Computer Communications 217 (2024) 41–56

Contents lists available at ScienceDirect

Computer Communications

journal homepage: www.elsevier.com/locate/comcom

LAMP: A latency-aware MAC protocol for joint scheduling of CAM and DENM traffic over 5G-NR sidelink[☆]

Suranjan Daw [a,*], Anwesha Kar [a], Venkatarami Reddy Chintapalli [b], Bheemarjuna Reddy Tamma [a], Siva Ram Murthy C. [c]

[a] Department of Computer Science and Engineering, Indian Institute of Technology Hyderabad, Hyderabad 502285, India
[b] Department of Computer Science & Engineering, National Institute of Technology Calicut, Calicut 673601, India
[c] Department of Computer Science and Engineering, Indian Institute of Technology Madras, Chennai 600036, India

ARTICLE INFO

Keywords:
New radio-vehicle-to-everything (NR-V2X)
Mode-2
Semi-persistent scheduling (SPS)
Cooperative awareness message (CAM)
Decentralized environmental notification message (DENM)
Network simulator-3 (NS-3)
Latency

ABSTRACT

Cooperative Awareness Messages (CAMs) and Decentralized Environmental Notification Messages (DENMs) are two types of messages used in Intelligent Transport Systems (ITS) for Vehicle-to-Everything (V2X) communication. CAMs are used to periodically exchange the current state of a vehicle with its nearby vehicles and the DENMs are used to aperiodically provide critical and time-sensitive information about current environmental conditions to other vehicles and infrastructure entities. While considerable research has been conducted on the efficient scheduling of CAM and DENM separately or at the network level coexistence, no work has been done to integrate the scheduling of both message types at the granularity of the per-vehicle level. The scheduling of CAM is commonly done through Semi-Persistent Scheduling (SPS). However, no equivalent scheduling algorithm has been developed for the aperiodic and variable-sized DENMs. As a result, there is a need for novel mechanisms that can efficiently prioritize and schedule mixed traffic of CAM and DENM messages. This paper introduces a Quality of Service (QoS) scheduler called *LAMP* for segregating traffic in the Radio Link Control (RLC) layer for joint sidelink scheduling of CAM and DENM at the vehicular level. The *LAMP* scheduler is aided with a special resource selection and reservation scheme for mixed traffic scenarios. The groundwork involves an experimental analysis in Network Simulator-3 (NS-3) that uses the New Radio (NR) Vehicle-to-Everything (V2X) module in Mode-2. The simulation findings demonstrate that *LAMP* could significantly reduce the end-to-end latency of DENM by 89.36% and CAM by 40.2% while also increasing the packet reception rate by 12.1% and 9.74% for CAM and DENM with repetitions, respectively.

1. Introduction

The 3rd Generation Partnership Project (3GPP) standardized Cellular Vehicle-to-Everything (C-V2X) in Release 14 [1], which marked the first version of Vehicle-to-Vehicle (V2V) sidelink (SL) communications for basic safety applications using Long Term Evolution (LTE) as the underlying technology. Release 15 [2] of 3GPP identified a complete set of 5G V2X use cases, highlighting the potential of V2X technology in enhancing road safety and traffic efficiency. The subsequent developments in release 16 [3] have paved the way for additional Ultra-Reliable and Low Latency Communication (URLLC) services in NR-V2X, which are expected to provide reliability in the range of 90–99.999% and latency in the range of 5–100 ms [1].

The European Telecommunications Standards Institute (ETSI) has standardized two types of messages to enable the implementation of Intelligent Transport System (ITS) applications. These messages are (i) Cooperative Awareness Messages (CAMs) [4]– periodic heartbeat messages that contain information regarding the vehicle's speed, current position, etc. and (ii) Decentralized Event Notification Messages (DENMs) [5]– event-triggered notifications generated by a Vehicle User Equipment (VUE) upon detection of road hazards and events like wrong-way driving, post-collision warning, and other similar events. Thus reliability and in-time delivery of these messages[1] become crucial factors. While CAMs have received a lot of attention in V2X research, DENMs have not been studied as extensively.

☆ This research work was supported by the Science and Engineering Research Board, New Delhi, India. Grant number: JBR/2021/000005.
* Corresponding author.
E-mail addresses: cs21mtech12008@iith.ac.in (S. Daw), cs21mtech12006@iith.ac.in (A. Kar), venkataramireddyc@nitc.ac.in (V.R. Chintapalli), tbr@iith.ac.in (B.R. Tamma), murthy@iitm.ac.in (Siva Ram Murthy C.).
[1] The packet formats of CAM and DENM messages are given later in Section 2.

https://doi.org/10.1016/j.comcom.2024.01.011
Received 19 August 2023; Received in revised form 29 December 2023; Accepted 14 January 2024
Available online 22 January 2024

The Semi-Persistent Scheduling (SPS) [6] algorithm was designed to cater to the periodic requirements of CAM of fixed packet size (300 Bytes), where resources are reserved in advance for limited future transmissions. However, there is no equivalent scheduling algorithm that has been developed specifically for event-triggered DENMs. A DENM due to its varied packet size (200–1200 Bytes) [7] can potentially consume a significant amount of the available radio bandwidth, which can impact the performance of the entire V2X system. Previous studies [8] have shown that the presence of DENM can negatively impact the performance of the SPS algorithm. In presence of DENMs, the End-to-End (E2E) latency of CAM packets suffers a magnified delay as more CAM packets get queued up in the RLC buffer till the large variable sized DENM packet is completely transmitted by the vehicle. The MAC scheduler unable to distinguish between the nature of the packets, treats the DENM packet like a CAM packet leading to fragmented scheduling of DENM in the transmission slots reserved for periodic transmission of CAMs. This leads to increased E2E latency of CAMs and DENMs. Only a few studies have been conducted to address the joint scheduling of CAM and DENM at the vehicle level, based on message type requirements. Therefore, there is a clear need for further research to address these limitations in efficiently supporting mixed traffic at the vehicle level.

QoS handling for V2X communication over PC5 is based upon the 5G QoS Indicator (5QI), also known as PC5 QoS Indicator (PQI). Based on resource type (GBR, Delay critical GBR, or Non-GBR) and Packet Delay Budget (PDB), QoS requirements of CAM and DENM are mapped to PQI value 23 and 90 respectively [9]. In this work, we propose a Latency-Aware MAC Protocol (LAMP), to classify and mark the user plane traffic by mapping the PC5 QoS Flows to two Data Radio Bearers (DRBs) at the RLC layer. The MAC scheduler is enhanced to guarantee the PQI requirements of the respective DRBs by being aware of the contents of DRBs at every time instant. The *LAMP* ensures efficient handling of CAM and DENM without compromising any of their performance. It also boosts the reliability of DENM through repetitions. Compared to the State-of-the-Art MAC protocol (Legacy MAC protocol) the application-to-application layer or end-to-end (E2E) latency drops significantly for DENMs by 89.36% and CAM by 40.2%, ensuring on-time delivery of CAM and DENM packets.

Our contributions can be summarized as follows:

- First work to introduce a Quality of Service (QoS) Scheduler for segregating traffic in the Radio Link Control (RLC) layer for joint sidelink scheduling of CAM and DENM at the vehicular level, called LAMP.
- A Semi-Reservation Scheme (SRS) to give flexibility of choosing dynamic repetition interval for DENMs to ensure reliability.
- Reducing DENM fragmentation by using a Random Fit Slot Selection Scheme.

The remainder of the paper is organized as follows. Section 2 provides the basics of the 5G NR V2X protocol stack, physical layer, Mode-2 resource allocation scheme in Release 16, and a brief discussion on support for DENM management in Mode-2. Section 3 positions our work among recent similar existing works in the co-existence of CAM and DENM. Section 4 introduces the system model for our proposed work. The limitations of the existing framework are debated in Section 5, and our proposal for evolved MAC layer protocol - *LAMP* to schedule CAM and DENM jointly is described in Section 6. Sections 7 and 8 discuss the simulation setup and report the achieved results, respectively. Conclusive remarks and scope for future works are reported in Section 10.

