Towards 5G NR ProSe-based Platoon Services supporting URLL Vehicular Communication

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***Abstract*—Effective vehicular platooning requires the Ultra-Reliable, Low-Latency Communication (URLLC) capabilities provided by 5G New Radio (NR) sidelink (SL). These advanced communication features also impose constraints on platoon size and organizational structure. This paper introduces a framework that integrates platoon management with 5G Proximity Services (ProSe), defined by the 3rd Generation Partnership Project (3GPP) Release.18, to accommodate these constraints. We propose a 5G ProSe-based distributed service for platoon management, incorporating join and leave functions for platoons. The system features a combined slice design supporting both general vehicular and platooning communication, along with admission control tailored to URLLC SL slice requirements. Incorporating both a deterministic scheduler and a high 5G NR numerology, our described 5G ProSe-based platoon service supports strict URLLC requirements.**

I. Introduction

Vehicular platooning involves organizing multiple vehicles into a convoy consisting of one Platoon Leader (PL) and various Platoon Members (PMs). Direct vehicle-to-vehicle (V2V) communication is essential for enabling cooperative driving among these vehicles. To support V2V-based communication for vehicular platooning, early works have been based on IEEE 802.11p, also known in Europe as ITS-G5.

In addition to join/leave functions required for platoon management, platooning requires safety-critical Cooperative Adaptive Cruise Control (CACC) to provide string-stable control on each platoon vehicle. Numerous works [1]–[3] have emphasized the need for high-reliability, low-latency communication to meet these stringent demands. While IEEE 802.11p struggles to meet these criteria, Hegde et al. [4] also noted the limitations of 3GPP 4G C-V2X in that context.

3GPP 5G NR SL offers a promising alternative, especially complementary to the introduction of 5G NR URLLC services in the 3GPP Rel. 17 [2]. The feasibility of jointly supporting platoon management and highly stringent URLLC services over 5G NR SL (i.e. dedicated slices for direct V2V communications) for platoon control yet remains an open area of research. For platoon control, previous works like Alexios et al. [3] have attempted to design dedicated slices for platooning communication to achieve URLLC services, these efforts often require higher-layer 5G infrastructure control. On a pure sidelink perspective, various resource allocation techniques have been explored to improve communication reliability [4]–[6]. Additionally, many studies, including key industrial initiatives like ENSEMBLE [7], proposed to integrate platoon-specific messages with standard V2X safety messages such as CAM (Cooperative Awareness Message). Despite these efforts, questions about how these messages should be interpreted within the system, as well as how to ensure security and reliable transmission, remain unresolved.

The 3GPP 5G NR ProSe standard, designed to provide service and group management to future 5G NR SL applications, is well-suited to platoon management. ProSe service announcements can seamlessly announce the existence of a platoon service, enable group communications between platoon members and trigger resource allocation and scheduling decisions for 5G SL between platoon members. Yet, while 5G NR SL is required for direct platoon communication, 5G NR URLL critical for platoon CACC control, and 5G ProSe necessary to manage platoon as a service, these three complementary aspects have not been jointly explored.

In this study, we specifically address these three aspects jointly. Initially, we utilize 5G NR ProSe for platoon announcement & configuration, using SL service announcements for advertising & joining platoons. Next, we design a ProSe-triggered SL slice management system, where one dedicated slice facilitates URLLC services for platoon control and another ensures general C-ITS/V2X communication. Finally we integrate the SL URLL slice admission control into the 5G ProSe group management to limit platoon members to the capacity of the URLL SL slice. The rest of the paper is organized as follows: Section II provides background on 5G sidelink and ProSe standard, network slicing and vehicular platooning. Section III outlines the methodology and our design, while Section IV presents evaluation results. Section V summarizes the key findings.

II. Background

A. 5G NR Sidelink and ProSe

Sidelink (SL) is an extension of 5G NR for device-to-device communication. 5G NR SL V2X physical resources are similar to 5G NR, as shown in Fig. 1, resources span both time and frequency domains. Frequency-wise, bandwidth is divided into 15kHz Physical Resource Blocks (PRBs). In time, a 10 ms frame comprises 10 sub-frames, further partitioned into mini-slots. Unlike 4G LTE's fixed sub-carrier spacing, 5G NR offers flexible frame structures. Transmission time intervals (TTI), or mini-slot durations, can vary from 1 ms to 0.125 ms.

