vehicle distances, and then extrapolate them to fuel efficiency.

B. Simulation results

TABLE II. RESULTS FOR MESSAGES IN THE C-ITS SPECTRUM AT $d \leq 200$M WITH DIFFERENT PENETRATION RATES OF RADCOM

RadCom Penetration Rate	PDR	S-CBR	Latency
0%	0.6985	0.6176	136.80 ms
50%	0.7859	0.6119	109.57 ms
100%	0.9015	0.2217	1.45 ms

Table II shows the results of our experiment. The table shows the average PDR and latency for PCMs. For the 100% rate, only the leaders send messages on the C-ITS spectrum and the rest of the platoon communicates using RadCom. Thus, the PDR for PCMs is mostly affected by propagation phenomena and the interference from CAMs. Therefore, even sending command-and-control messages at a high rate, offloading to RadCom allows platoon members to listen to leaders with significantly increased reliability.

It is worth noting that, even with half of the fleet not sending PCMs, channel occupancy stays at similar levels as when all vehicles send PCMs. This number, slightly above 0.61 is close to the theoretical CBR limit for ETSI ITS-G5 (0.68) and to the point where medium occupancy converges ($CBR = 0.65$) [10]. While occupancy stays similar, the effect of offloading to RadCom is noticeable in PDR and in latency: more packets arrive, and they do so faster. Nevertheless, even at this vehicle density (30 veh/km per lane), the stress on the medium is noticeable. However, when only platoon leaders send PCMs (100% penetration rate), besides the increased PDR, the value for latency significantly better. Delays are minimal, and thus, more messages arrive, and they do so in a timely fashion.

V. OPTIMAL DISTANCES AND FUEL CONSUMPTION

Increased offloading of V2X channel results in increased PDR (Table II). Consequently, Inter-Vehicle Distances (IVDs) within the platoon can be decreased without compromising safety. Figure 3 shows how distances between vehicles of one platoon can be shortened with the increased RadCom penetration rate. The minimum safe IVDs were obtained as a Pareto optimal solution that minimizes IVDs' weighted sum under safety constrains (see (2), (4) in [15]) for a simulated scenario involving a four-vehicle platoon on a flat and straight road section. Reduced distances between vehicles contribute to a decrease in air drag force, subsequently resulting in reduced fuel consumption. In our simulation, the platoon of four heavy-duty trucks can save 2% of fuel with 50% RadCom penetration rate compared to the scenario when radar communications are not utilized. Furthermore, a 100% offload of the V2X channel leads to even greater fuel efficiency, with a substantial 5.6% reduction in fuel used. Lower fuel consumption leads to cost savings for individuals and businesses, as well as diminishes environmental impact.

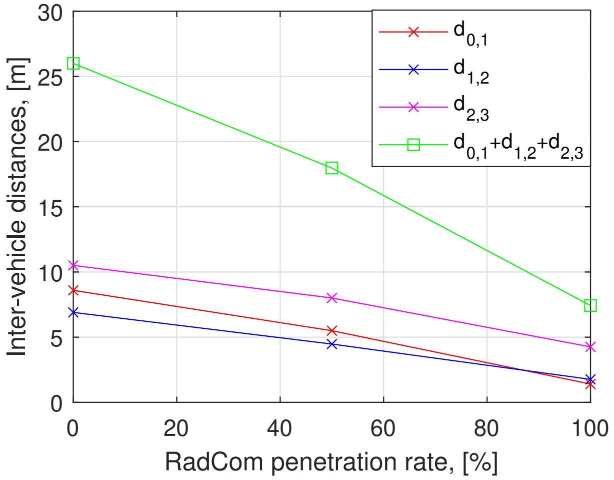

Fig. 3. Safe inter-vehicle distances in a platoon of four vehicles versus RadCom penetration rate. Here, $d_{i-1,i}$ denotes an inter-vehicle distance between vehicles $i-1$ and i where vehicle 0 is the leader.