2. Background

This section recalls an overview of the end-to-end user plane architecture of 5G protocol stack, emphasizing the NR physical layer and its resource allocation scheme with the working of SPS in Sections 2.1, 2.1.1 and 2.1.2, respectively. Section 2.2 addresses the need to handle aperiodic messages (DENMs) in the existing system.

2.1. 5G NR V2X protocol stack operations

The Release 16 NR V2X extends to support the out-of-coverage operation and QoS provisioning when the User Equipment (UE) is in the Radio Resource Control (RRC) idle state [10]. At the user plane of Sidelink (SL) communication in NR-V2X, the application layer generates the packets to be transmitted by the user protocol stack. V2X application packets are mapped into QoS flows identified with a PC5 QoS Flow ID. The mapping from QoS flows to radio bearers is performed at the Service Data Adaptation Protocol (SDAP) layer. Each destination communication, whether unicast, groupcast, or broadcast, requires only one SDAP entity. The SL-DRBs are thus established with the peer node and configured. The Packet Data Convergence Protocol (PDCP) provides several services and functions, including header compression/decompression, ciphering/deciphering, duplication control, in/out of order delivery, and sequence number maintenance. The PDCP layer also supports integrity protection and verification. However, when used in the SL protocol, certain restrictions apply. Specifically, out-of-order delivery is only supported for unicast communication, and duplication is not supported in the SL protocol. The SL Radio Link Control (RLC) protocol supports three transmission modes: Transparent Mode (TM), Unacknowledged Mode (UM), and Acknowledged Mode (AM). UM is the only transmission mode for groupcast and broadcast, although it can also be used for unicast. In UM mode, the SL RLC protocol provides sequence numbering, segmentation, and reassembly services. The SL Medium Access Control (MAC) protocol controls radio resource selection (SPS), packet filtering, priority handling between uplink and SL in a UE, and SL channel state information reporting. These functionalities are in addition to the MAC entity functionalities in a UE, including multiplexing and demultiplexing, Hybrid Automatic Repeat Request (HARQ) procedure, and logical channel prioritization [11]. Therefore, the SL MAC protocol extends the capabilities of the MAC entity in a UE for SL communication.

The RLC buffer contains the queued packets from upper layers, based on which the MAC layer services the requirement of each packet using SPS. The Physical (PHY) layer checks if the current slot has been allocated by MAC and sends it over the air, or the control returns to MAC. The protocol stack of the legacy system uses one PDCP-RLC stack with no logical channel prioritization and handles different QoS flows as a single entity. However, this paper explores the benefit of UEs assigning different PDCP-RLC stacks (or Logical Channels) based on Source Layer 2-ID, Destination Layer 2-ID, and message type.

2.1.1. 5G-NR V2X physical layer

Each VUE uses a pool of resources within a bandwidth of 10–20 MHz configured by the Radio Resource Control (RRC) layer of the 5G Control Plane (CP) protocol stack for the Mode-1 and Mode-2 resource allocation schemes. The PHY layer configuration includes the setting up of numerology, symbols per slot, bandwidth, bitmap, and Time Division Duplex (TDD) pattern. The resources available for SL transmissions are given by a valid combination of the TDD pattern and the sidelink bitmap structure, specified by the standard [12].

In the frequency domain, the sidelink resource pool is split into contiguous subchannels [13]. The size of each subchannel is fixed and can contain a count of 10, 15, 20, 25, 50, 75, and 100 Resource Blocks (RBs) [14]. In the time domain, the resource pool is dissected into frames, and further divided into subframes and slots. The bitmap is repeated and mapped to the uplink slots of the TDD pattern. These RBs or slots become eligible for transmission. Each subframe is further fractionated into 2^{μ} slots consisting of 14 OFDM symbols. The number of slots per subframe varies with the numerology (μ) used (where μ = 0,1,2,3). Data received from the higher layers is transmitted as a Transport Block (TB) along with SideLink Control Information (SCI) which contains critical information about the subframe/resource usage, which other VUEs require to decode the sensed transmission. The TB holds a CAM or DENM message/packet and can occupy one or more subchannels based on the size of the packet, the Modulation and Coding Scheme (MCS), and the sub-channel size.

2.1.2. NR sidelink mode-2 resource allocation and Semi-Persistent Scheduling (SPS)

The PC5 interface was introduced to enhance the flexibility of 5G NR communications in out-of-coverage operation where vehicles select radio resources in a distributed manner without the participation of any gNodeBs using Semi-Persistent Scheduling (SPS) algorithm.

Algorithm 1: Semi-persistent Scheduling Algorithm

Input : Current Slot *sfn*, Sensing Data S_D, T_1, T_2, RC
Output: Available Resources for Tx (L_B)

1 Set $RSRP_{Th}$
2 $L_A \leftarrow All\ T_x\ resources\ [T_1, T_2]$
3 $L_{busy} \leftarrow \Phi, L_B \leftarrow \Phi$
4 **for** $s_i \in S_D$ **do**
5     $rsvp_i = s_i \rightarrow RRI$
6   **for** *i in range (RC)* **do**
7         $L_{busy} \leftarrow L_{busy} \cup \{sfn + (rsvp_i \times i)\}$
8 **while** *true* **do**
9     $L_B \leftarrow L_A \setminus L_{busy}$
10   **for** $l_i \in L_B$ **do**
11   **if** $l_i \rightarrow RSRP < RSRP_{Th}$ **then**
12             $L_B \leftarrow L_B \setminus l_i$
13   **if** $|L_B| < 0.2 \times |L_A|$ **then**
14         $RSRP_{Th} \leftarrow RSRP_{Th} + 3dBm$
15   **else**
16   break
17 *return* L_B

The VUEs continuously monitor the channel resources to create a list of Sensing Data (S_D). A VUE triggers resource selection at every subframe (*sfn*). The SPS Algorithm 1 runs in MAC Layer, finds out best available resource (L_B) from the set of all possible transmissible slots in selection window - List A (L_A). The selection window is bounded by T_1 and $T2$ ($\leq PDB$), which varies according to QoS requirements of each packet. A re-selection counter (RC) is used to determine the future busy slots L_{busy}. Lines 4–7 find out the potential pre-occupied slots (L_{busy}) based on the chosen RC and the resource reservation period (*rsvp*) of each slot of S_D. Line 9 extracts a list of free resources (L_B) by eliminating L_{busy} from L_A. Further deletion of slots from L_B is done based on Reference Signal Received Power Threshold ($RSRP_{Th}$). The SPS algorithm checks if the obtained number of resources is greater than or equal to 20% of the total resources in the initial selection window (L_A). Otherwise, the $RSRP_{Th}$ is increased by 3 dBm and the process is repeated. This is explained in Lines 8–16.

2.2. Intelligent transport system messages

Intelligent Transport System (ITS) messages can be broadly classified into two categories: CAM and DENM supporting Cooperative Awareness Basic Service and Decentralized Environmental Notification Basic Service, respectively. In this subsection we provide a detailed overview of CAM and DENM messages along with their format and fields [4,5].

- **Cooperative Awareness Message (CAM):** CAMs have been standardized in 3GPP Release 15 to support basic safety and traffic-awareness use cases. The CAM messages are fixed-sized packets transmitted periodically at a frequency of 10 Hz. The packet structure of a CAM message is given in Fig. 1. These packets enclose key parameters like vehicle ID, type and role in the road traffic, length, width, position, speed, heading angle, lateral and vertical acceleration, etc. to provide context-awareness to nearby vehicles using broadcast communication.

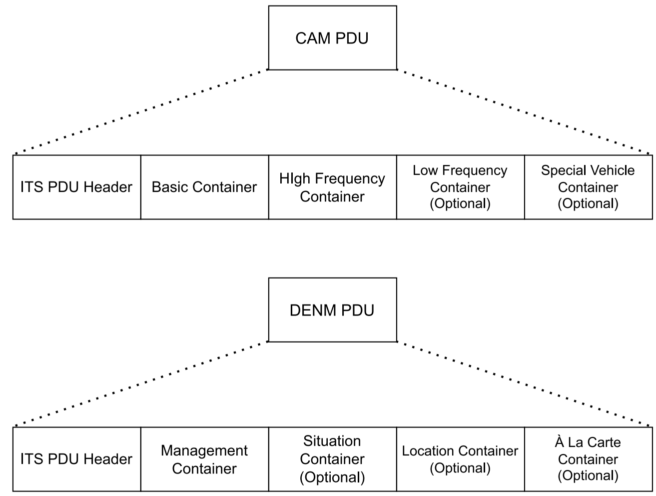

Fig. 1. Packet formats of CAM and DENM messages.