In 5G NR V2X SL communication, MAC layer mode 2 offers various scheduling options. Mode 2(a) is sensing-based; 2(b) features cooperative, distributed scheduling, where User

Equipment (UE) can assist each other in resource selection; 2(c) and 2(d) involve Vehicle-UEs (VUE) assigning resources, either based on pre-configured patterns or neighbouring VUEs based scheduling scheme. The latter two are deterministic, which provide delay bound while maintaining reliability, and thus suitable for URLLC needs. For more details on scheduling modes, please refer to Garcia et al. [1].

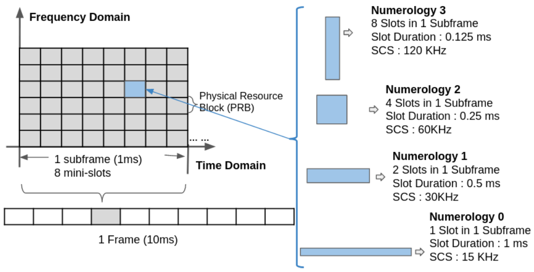


Figure 1: 5G NR Sidelink Physical Architecture

The SL-based ProSe standard, originally introduced by 3GPP in LTE release 12, has been adapted for 5G NR with notable enhancements in releases 17 [8] and 18 [9]. Within 5G ProSe, two crucial features are defined: 5G ProSe Direct Discovery and 5G ProSe Direct Communication. These features enable SL group management related to SL services, and support link establishment, modification, and release related to these services. Considering platooning as a service, ProSe can seamlessly transition from group management to platoon management, simplifying the linkage to physical layer resource allocation management. The *Ensemble* Project [7] notably pointed out the need of service announcement for platoon communication due to backward compatibility issues. 5G ProSe also provides enhanced safety and privacy for group management during the direct discovery procedure.

B. Network Slicing and URLLC Service

5G introduces network slicing, an architecture that enables multiple services, including URLLC, to coexist on a single physical 5G infrastructure. Network slicing divides the network into segments, allowing for efficient resource utilization. Vehicular platooning, as a safety-critical application, falls under the URLLC services category defined in 3GPP release 17 [2]. URLLC aims for a reception reliability of 1 ms for 32-byte packets with a rate of 10^{-5}. Adapted requirements for 5G NR V2X SL mandate a reception reliability of 10^{-5} with a 3-10 ms delay for 300-byte packets.

In the context of vehicular platooning, the system needs to offer integrated network slicing. One slice must be allocated to support critical communication, while another separate slice is required to support other essential V2X communication protocols. Previous work by Lekidis et al. [3] suggested a framework for platoon network slicing that combines V2V and V2I control, facilitated by higher-level Roadside Unit (RSU) assistance. However, the specifics of URLLC slice design and slice segmentation remain unclear. Chang et al. [10] explored dynamic resource reservation for CACC platooning and emergency situations, but offered limited insight into the physical layer implementation of network slicing.

The realization of URLLC on 5G NR sidelink has already been investigated by Yan et al. [11]. However, a more nuanced design is needed to accommodate both platooning and general V2X communications for vehicles into different slices. Importantly, given that URLLC is intended for limited access and that platoon size is restricted in realistic scenarios, the admission control strategy need to be integrated into the platoon management.

C. Vehicular Platooning

According to Ensemble Project [7], there are two types of platoon messages, as depicted on the left in Fig. 2: platooning management message (PMM) and platooning control message (PCM). PMM focuses on forming and stabilizing a cohesive platoon group, while the PCM performs a centralised control from the PL to all PMs, certain control messages must be guaranteed with high QoS in order to achieve platoon string stability. In practice, PCM are based on CACC control algorithms as suggested by Lefeber et al. [12]. Additionally, all vehicles must support general C-ITS messages, such as CAM, Decentralized Environment Notification Message (DENM), Collective Perception Message (CPM), to establish a foundational vehicular awareness and road safety. The impact of these V2X messages on platooning communication remains under active investigation.