VI. DISCUSSION

Below we discuss various issues related to using RadCom for intra-platooning communications. All of them represent possible directions for further research.

The energy savings in Section V are presented for one particular scenario only. The full mechanical model (see Equations (1,2) in [30]) takes into account road and vehicles' geometry (possible bumps, inclinations, curvatures) as well as their dynamical properties (variable friction and resistance coefficients). One might also consider possible thermal effects. Thus, for Internal Combustion Engine (ICE) vehicles, too small distances imply additional heating that, in turn, increases fuel consumption [31]. However, this is not the case for electrical vehicles.

Another factor that ambiguously affects energy costs is PCM rate. Low PCM rates lead to decreasing service costs (e.g., resource usage, and data transmission costs), whereas the high ones allow for shorter inter-vehicle distances. Thus, energy consumption is determined by the balance between low/high maintenance costs and savings related to shorter/longer distances.

One of the points to evaluate is the pertinence of having PCMs sent at a fixed interval, as considered in [7]. While these *heartbeat* messages keep platoon members informed about the status of the cluster, there are situations where PCM frequencies can be lowered (e.g., in flat, straight stretches of a highway). Further work is required in order to determine if variable PCM rates are energy beneficial and whether RadCom can support such scenarios.

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The weather causes interference for radar in general and RadCom specifically. The detection capabilities of radars are affected by adverse weather conditions [32], [33] which are likely to affect RadCom links as they do with certain cases of V2X communications [34]. Further exploration is needed to understand the impact of weather-related failures, assess potential mitigation strategies (e.g., adding re-transmission protocols with or without forward error correction), and evaluate their effects on throughput.

Another issue that can affect performance in general for RadCom-enabled platooning is security. The ETSI ITS framework specifies a security architecture [35] with different requirements for each ITS service. For example, confidentiality and privacy requirements are different for CAMs and for DENMs, given their different nature. In DENM cases, such as road hazard warnings, the trade-off between confidentiality and road safety is leveraged differently. Work has to be performed to assess the need to encrypt RadCom-exchanged PCMs since they have a different dissemination scheme than those exchanged using the C-ITS spectrum.

Finally, one of the contributions of this paper was the evaluation of the effect of RadCom penetration rates. The nature of the vehicular industry creates a phenomenon where the average age of a vehicle is 12 years for passenger vehicles and 14.2 years for trucks [36]. This means that, even if 100% of vehicles produced starting today include RadCom nodes, it is unlikely that the penetration rate will reach 100% before several decades pass. However, one solution could be to retrofit radar-equipped vehicles (especially heavy-duty vehicles) with nodes adapted to their currently existing radars. Further work on the effect of a mixed-capability fleet shall be performed.

VII. CONCLUSION AND FUTURE WORK

We presented a proposal to offload intra-platoon communications, which are expected to use PCMs sent in the 5.9 GHz V2X spectrum, to RadCom. We measured the potential benefit of the use of this additional access technology in a less congested V2X spectrum when adoption rates are high. Thus, lower congestion is reflected in increased network reliability and reduced end-to-end delays for safety-critical messages.

This increased reliability allows reducing the minimum inter-vehicle distance required for safe platooning. Therefore, other efficiency metrics are also boosted as a consequence of offloading communications to RadCom. We showed that fuel efficiency is increased with reduced distances, and with this efficiency, it can be argued that other beneficial societal and economical impacts occur.

Finally, we elaborated on other issues affecting platooning in general and RadCom-enabled platooning specifically:

- lowered distances effects on platoons of ICE and electric vehicles,
- fixed and dynamic PCMs rates,
- effects of adverse conditions on RadCom, and
- security requirements.

Future work includes the thorough evaluation of RadCom to comply with the requirements set for existing services and *Future Mobility* services based on V2V communications, such as intention sharing and maneuver coordination.

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