- **Decentralized Environmental Notification Message (DENM):** Subsequent enhancements in Releases 16 and 17 brought in progressive V2X use case groups where periodic messages alone are not sufficient. As per 3GPP Release 16 [15] and Alalewi et al. [16], the advanced use case groups require a latency between 3–100 ms and reliability of a minimum of 90%. It demanded new techniques to tackle the application traffic with messages exhibiting aperiodic arrival rates with variable packet sizes that require stricter latency and higher reliability [5]. The packet structure of a DENM message is given in Fig. 1. These aperiodic messages are event-triggered, indicating sudden environmental changes like Collision Risk Warning, Cooperative Collision Avoidance, Pre- or Post-Crash Warning, Road Hazard Signaling, etc. Due to their higher impact on maintaining road safety and increasing awareness of the driver, these messages must be quickly disseminated over the relevant geographical regions. The DENM messages can have different priorities based on the type of event that triggered its generation. However, without the loss of generality, a DENM message transmission takes precedence over a CAM message. In the interest of increasing the reliability of such messages, ETSI [5] stated the support of re-transmissions from the originating VUE over a certain period of time called repetition duration (corresponds to the PDB) at equally spaced repetition intervals. For example, repetition 0 indicates that the DENM packet is sent only once. Similarly, repetition 1 indicates the transmission of the original DENM plus one of its copies and so on. The following equation represents the generalization.

$$Repetition\ \phi = Original\ \ DENM + \phi\ copy(s) \tag{1}$$

where ϕ varies as, $0 \leq \phi \leq 3$.

3. Related work

The legacy MAC protocol was designed to work on the assumption of periodic packet transmission patterns. Once a VUE selects a resource, it is reserved and re-used RC times for a fixed RRI. This lets other VUEs be informed about the free radio resources available. Release 16 introduced use cases dealing with large variable packet sizes with aperiodic arrival rates (DENMs). In 2018, Lorenzo and Maria [17] were the first to substantiate the feasibility of multi-hop dissemination of DENMs carrying alert notifications via C-V2V and study the latency. However, the aperiodic traffic patterns based on the models reported in the 3GPP guidelines [7] were not taken care of. The vehicles sent DENM only once over the simulation duration, as reliability was not the primary

Table 1
Positioning of our work among recent similar existing research works.

Reference	Area of contribution					
	Can each VUE Tx both CAM+DENM?	Is 3GPP aperiodicty followed?	Do DENMs have variable size?	Is Repetitions of DENM considered?	Is SCI unmodified?	Has E2E latency been considered?
[17]	✓	✗	✗	✓	✓	✓
[18]	✗	✓	✗	✗	✗	✗
[20]	✗	✗	✗	✗	✗	✗
[21]	✗	✗	✗	✓	✗	✗
[22]	✓	✗	✗	✓	✓	✗
[23]	✓	✗	✗	✓	✗	✗
[24]	✓	✗	✗	✓	✓	✗
[25]	✗	✓	✓	✗	✓	✗
[26]	✗	✓	✓	✗	✓	✗
Our work	✓	✓	✓	✓	✓	✓

concern. In their next work in 2022 [18], they brought heterogeneity at the network level, a more realistic scenario, by incorporating the 3GPP periodic and aperiodic traffic model patterns. A vehicle could either transmit a CAM or DENM. They studied the effect on CAM by varying the percentage of VUEs sending out DENM. To sustain DENM transmission in SPS, the authors modified the standard SCI to send RC = 0 in SCI to prevent neighboring VUEs from being deceived with the information of resources being reserved from past history. The limitation of their work is that in real-time, every vehicle must be capable of sending CAM/DENM as per its need, and an additional field in SCI had to be injected to serve the scheduling of CAM and DENM together. The authors in [19], call attention to the unutilized resources that are reserved by SPS when one tries to schedule the aperiodic CAMs using SPS. The aperiodic CAMs are variable-sized packets ranging from 200–1200 B generated aperiodically compliant to 3GPP traffic model with the same PDB as CAMs i.e. 100 ms. They employed a method called "Split and Transmit the Aperiodic CAMs into Periodic CAMS" where a larger-sized CAM packet would be split into chunks and sent at an increased transmission rate. The transmission rate is set based on the channel congestion and occupancy ratio given by a deep reinforcement learning algorithm to minimize the age of information. This method of handling the aperiodic CAMs is not applicable for DENMs which are of greater priority and need to be scheduled immediately whenever we find a free slot instead of waiting for the reservation. They focused on reducing the Age of Information of aperiodic CAMs by fragmenting the larger-sized packets. However, this method cannot guarantee a lower E2E latency which is of utmost priority, as if one of the fragments is lost, it would increase the latency. In contrast, we introduce random fit slot selection in this work to ensure that we select a CSSR that fits the TB completely to reduce fragmentation and thereby E2E latency of DENMs.

Claudia Campolo et al. through their series of investigations in [20–24,27] have studied and analyzed the effect of supporting DENM transmissions in coexistence with CAM at the vehicular level as well as network level. They implemented various methods like Re-Evaluation, Maximum Ratio Combining, short-term sensing with variable selection window, and Random Resource Selection. They varied the number of repetitions, etc, to check the effect in terms of PRR, signal strength, etc. However, they ignored the aperiodic traffic generation model for DENM transmission as specified by 3GPP and its vulnerability to being received within a specific time period. The DENM sizes were fixed to the size of CAM (300 B). The main problem of resource management arises when larger-sized DENMs (800–1200 B), as defined by 3GPP [7], do not fit resources sufficient for CAM. The work in [25] brings up the instability of 5G-NR V2X mode 2 when transmitting aperiodic traffic with variable packet size using SPS. These instabilities reduce the PRR and increase packet collisions concerning scenarios where vehicles generate packets periodically. It further calls for enhancements in MAC of 5G NR V2X mode-2 to handle packet generation and size variability efficiently. The study in [8] concludes the importance of designing more effective dedicated aperiodic scheduling mechanisms that either work in conjunction with existing legacy SPS scheduling or as a standalone approach. The need for prioritizing packets based on message type and requirements instead of a VUE as a whole as in [28] has also been solved through our current research work. Another recent work [26] in the domain of NR-V2X mode 2, examines SPS and dynamic scheduling (DS) schemes where a vehicle trigger a resource reselection for every generated message and do not reserve any resources for future transmissions. A meticulous evaluation is conducted on the behavior of vehicles in terms of Packet Reception Rate (PRR) as a function of transmitter and receiver distance under different PDBs in four single traffic scenario cases where all vehicles perform SPS and the other with DS for periodic and aperiodic traffic separately. Next, they proposed a mixed traffic scenario with adaptive scheduling (AS) that allows vehicles to select the scheduling scheme that best suits their generated traffic type. So a vehicle has to select SPS or DS and showed that AS achieved better PRR than the other four cases. However, it does not provide the flexibility of a single vehicle generating both kinds of traffic. Our paper offers a solution at the level of the MAC layer, where the scheduler has the freedom to schedule a packet immediately or on reservation based on its characteristic (CAM or DENM). The DENM packets are scheduled immediately when a free slot is found and in the worst case can take up the slot reserved for it by SRS if it does not find a free slot. This ensures that we meet the latency constraints of DENMs and reduce the packet collision as much as possible.

Table 1 summarizes the recent research on the co-existence of CAM and DENM and their fall-through addressed by our paper. Compared to these prior works, in this work, we propose a detailed and evolved MAC protocol to support joint sidelink scheduling empowering each VUE with the capability of transmitting both periodic CAM and situation-driven DENM messages. The proposed protocol could drastically reduce the E2E latency without compromising reliability in strict compliance with 3GPP standards.

4. System model

We consider a road network highway scenario having m lanes and n vehicles in each lane as shown in Fig. 2. Each vehicle has a sidelink NR-V2X module which assists in traffic safety and awareness services. The vehicles within a single collision domain are in awareness range of R meters and are running from East to West on m lanes with a variable speed. The inter-lane distance is X meters. The Inter Vehicular Distance, IVD (K) is varied based on different traffic density scenario to generate multiple collision domain in V2X communications.