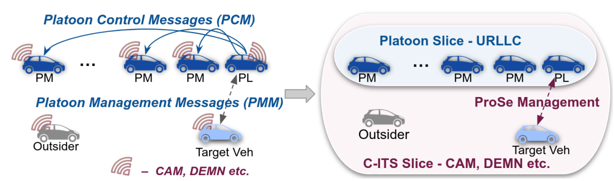


Figure 2: Vehicular Platooning Scheme

To address these issues, Cao et al. [5] proposed an enhanced random resource selection from PL for platoon members and applied reinforcement learning-based semi-persistence for intra-platoon communication, significantly reducing external communication impact. Wang et al. [6] proposed combined predecessor-leader communication from PMs to PL, facilitating platoon formation and ensuring high QoS. However, details about manipulating unicast and groupcast communication modes were not provided.

In this study, we introduce a novel framework for integrated slice design tailored to platooning communication, as illustrated in Fig. 2 on the right. Separate slices are allocated for both fundamental V2X communication and vehicular platooning to minimize interference and ensure independent operations. The slice for platooning is specifically aimed to support URLLC for critical intra-platoon messages. Additionally, ProSe is employed to announce platoon services and handle PMMs, notably the join and leave functions.

III. Methodology

A. ProSe-Based Platoon Configuration Architecture

This section presents the proposed ProSe-based platoon join&leave management and slice assignment procedures. Fig. 3 details these in four main phases:

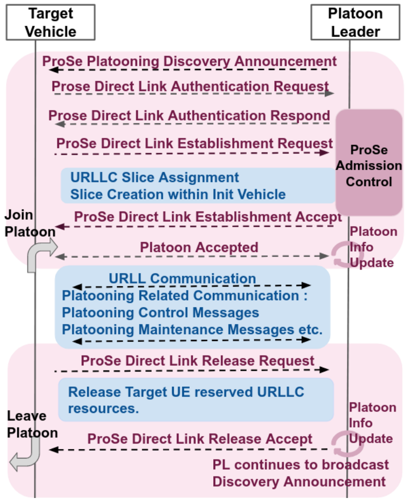


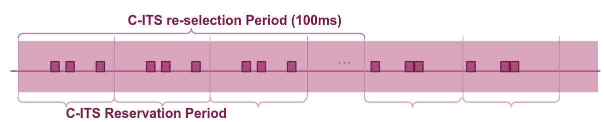
Figure 3: Proposed Platoon Configuration Architecture

- *Platoon Initial Announcement:* Initially, the PL is authorised to act as the announcing UE, allowing it to transmit platoon service announcements to its neighbours via the ProSe PC5 Discovery Message. Nearby target vehicles who want to join platoon act as monitoring UEs, constantly listening to their neighbours' ProSe discovery messages from current adjacent platoons before they are accepted by any platoon. To simplify the system, we applied the ProSe Model-A discovery procedure, where no response is required from neighbouring vehicles.
- *Joining Platoon:* When a new vehicle wants to join a platoon, it will piggyback its joining request through a ProSe Direct-Link-Request message to the PL. The PL is obliged to check its local platoon list first. We apply an admission control scheme through adjustment of the ProSe Standard Section 7.2.3.5 in [8], under condition #5: "when leader rejects a joining request because of lack of resources for 5G ProSe direct link." The PL is obliged to compare the current platoon size with its local admission control capacity; this capacity is determined by its ability to provide high-quality URLLC services to each PM. Only if there are still available spots can the current platoon accept this new arrival; otherwise, a rejection is issued.
- *URLLC for Intra-platoon Communication:* Upon acceptance, the new platoon member triggered by the ProSe establish messages, starts to allocate its local resources for URLLC slices according to the platoon slice design. Additionally, the PL assigns a slot to this new member based on a predetermined pattern from the deterministic Mode 2(c) scheduler scheme. The new member is allocated a specific URLLC resource slot according to the PL's scheduling pattern, this scheduling pattern design is to be investigated in the following. Note that security configurations are not considered in this study. Subsequently, each platoon member is restricted to transmitting intra-platoon messages solely on its reserved slots and continues listening during other slots within the URLLC Slice. Therefore, high reliability and low latency can be guaranteed for platoon critical URLL communication.
- *Leaving Platoon:* When a member vehicle wants to leave the current platoon, it generates a ProSe Direct-Link-Release message to inform the PL of its request to leave. The PL first releases the reservation within the URLLC slice for this target vehicle and then replies with a ProSe Direct-Link-Release Accept message to complete the departure procedure. This target vehicle will then release its local platoon slice reservation and return to its initial state; meanwhile, the PL must update the local information of the platoon.

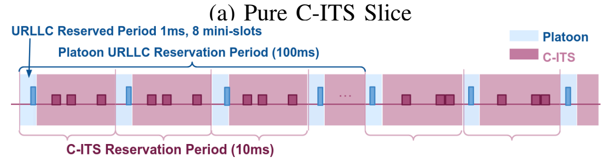
Under this construction, platoon management and intercommunication can be fully realised using ProSe-based sidelink communication. It should be noted that the URLLC slice assignment and release require authentication and authorization from the upper-layer infrastructures, which are beyond the scope of this study and are assumed to be fully functional.

B. Platoon URLLC Slice Design

The default pure C-ITS communication frequency band, as illustrated in Fig.4a, is to support general ITS messages for basic road safety, such as CAM, DENM, and CPM. In this study, we propose a novel combined-slice design, outlined in Fig.4b, where a periodic reservation in the time domain is allocated for platooning communication. The platoon slice (depicted in light blue) is designed for communication needs of high stringency with minimal resource demands. Consequently, the reservation period for the platoon slice is significantly shorter than that of the C-ITS slice. Additionally, adhering to the standard inter-packet gap of 10 ms in V2X technologies, as recommended by 5GAA [13], only 1 ms is designated for the platoon slice within each 10 ms C-ITS slice.



(a) Pure C-ITS Slice



(b) Combined Slice : C-ITS and Platoon

Figure 4: Slices Physical Layer Illustration

To meet the stringent demands of URLL communication in terms of low latency and high reliability, certain parameters are reconfigured. A comparison between general C-ITS and platoon slices is presented in Table I, particularly for the platoon slice:

- A higher numerology, denoted as $\mu - 3$, is applied, which reduces the duration of the *mini-slot* to 0.125 ms. This allows for eight transmissions within every 1 ms, as indicated by the blue partitions in Fig. 4b. This adjustment ensures the 1 ms latency bound is met [11].

- Resource reservation is segmented into 10 ms periods. Within each 10 ms period, the first 1 ms is reserved exclusively for the URLLC Slice, while the remaining time is allocated for the general V2X communication. Periodic reservations is made every 100 ms.
- Unlike the traditional sensing-based Scheduling mode 2(a) used in the C-ITS slice, the URLLC slice employs a deterministic Time-Division Multiple Access (TDMA) scheduler, mode 2(c). A pre-allocated pattern is created by the PL and disseminated to its platoon members. In this study, each platoon member is assigned one mini-slot within a single millisecond, as illustrated in Fig. 4b. This allows for a total of eight assignments. If the platoon size exceeds this limit, a random slot selection is generated within the current slice reservation to analyse the maximum admission control limit. As a result, all platoon members can guarantee direct transmission under low latency.

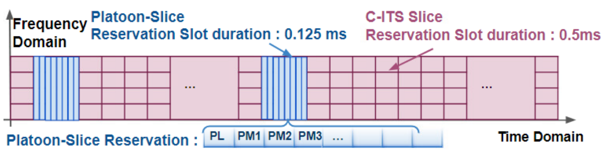


Figure 5: Combined Slice Design and Reservation Indication

Table I: Slices Configuration Parameters

Parameters	C-ITS Slice	Platoon Slice
Numerology	1	3
Reserved Period	9ms/10ms	1ms/10ms
Re-selection Period	100 ms	-
Operation Frequency	5.9 GHz	5.9 GHz
Applied Bandwidth	20 MHz	20 MHz
MAC resource Allocation	mode 2(a)	mode 2(c)

IV. Performance Evaluation

A. Simulation Environment Campaigns

We implement the combined slice design described in Section III-B on 5G-LENA Network Simulator (NS3), on version *nr-v2x-dev* which enables 5G-NR direct sidelink communication simulation [14]. For performance evaluation we focus on the general communication traffic performance between different slice designs, therefore Section III-A proposed ProSe-based platoon configurations are taking operational assumptions as completed.