In a single collision domain one time-frequency resource — Candidate Single-Subframe Resource (CSSR) can be used by only one vehicle

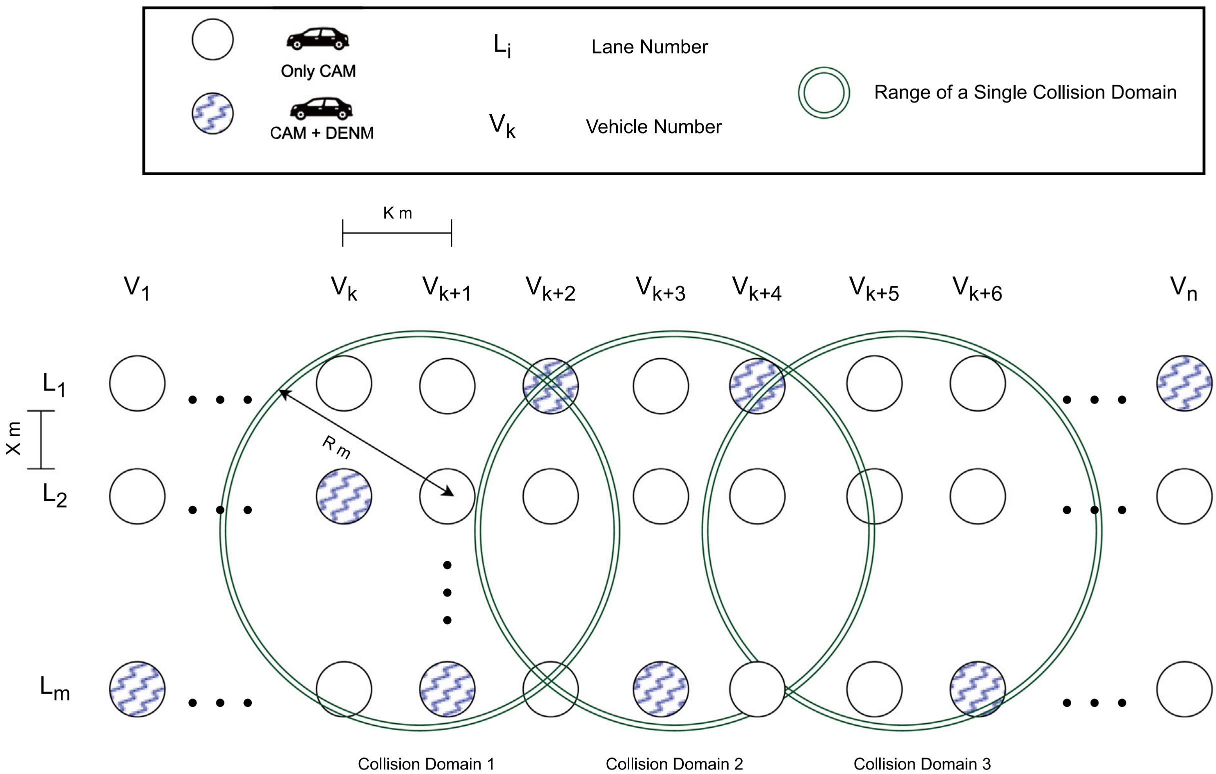

Fig. 2. System model.

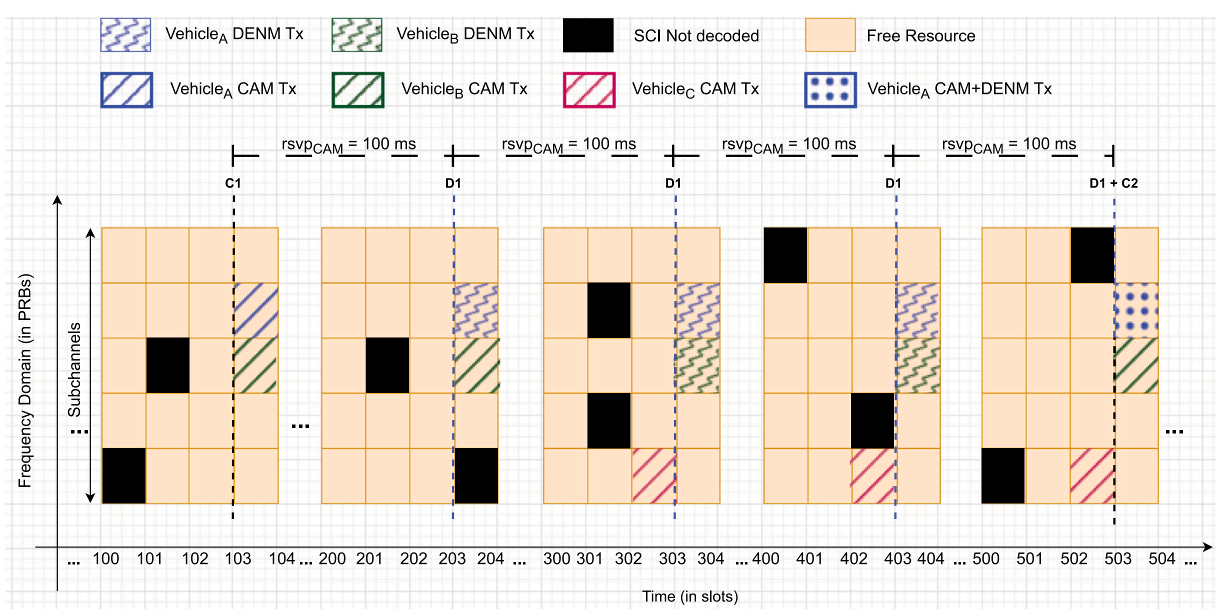

Fig. 3. Legacy resource allocation diagram for CAMs and DENMs.

at any instant of time. All the vehicles transmit CAM at regular intervals given by RRI, to exchange location information and a certain percentage of vehicles also transmit event-triggered DENM aperiodically. The traffic generation model for periodic and aperiodic traffic has been explained in Section 7.1. The percentage of vehicles transmitting both CAM and DENM, denoted by Δ, has been varied. The positions of such vehicles (denoted by circles having blue zigzag line) have been uniformly distributed across the given scenario. The DENMs are also repeated ϕ number of times to ensure reliable transmission as defined in Eq. (1). Our work assists the vehicles in need of DENM transmission to send DENM packets as quickly as possible and also choosing a high quality CSSR.

5. Motivation

The legacy MAC scheduler cannot cater to the QoS requirements of different ITS messages. Thus it is unable to differentiate between CAM and DENM traffic coming from application layer. It uses only one sidelink bearer with a single RLC entity to queue all the sidelink packets. The working of the legacy MAC layer protocol comprising of

Algorithm 2: Legacy MAC Protocol

Input : Current Slot *sfn*, $SensingData\ S_D$, Grant List G, $rsvp_{CAM}$
Output: Updated Grant List G

1 $Set\ T_1 = 2, T_2 \leq PDB_{CAM}$
2 **if** $G = \Phi$ **then**
3 $RC \leftarrow random\,[5, 15]$
4 $L_B \leftarrow Semi-PersistentScheduling(sfn, S_D, T_1, T_2, RC)$
5 **if** $RLC_{Buffer} \neq \Phi$ **then**
6 $R \leftarrow$ $Req\ Number\ of\ Subchannels(S_{ch})\ to\ satisfy\ the\ RLC_{Buffer}$
7 $s \leftarrow Choose\ a\ slot\ randomly\ from\ L_B$
8 $cssr \leftarrow \{i \mid 1 \leq i \leq N, i \in \mathbb{N}, (|S| - R)_{min}\}\ where\ S = \{S_i, S_{i+1}, .., S_{i+k}\}\ are\ contiguous\ free\ S_{ch}\ in\ s\ and\ N = Number\ of\ S_{ch}$
9 $G \leftarrow G \cup \{cssr, cssr + (rsvp_{CAM} \times 1), .., cssr + (rsvp_{CAM} \times RC)\}$
10 **else**
11 break
12 $Send\ data\ using\ G$
13 $Delete\ used\ grant\ from\ G$
14 *return* G

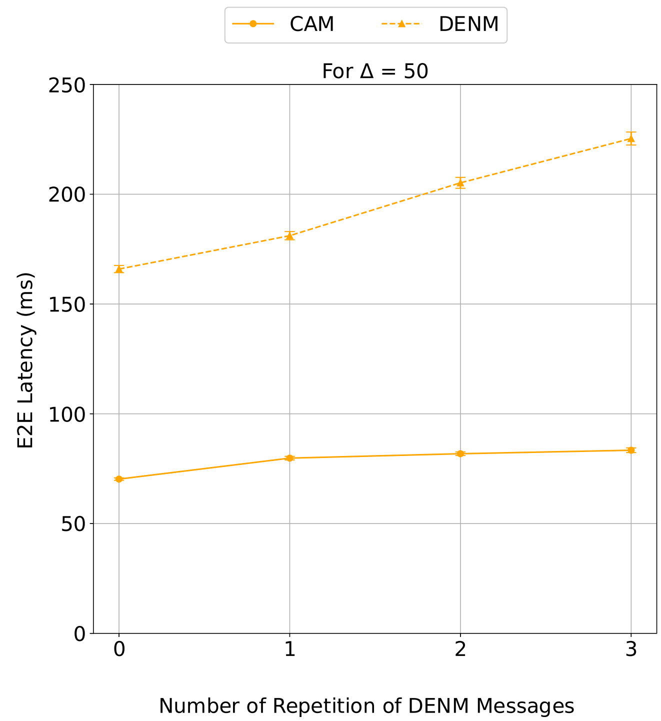

Fig. 4. Latency trends for DENMs and CAM.

SPS is described in Algorithm 2. At every subframe (*sfn*), the MAC scheduler is invoked to update the scheduling grants based on Sensing Information (S_D). When a vehicle senses the channel for the first time and no transmission is scheduled (i.e $G = \Phi$, Line 2), it performs SPS [1] to get the list of available resources (L_B) at *sfn* as in Line 4 using RC chosen from a uniform random distribution [5, 15] [1]. Lines [5–9] process data packets from the upper layer that get stored in the RLC_{Buffer}. The MAC scheduler picks up the data and calculates the number of Subchannels (S_{ch}), R required to satisfy it. Next, a free subframe (s) from L_B with equal probability is chosen. A contiguous sequence of S_{ch} (S) in s is picked such that $|S| - R$ is minimized and defined as $cssr$. A grant list (G) is generated based on $cssr$ using $rsvp_{CAM}$ and RC. The MAC scheduler checks next subframe if the RLC_{Buffer} is empty as in Line 11. Also, if there were pre-scheduled grants in G, then data would have been transmitted using the existing grants directly as per Line 12.

5.1. Packet inter-transmission time analysis

A mathematical representation of packet inter-transmission time in the case of legacy MAC protocol for CAMs is shown below:

The delay from application layer to RLC layer is denoted as follows: The application, SDAP, PDCP, RLC and scheduling delays can be represented as $\Delta_{App}, \Delta_{SDAP}, \Delta_{PDCP}, \Delta_{RLC}, and\ \Delta_{sch}$, respectively. The queueing delay at RLC layer is not considered as a vehicle is guaranteed to get a free resource in its selection window, assuming sufficient availability of channel resources. A packet is generated at t_C. The time at which the packet generated at t_C is ready for transmission over the air interface is defined as C_i.

$$
\begin{aligned}
C_i &= t_C + \Delta_{App} + \Delta_{SDAP} + \Delta_{PDCP} + \Delta_{RLC} + \Delta_{sch} \\
&= t_C + X + k_C
\end{aligned}
\tag{2}
$$

where $k_C = \Delta_{sch}$, $T_1 \leq \Delta_{sch} \leq T_2$ and $X = \Delta_{App} + \Delta_{SDAP} + \Delta_{PDCP} + \Delta_{RLC}$. CAM packets are generated every 100 ms apart. Thus the next packet is ready for transmission at time C_{i+1} given by,

$$
\begin{aligned}
C_{i+1} &= t_C + 100 + \Delta_{App} + \Delta_{SDAP} + \Delta_{PDCP} + \Delta_{RLC} + \Delta_{sch} \\
&= t_C + 100 + X + k_C \\
&= C_i + 100
\end{aligned}
\tag{3}
$$

From Eqs. (2) and (3) Δ_{sch} is same due to future reservation by CAMs [Algorithm 2: Line 9]. Thus inter-packet transmission time between C_{i+1} and C_i,

$$\boxed{C_{i+1} = C_i + 100\ \text{ms}} \tag{4}$$

Hence for two consecutive packets the application layer delay propagates to scheduling delay.

5.2. Illustrative example

In the illustrative example shown in Fig. 3, three vehicles - A, B and C are transmitting CAMs. $Vehicle_A$ and $Vehicle_B$ are also transmitting DENMs. $Vehicle_A$ has scheduled its first transmission C_1 at subframe 103 and as a result resources at periodic interval of 100 subframes are reserved for future transmission at 203, 303, 403, 503 subframes. Refer to Table 2 for a detailed event description timeline. A DENM packet (D_1) of size 1000 B is generated in between the CAM transmission and is queued into the RLC Buffer. The MAC unaware of this sudden arrival of the DENM, fragments the DENM to fit the CSSR reserved for CAM and schedules it at subframe 203. The consecutive DENM fragments get further scheduled 100 subframes apart. This adds up to increased delay of DENM as well as delaying the transmission of CAMs. Finally, the first DENM packet gets scheduled completely at subframe 503 with a delay of 324 subframes. The DENM repetition packets (D_2, D_3, D_4) along with the future CAMs stay queued up in the RLC Buffer. This can also be observed in the state-of-the-art result Fig. 4 on the performance of E2E delay of CAM and DENM using legacy MAC scheduler. The CAM suffers a latency of 65 ms and the latency of DENM alarmingly reaches to 225 ms with three repetitions.

6. Latency aware MAC protocol (LAMP)

We first present an overview of *LAMP* supporting the QoS requirements of mixed traffic. The algorithmic flow of *LAMP* has been described in Section 6.4 followed by a resource allocation diagram of CAM and DENM paired with event description timeline in Section 6.5.

Table 2
Event time table for legacy MAC protocol corresponding to Fig. 3

Steps	Analytical time	In example time	Event
1	t_C	90	$CAM(C_1)$ generated
2	$t_C + X$	93	C_1 at RLC
3	$t_C + X + k_C$	103	C_1 scheduled
4	t_{D1}	179	$DENM(D_1)$ generated
5	$t_{D1} + X$	182	D_1 at RLC
6	$t_C + 100$	190	C_2 generated
7	$t_C + 100 + X$	193	C_2 at RLC
8	$t_{D2} = t_{D1} + 20$	199	D_2 generated
9	$t_{D2} + X$	202	D_2 at RLC
10	$t_C + X + k_C + 100$	203	Part of D_1 scheduled
11	$t_{D3} = t_{D2} + 20$	219	D_3 generated
12	$t_{D3} + X$	222	D_3 at RLC
13	$t_{D4} = t_{D3} + 20$	239	D_4 generated
14	$t_{D4} + X$	242	D_4 at RLC
15	$t_C + 200$	290	C_3 generated
16	$t_C + 200 + X$	293	C_3 at RLC
17	$t_C + 200 + X + k_C$	303	Part of D_1 scheduled
18	$t_C + 300$	390	C_4 generated
19	$t_C + 300 + X$	393	C_4 at RLC
20	$t_C + 300 + X + k_C$	403	Part of D1 scheduled
21	$t_C + 400$	490	C_5 generated
22	$t_C + 400 + X$	493	C_5 at RLC
23	$t_C + 400 + X + k_C$	503	Part of D1 scheduled + Part of C_2 scheduled

*The cumulative delay of App, SDAP, PDCP, RLC layer(X) is considered to be 3 subframes.