A four-lane highway V2X scenario is constructed for our simulation topology, as shown in Fig. 6. One lane is reserved for platoon vehicles, the rest lanes are occupied by outside vehicles. Vehicle-to-vehicle (V2V) distance varies according to target communication densities. For C-ITS communication, transmitters broadcast typical CAM messages of 300 bytes at a rate of 1Hz, all directed to a single reception vehicle.[1]. For inter-platoon communication, transmissions are generated by all other platoon members to one platoon receiver. To evaluate the maximum capacity of this platoon slice, the sent packet size is set to 300 bytes, at a high transmission rate of 10 Hz.

[1]The broadcast transmission is intended to all vehicles, but we only consider 1 receiving vehicle for analysis purpose.

3GPP Channel Model [15] is applied in the simulation, which takes into consideration for both fading and shadowing to produce a realistic physical channel environment. For each scenario, 40 random channel realisations are performed in order to acquire statistical performance results. All results are illustrated within a confidence interval (CI) of 90%.

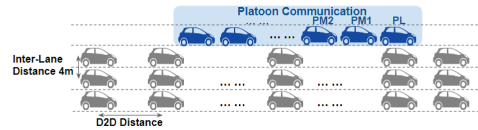


Figure 6: Scenario Topology

When analysing impact on the overall performance, in order to not to lose generality, we rely on a harmonizing metric which is called *Communication Density*, defined as follows:

$$Dens^{Comm} = \frac{Msg^{Rate} \times Tx^{Range}}{Dist^{V2V}} \tag{1}$$

Varying the parameters of transmit range, traffic density, and message rate, while maintaining a overall constant communication density, will lead to similar broadcast communication performances as discussed in [16].

Table II: Simulation Parameters Setting

Parameter	Value
Inter-Lane Distance	4m
C-ITS & Platoon Packet Size	300 bytes
C-ITS Packet Rate	10 Hz
Platoon Packet Rate	100 Hz
Channel Model	3GPP Channel Model
Communication Mode	Broadcast
Number of Platoon	1
Simulation time	10 s
Independent Runs	40

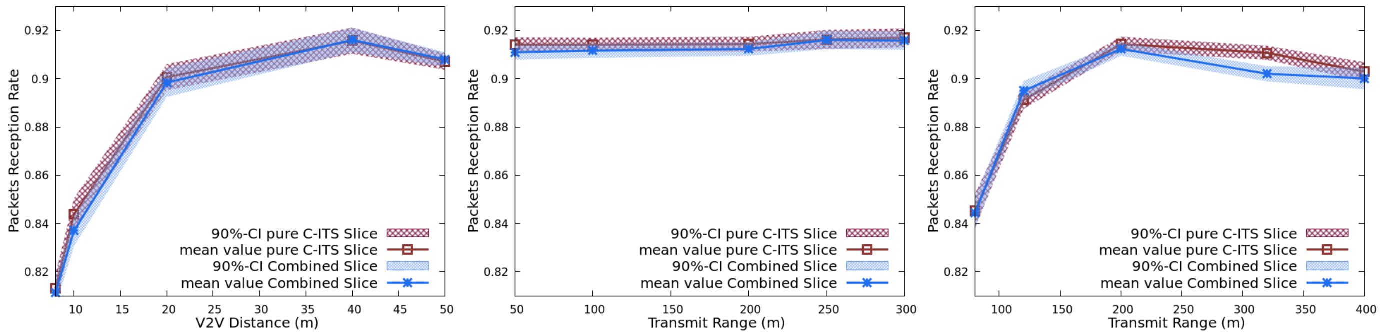
B. Platoon Slice Impact on Overall Performance

This section explores the impact of platoon slices on general V2X communication, focusing on general C-ITS message exchanges; the intra-platoon performance will be discussed in the following section. In practice, all vehicles, including those in platoons, are required to communicate general C-ITS messages. To simplify the scenario and maintain equivalent topology across both slice designs, for platoon topology, we assign 8 vehicles at a distance interval of 10 meters, this distance interval will be investigated in the following section. These vehicles are configured solely to transmit platoon messages and to function as receivers for C-ITS messages.

Table III: Different Groups Scenario Setting

	Group A					Group B				
$Dist^{v2v}$ (m)	50	40	20	10	8	10	20	40	50	60
Tx^{rg} (m)	200	200	200	200	200	50	100	200	250	300
Msg^{rt} (Hz)	12.5	10	5	2.5	2	10	10	10	10	10
	Group C									
$Dist^{v2v}$ (m)	40	40	40	40	40					
Tx^{rg} (m)	80	120	200	320	400					
Msg^{rt} (Hz)	25	16.7	10	6.25	5					

For the outside vehicles, three groups of simulations regarding to different aspect of communication densities are generated for both slicing designs, detailed topology settings



(a) $\mathbf{Tx^{Range}}$ maintained (b) $\mathbf{Msg^{Rate}}$ maintained (c) $\mathbf{Dist^{V2V}}$ maintained

Figure 7: Comparison of PRR between Pure C-ITS Slice and Combined Slice

are provided in Table III. Each group controls a specific density parameter: Group A focuses on a fixed transmission range; Group B keeps a constant overall message rate per vehicle; and Group C maintains a consistent V2V distance. Results regarding to the V2X C-ITS messages communication are depicted in Fig 7. These results are evaluated primarily on Packet Reception Rate (PRR), and averaged with confidence interval of 90% over 40 runs. Results from the pure C-ITS slice design are illustrated in red, whereas those from the combined slice design are plotted in blue.

From the overall distribution, under the same communication densities, Groups A and C, which maintain transmission range and V2V distance respectively, show that varying communication density significantly affects performance, while Group B maintains stable performance at a consistent message rate. Additionally, for all groups, deploying a platoon slice appears to have only a minor impact on overall C-ITS communication, as packet reception rates are similar for both slice designs.

Further observations reveal that the platoon slice has a slightly greater impact under conditions of lower transmission rates or lager transmission ranges. This is due to resource exemptions by platoon reservation leading to some packet reception loss. This effect is particularly noticeable when the actual reception rate is low; however, when the reception rate is relatively higher, such losses become negligible compared to other primary factors causing communication failures.

Consequently, we can conclude that the integrated platoon slice design effectively preserves the integrity of general 5G Sidelink V2X communication. The disparities between the two designs are minimal across a range of communication density settings and manifest only limited impacts on specific communication topology designs.

C. Intra-Platoon Performance Analysis

In this section we delves into the performance characteristics within the platoon slice, aiming to satisfy the stringent requirements for URLLC's high reliability and low latency. In the intra-platoon scenario, one vehicle serves as a receiver and the rest of platoon vehicles act as transmitters. By adjusting the number of transmitters, we assess the maximum capacity of the configured platoon slice.

We investigate two platoon topology layouts with V2V distances of 5 and 10 meters[2]. The differences in results between these two layouts can be attributed to the degradation of communication quality solely due to physical channel propagation. Packet reception rate results are shown in Fig. 8a, where both layouts exhibit stable communication until the number of transmitters exceeds 7. This behavior aligns with our designed resource allocation scheme. In this scheme, the MAC layer scheduler self-adjusts based on the actual platoon size. When the size is fewer than 8, *mini-slots* are deterministically allocated based on member indices using a TDMA scheduling scheme—specifically, one *mini-slot* per user over 1 ms. When the platoon size surpasses this limit, a random selection mechanism is triggered, leading to increased packet collision and loss.

The red lines represent the targeted URLLC service requirements of 99.999% and 99.99% reliability. While the 3GPP standard requires a 99.999% reliability level for URLLC services, this threshold is widely recognized as exceedingly challenging to meet in practice. Our results demonstrate this argument, indicating that such high reliability can only be achieved within a given confidence interval. Importantly, this decrease in reliability arises from realistic channel model limitations, not from any methodological issues in our system, and thus lies beyond the scope of this study. However, the 99.99% reliability level is readily achievable and is considered a practical requirement for current URLLC services.