The *LAMP* functions as a congregation of three schemes - Semi-Reservation Scheme (SRS), DENM aware slot selection and buffer selection schemes to support joint sidelink scheduling of CAM and DENMs efficiently. We propose two RLC-entity serving two traffic flow patterns for periodic (CAM) and aperiodic (DENM) traffic. The SDAP layer provides the mapping service in the user plane between the application layer data into SL Data Radio Bearer (SL-DRB). We thus now have two RLC entities, one dedicated to handling the aperiodic traffic flows (DENM buffer). In contrast, the other will handle the periodic flows (CAM buffer) as shown in Fig. 5. The three schemes have been described as follows:

6.1. Semi-Reservation Scheme (SRS)

When a DENM packet and its repetition are scheduled by LAMP scheduler (t_{D1}), the SCI field in Physical Sidelink Control Channel (PSCCH) contains $rsvp_{DENM}(= T_2)$ to inform the reservation of the physical channel resource. The neighboring vehicles are aware of the occupancy of the resource by same vehicle after $rsvp_{DENM}$. This guarantees the availability of a resource at $t_{D1}+rsvp_{DENM}$. However, LAMP scheduler does not create a grant giving the next DENM repetition freedom to select a better resource before the reserved slot as perceived by the other vehicles. This benefits the next DENM repetition (D_2) in two ways-

- It is ensured that D_2 will have $t_{D1} + T_2$ available for its transmission.
- Since, no reservation was actually made for D_2, it is flexible to choose any resource between the range $t_{D1} + T_1 \text{ to } t_{D1} + T_2$.

Inter-Packet Transmission Time Analysis:

A mathematical representation of packet inter-transmission time done by LAMP for DENMs is shown below:

The delay from application layer to RLC layer is denoted as follows: The application, SDAP, PDCP, RLC and scheduling delays are represented as $\Delta_{App}, \Delta_{SDAP}, \Delta_{PDCP}, \Delta_{RLC}, \Delta_{sch}$ respectively. The packet is generated at t_D. The total delay for a packet generated at t_D across all layers can be defined as D_i.

$$\begin{aligned} D_1 &= t_{D_1} + \Delta_{App} + \Delta_{SDAP} + \Delta_{PDCP} + \Delta_{RLC} + \Delta_{sch} \\ &= t_{D_1} + X + k_{D_1} \end{aligned} \tag{5}$$

where $k_{D_1} = \Delta_{sch}$, $T_1 \le \Delta_{sch} \le T_2$ and $X = \Delta_{App} + \Delta_{SDAP} + \Delta_{PDCP} + \Delta_{RLC}$

DENMs are generated every 20 ms with repetition. Thus the next packet is ready to be transmitted at,

$$\begin{aligned} D_2 &= t_{D_1} + 20 + \Delta_{App} + \Delta_{SDAP} + \Delta_{PDCP} + \Delta_{RLC} + \Delta_{sch} \\ &= t_{D_1} + 20 + X + k_{D_2} \end{aligned} \tag{6}$$

Generalizing Eqs. (5) and (6),

$$D_i = t_{D_i} + 20 \times (i-1) + X + k_{D_i} \tag{7}$$

Similarly,

$$D_{i+1} = t_{D_i} + 20 \times i + X + k_{D_{i+1}} \tag{8}$$

Subtracting Eq. (7) from Eq. (8),

$$\begin{aligned} D_{i+1} - D_i &= t_{D_i} + 20 \times i + X + k_{D_{i+1}} - t_{D_i} - 20 \times (i-1) - X - k_{D_i} \\ &= 20 + (k_{D_{i+1}} - k_{D_i}) \\ &= 20 + \delta \end{aligned} \tag{9}$$

where $\delta_{min} = -18$ and $\delta_{max} = 18$. From Eq. (9) we can conclude,

$$D_i + 2 \text{ ms} \le D_{i+1} \le D_i + 38 \text{ ms} \tag{10}$$

As we are using SRS, there will always be a resource available at D_i+20 for $(i+1)^{th}$ packet. Therefore, the effective range of resource selection for DENM packets will be:

$$\boxed{D_i + 2 \text{ ms} \le D_{i+1} \le D_i + 20 \text{ ms}} \tag{11}$$

Therefore, we are saving 18 subframes of time using SRS as compared to legacy MAC scheme.

6.2. Slot selection module

The legacy MAC scheduler checks the buffer requirement for contiguous S_{ch} occupancy after selecting a subframe randomly from L_B. This might deprive the legacy MAC scheduler of a better subframe which could have satisfied the entire data requirement based on the availability of free contiguous S_{ch} leading to DENM fragmentation. Thus, our LAMP scheduler chooses a subframe based on the availability of contiguous free S_{ch} that can fulfill the buffer requirements at best so as to minimize the fragmentation of packets. The DENM aware slot selection scheme — Random Fit Algorithm 3 described above takes $List_B$ and the number of required S_{ch}(R) as input and returns the subframes which satisfies R. Lines 2–5 filter out the subframes that cannot satisfy R from L_B.

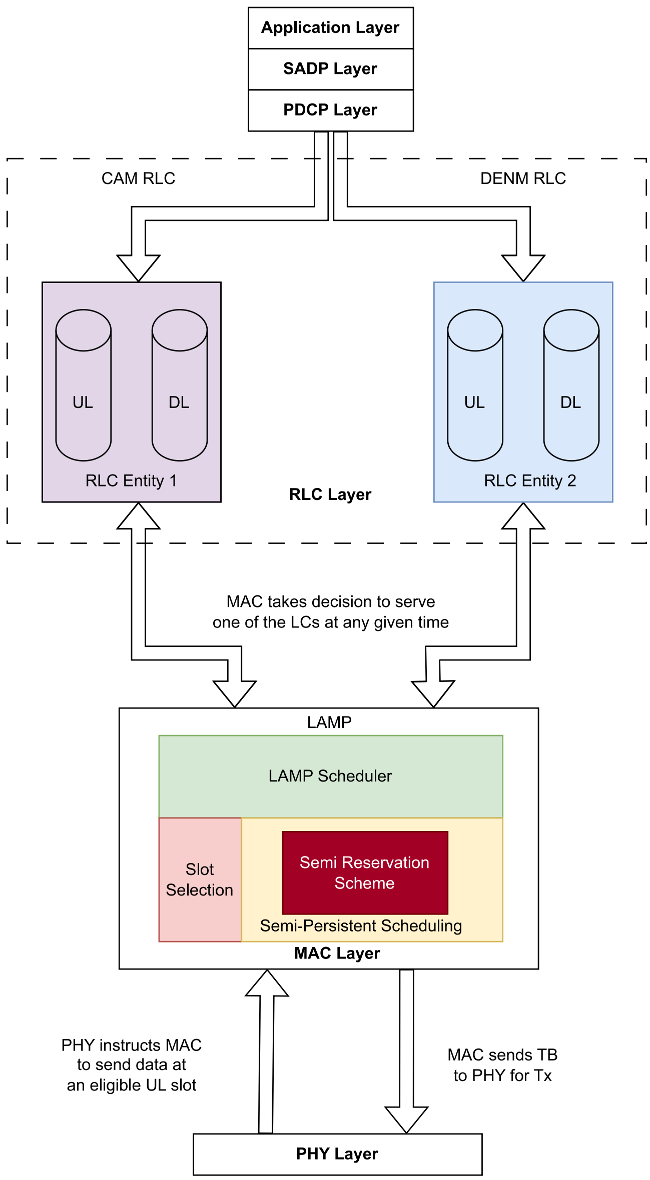

Fig. 5. Proposed architecture representing two separate PDCP-RLC stacks to jointly schedule CAM and DENM efficiently.

Algorithm 3: Random Fit Slot Selection

Input : $ListB\ L_B$, $Number\ of\ Required\ S_{ch}\ R$
Output: $Updated\ ListB\ L_B$

$L_{max} = \Phi$ // slot with maximum contiguous free S_{ch}
for $l_i \in L_B$ **do**
  if $MaxConsecutiveFreeResources(l_i) < R$ **then**
    $L_{max} = max(MaxConsecutiveFreeResources(l_i))$
    $L_B \leftarrow L_B \setminus l_i$
if $L_B = \Phi$ **then**
  return L_{max}
else
  return L_B

6.3. Buffer selection

At RLC layer, we have two RLC entities to segregate mixed traffic flows — periodic CAM and aperiodic DENM into low priority RLC_{CAM} Buffer and high priority RLC_{DENM} Buffer as in Fig. 5. The MAC scheduler at every subframe checks for the presence of packets in both the buffers and schedules the packet from buffer with higher priority first.