These findings show that to reach 99.999% reliability, only 6 and 5 transmitters can meet this criterion when the platoon vehicles are spaced 5 and 10 meters apart, respectively. This is achieved within a 90% confidence interval. If the reliability requirement is relaxed to 99.99%, then the system comfortably meets the criteria with 7 and 6 transmitters for platoon vehicles spaced 5 and 10 meters apart, respectively.

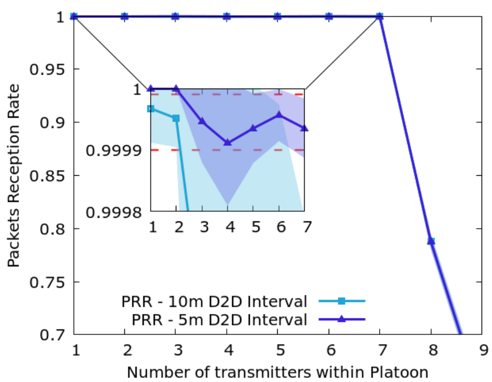
In regard to latency, Fig. 8b illustrates the average Packet Inter-Reception Time (PIR) as a function of time, serving as an indicator for latency performance within the platoon slice. Given that each platoon slice has a reserved duration of 1 ms and a period of 10 ms, the metric *(PIR - 10 ms)* can represent

[2]This distance is distinct from the physical vehicle interval; it represents the point-to-point distance from which the actual vehicle length must be subtracted

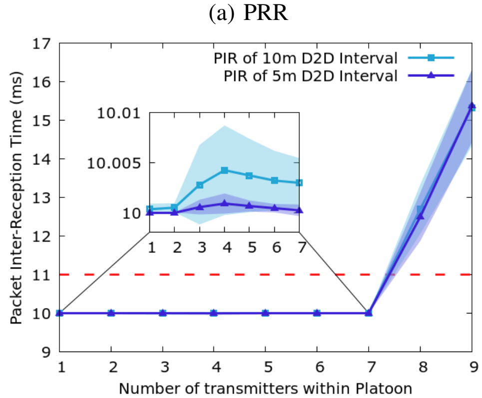
the average packet delay. The red dashed line signifies the delay bound mandated by URLLC requirements, which should not exceed 1 ms.

Our results show that, across different platoon topologies, the latency constraints can be comfortably met when the platoon size is fewer than 8 vehicles (including 1 receiver and 7 transmitters). However, when this number exceeds 8, a random resource allocation strategy is employed, thereby increasing the probability of collision and consequently degrading latency performance. Considering the PRR findings under same topology conditions, it can be concluded that with fewer than 8 vehicles in a single platoon, the communication among platoon members can reliably achieve a 99.99% success rate within the reserved 1 ms platoon slice period.

In conclusion, the proposed combined slice design can provide platoon vehicles with URLLC service, achieving high reliability and low-latency communication. However, sustaining this high quality of service necessitates strict admission controls, limiting platoon sizes to fewer than 8 vehicles.



(a) PRR



(b) PIR

Figure 8: Intra-Platooning Communication Results

V. Conclusion

In contrast to traditional methods embedding platoon messages in 5G NR V2X communication, our approach introduces an innovative configuration utilizing the ProSe standard, which enables direct platoon configuration through service announcements. Additionally, a dedicated 5G sidelink slice, allocated through ProSe-triggering for platooning communication, is established while preserving the integrity of general C-ITS communication.

Employing periodic time-domain reservations, high numerology, and deterministic scheduling, our method achieves a promising intra-platoon communication performance, ensuring up to 99.99% reliability and sub-millisecond latency. Our admission control strategy limits the platoon at a maximum of 8 vehicles, optimizing system performance.

Looking ahead, we intend to assess our system's performance within realistic traffic mobility scenarios, particularly emphasizing its behavior during emergency conditions. We also aim to explore the challenges associated with systems involving multiple platoons.

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