6.4. Pseudocode for LAMP

Algorithm 4: Latency Aware MAC Protocol

Input : Current Slot *sfn*, $Sensing Data\ S_D$, Grant List G, $rsvp_{CAM}$, $rsvp_{DENM}$
Output: Updated Grant List G

Set $T_1 = 2,\ T_{2,CAM} \le PDB_{CAM},\ T_{2,DENM} \le PDB_{DENM}$
$RC_{CAM} \leftarrow random[5, 15],\ RC_{DENM} \leftarrow 1$
if $G = \Phi$ **then**
  $L_B \leftarrow Semi-PersistentScheduling(sfn, S_D, T_1, T_{2,CAM}, RC_{CAM})$
  if $RLC_{DENM} \ne \Phi$ **then**
    $L_B \leftarrow L_B \setminus \left\{ l_i \in L_B \mid \left| l_{i,sfn} - sfn \right| > PDB_{DENM} \right\}$ // $l_{i,sfn}$ is slot no. of l_i
    $R \leftarrow Req\ Number\ of\ Subchannels(S_{ch})\ to\ satisfy\ the\ RLC_{DENM}$
    $s \leftarrow Random\ Fit\ Slot\ Selection(L_B, R)$
    $cssr \leftarrow \{ i \mid 1 \le i \le N, i \in \mathbb{N}, (|S| - R)_{min} \}$ *where* $S = \{ S_i, S_{i+1}, .., S_{i+k} \}$ *are contiguous free* S_{ch} *in s and* $N = Number\ of\ S_{ch}$
    $G \leftarrow G \cup \{cssr\}$
  else
    if $RLC_{CAM} \ne \Phi$ **then**
      $R \leftarrow Req\ Number\ of\ Subchannels(S_{ch})\ to\ satisfy\ the\ RLC_{CAM}$
      $s \leftarrow Random\ Fit\ Slot\ Selection(L_B, R)$
      $cssr \leftarrow \{ i \mid 1 \le i \le N, i \in \mathbb{N}, (|S| - R)_{min} \}$ *where* $S = \{ S_i, S_{i+1}, .., S_{i+k} \}$ *are contiguous free* S_{ch} *in s and* $N = Number\ of\ S_{ch}$
      $G \leftarrow G \cup \{ cssr, cssr + (rsvp_{CAM} \times 1), .., cssr + (rsvp_{CAM} \times RC_{CAM}) \}$
    else
      Exit
else
  // Create Grant for DENM and append into G by insertion sort when RLC_{DENM} is non-empty
  $L_B \leftarrow Semi-PersistentScheduling(sfn, S_D, T_1, T_{2,DENM}, RC_{DENM})$
  if $RLC_{DENM} \ne \Phi$ **then**
    $R \leftarrow Req\ Number\ of\ Subchannels(S_{ch})\ to\ satisfy\ the\ RLC_{DENM}$
    $s \leftarrow Random\ Fit\ Slot\ Selection(L_B, R)$
    $cssr \leftarrow \{ i \mid 1 \le i \le N, i \in \mathbb{N}, (|S| - R)_{min} \}$ *where* $S = \{ S_i, S_{i+1}, .., S_{i+k} \}$ *are contiguous free* S_{ch} *in s and* $N = Number\ of\ S_{ch}$
    $G \leftarrow G \cup \{cssr\}$ // cssr inserted in sorted way based on slot no.
Send data using G
Delete used grant from G
return G

The PHY layer triggers MAC at every eligible sidelink subframe given by TDD pattern and bit map, and the MAC schedules a packet

Table 3
Detailed time and event diagram with respect to Fig. 6.

Steps	Analytical time	In example time	Event
1	t_C	90	$CAM(C_1)$ $generated$
2	$t_C + X + k_C$	103	C_1 $scheduled$
3	t_{D1}	179	$DENM(D_1)$ $generated$
4	$t_C + 100$	190	C_2 $generated$
5	$t_{D2} = t_{D1} + 20$	199	D_2 $generated$
6	$t_{D1} + X + k_{D1}$	202	D_1 $scheduled$
7	$t_C + X + k_C + 100$	203	C_2 $scheduled$
8	$t_{D3} = t_{D1} + 40$	219	D_3 $generated$
9	$t_{D2} + X + k_{D2}$	220	D_2 $scheduled$
10	$t_{D3} + X + k_{D3}$	228	D_3 $scheduled$
11	$t_{D4} = t_{D1} + 60$	239	D_4 $generated$
12	$t_{D4} + X + k_{D4}$	248	D_4 $scheduled$
13	$t_C + 200$	290	C_3 $generated$
14	$t_C + 200 + X + k_C$	303	C_3 $scheduled$

transmission based on the grant list. An empty grant list indicates that the vehicle has no packet scheduled for transmission [Algorithm 4: Line 3]. The MAC performs SPS to aggregate the available resources for scheduling packets from RLC_{CAM} Buffer and RLC_{DENM} Buffer. The higher priority RLC_{DENM} Buffer is scheduled first for transmission using a filtered set of resources from L_B such that it satisfies PDB_{DENM} as well as the number of required subchannels (R) as in Lines 6 and 7. Random Fit Slot Selection is applied to this filtered set of resources and a single grant is generated based on the obtained CSSR [Line 8–10]. This single grant with $rsvp_{DENM}$ set in the SCI enables the semi-reservation scheme (SRS) for DENMs as discussed in Section 6.1. By setting RC_{DEMN} as 1, we ensure that we are granting freedom to the source VUE to choose a better resource within the PDB$_{DENM}$. At the same time, in the worst case, there is a resource available for the source VUE, unoccupied by others. The MAC is well aware of the arrival of DENM packets by repeatedly checking the RLC_{DENM} Buffer at every subframe, even when packets are pre-scheduled for transmission. In case of an existing grant list, Lines 21–26 merge the single grant to the pre-scheduled grant list. Between transmitting two CAM packets, MAC checks if any packet has arrived in the DENM buffer and schedules it immediately. Thus the scheduling of CAM is now done being fully conscious of the fact that DENM packets can arrive at any time, and its scheduling must be done straight away. This ensures we prioritize the time-sensitive DENM packets.

If there is no data packets waiting to be serviced in RLC_{DENM}, the MAC scheduler checks for the presence of data in RLC_{CAM}. A CSSR is obtained using Random Fit Slot selection satisfying PDB_{CAM} and R. Based on the CSSR obtained, a grant list is generated using RC_{CAM} and $rsvp_{CAM}$ [Lines 13–16].

6.5. Illustrative example

In LAMP resource allocation diagram shown in Fig. 6, three vehicles - A, B, and C are transmitting CAMs. $Vehicle_A$ and $Vehicle_B$ are also transmitting DENMs. $Vehicle_A$ has scheduled its first transmission C_1 at subframe 103 and as a result resources at periodic interval of 100 subframes are reserved for future transmission at 203, 303, 403, and 503 subframes. Refer to Table 3 for a detailed event description timeline. A DENM packet (D_1) of size 1000 B is generated in between the CAM transmissions is queued into the RLC Buffer at 182 subframe and then chooses K_{D_1} as 17 according to Eq. (5) and gets scheduled at subframe 202. Similarly, the next DENM (D_2) gets generated at 199 and scheduled at subframe 220 following Eq. (11). Thus the DENM transmissions do not hamper and occupy the pre-reserved resources of CAM. Following the same pattern, DENMs - D_2, D_3, D_4 get transmitted within PDB_{DENM}.

Table 4
Simulation parameters.

Parameter	Value
Deployment	240 Vehicles (6 Lanes and 40 Vehicles in each Lane)
Traffic density (σ) (Number of VUE/km/lane)	Low: 13.33 Medium: 25 High: 50
Highway length Vehicle speed Simulation time	3000 m [80–100] km/h 20 s
Packet size	CAM: 300 Bytes DENM: As per 3GPP Rel. 15 TR 37.885 [200–1200] Bytes with a Quantization step of 200 Bytes
Transmission interval	CAM: 100 ms DENM: As per 3GPP Rel. 15 TR 37.885 50 ms + an exponential random variable with the mean of 50 ms
Frame structure TDD Pattern SL Bitmap	μ = 0 (SCS = 15 kHz) DL F UL UL UL UL UL UL UL UL 1|1|1|1|1|1|1|1|1|1|1|1|1|1|1|1|1
RSRP Threshold	Min = −128 dBm Max = −80 dBm
MCS Radio reservation interval	14 CAM: 100 ms
Reselection counter	For CAM packets: [5,15] For DENM packets: 0
DENM Repetitions (ϕ) DENM Repetition interval	0, 1, 2, 3 20 ms
Percentage of vehicles sending DENMs (Δ)	10, 25, 50, 100
Carrier frequency Channel bandwidth Number of subchannels Subchannel size PDB$_{CAM}$ PDB$_{DENM}$ Simulation runs	5.89 GHz 10 MHz 5 10 RBs 100 ms 50 ms 20

Table 5
Traffic density setting.

	IVD (in m)	Traffic density (σ)	Number of vehicles in one collision domain
Low	75	13.33	~36
Medium	40	25	~60
High	20	50	~120

7. Experimental setup

To investigate the performance of *LAMP*, we describe the simulation environment in Section 7.1 followed by the description of Key Performance Indicators (KPIs) used for evaluation in Section 7.2. We also have tested LAMP against Dynamic Scheduling (DS) [26], a recent work to handle aperiodic DENMs. We considered no reservation in contrast to our semi-reservation scheme to transmit DENM packets. Our implementation of DS is also supported with a two RLC buffer solution to schedule CAM and DENM packets effectively at per vehicular level, thus ensuring a fair comparison.

7.1. Simulation environment

The proposed enhancements are implemented on the NR V2X Mode-2 (out-of-coverage) module of Network Simulator-3 (NS-3) [29] with a single-hop Highway Scenario as defined in 3GPP TR 37.885 [7] has been considered. There are six lanes, with an inter-lane distance of 4 m. There are 40 VUEs per lane moving at a variable speed between 80 and

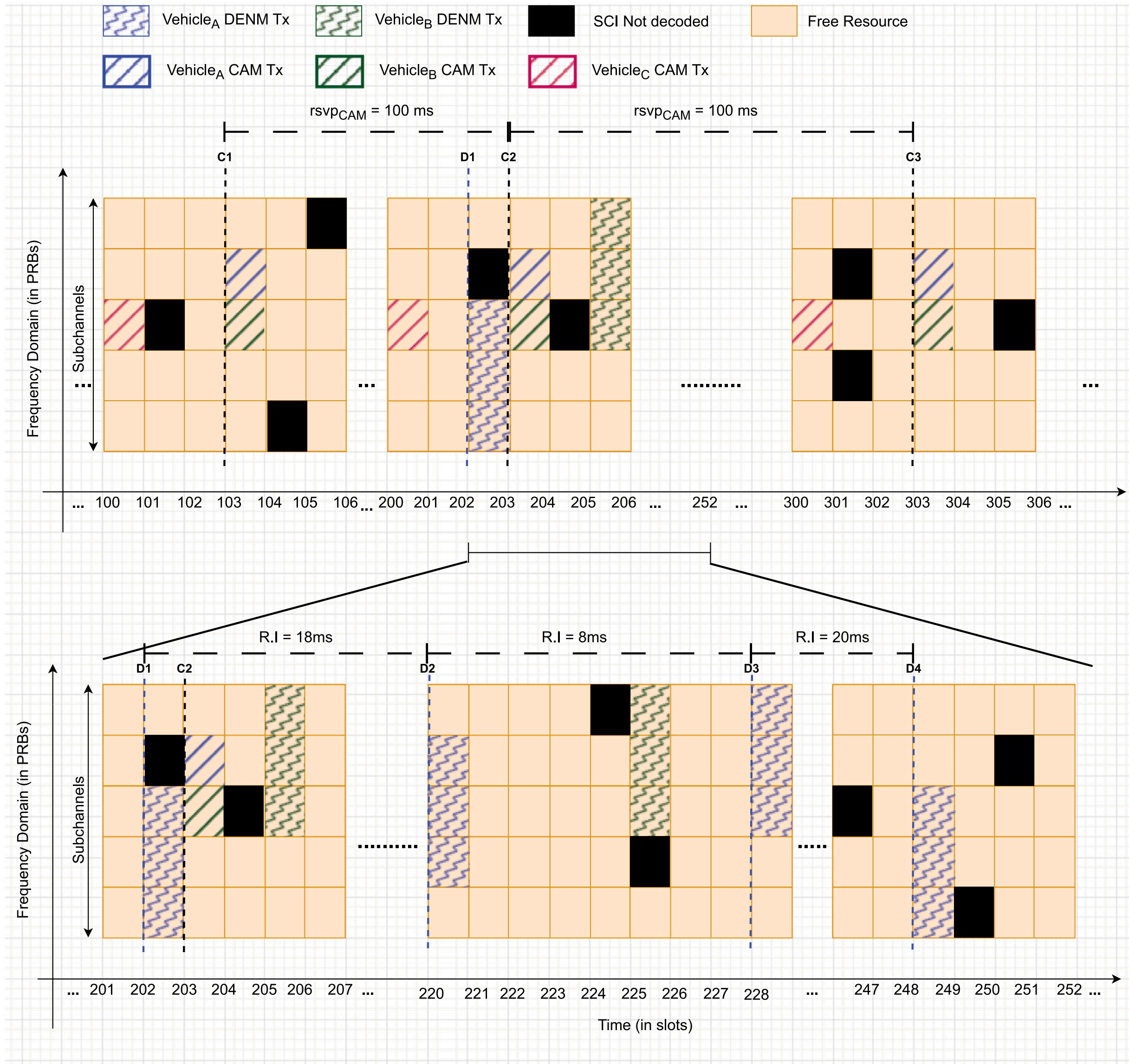

Fig. 6. Resource allocation diagram in LAMP for CAMs and DENMs with respect to Table 3.

100 km/h, replicating a realistic highway scenario spanning over 3.5 km in a simulation run of 20 s. The initial inter-vehicular distance is varied to simulate low, medium, and high density traffic as given in Table 5.

The traffic density(σ) is defined as

$$Traffic\ Density(\sigma) = \frac{No.\ of\ Vehicles}{No.\ of\ lanes \times No.\ of\ \text{km}} \tag{12}$$

Vehicles within an awareness region of 200 m [6] are considered to be neighbors. Packet transmission is done over the 5.9 GHz band, assuming a channel bandwidth of 10 MHz. There are five sub-channels of size 10 RBs each. We consider the TBs to be transmitted with a Transmission Power of 23 dBm and with a Modulation Coding Scheme (MCS) of 14. The experimental parameters can be found in Table 4.

We focus on the co-existence of CAM and DENM at the vehicular level, and hence each vehicle is capable of broadcasting CAM and DENM based on the two models of traffic generation described below:

Periodic Traffic Model: The periodic traffic model sends a 300 B CAM packet at an interval of 100 ms which leads to a data rate of 24 kbit/s.

Aperiodic Traffic Model: The aperiodic traffic model is characterized by the transmission of DENM messages of variable size in the range of [200 – 1200] B, with a 200 B quantization step. The inter-arrival rate is given by: $\tau = c + r$, where c is constant and r is an exponentially distributed random variable as per [7]. The model considers $c = r_{mean} =$ 50 ms where r_{mean} is the mean of the exponential random variable.

7.2. Key performance indicators

The performance of the proposed scheme is evaluated by using the following performance metrics.

- *Packet Reception Rate (PRR):* It is defined as the ratio of the number of vehicles that successfully received the CAM packets of a target vehicle to the total number of neighboring vehicles in its vicinity of 200 m. PRR of a $vehicle_i$ is calculated by averaging the individual ratios for its transmitted CAM packets during the simulation time.

$$PRR_i = \frac{\sum_{j=1}^{M} \frac{Number\ of\ vehicles\ successfully\ received\ CAMs}{Total\ number\ of\ neighbors\ of\ vehicle_i}}{M} \tag{13}$$

where M is the total number of CAM messages transmitted by $vehicle_i, 1 \leq j \leq M$.

- *End-to-End (E2E) latency:* It is the delay the message (CAM/DENM) incurs from the point the message is generated at the

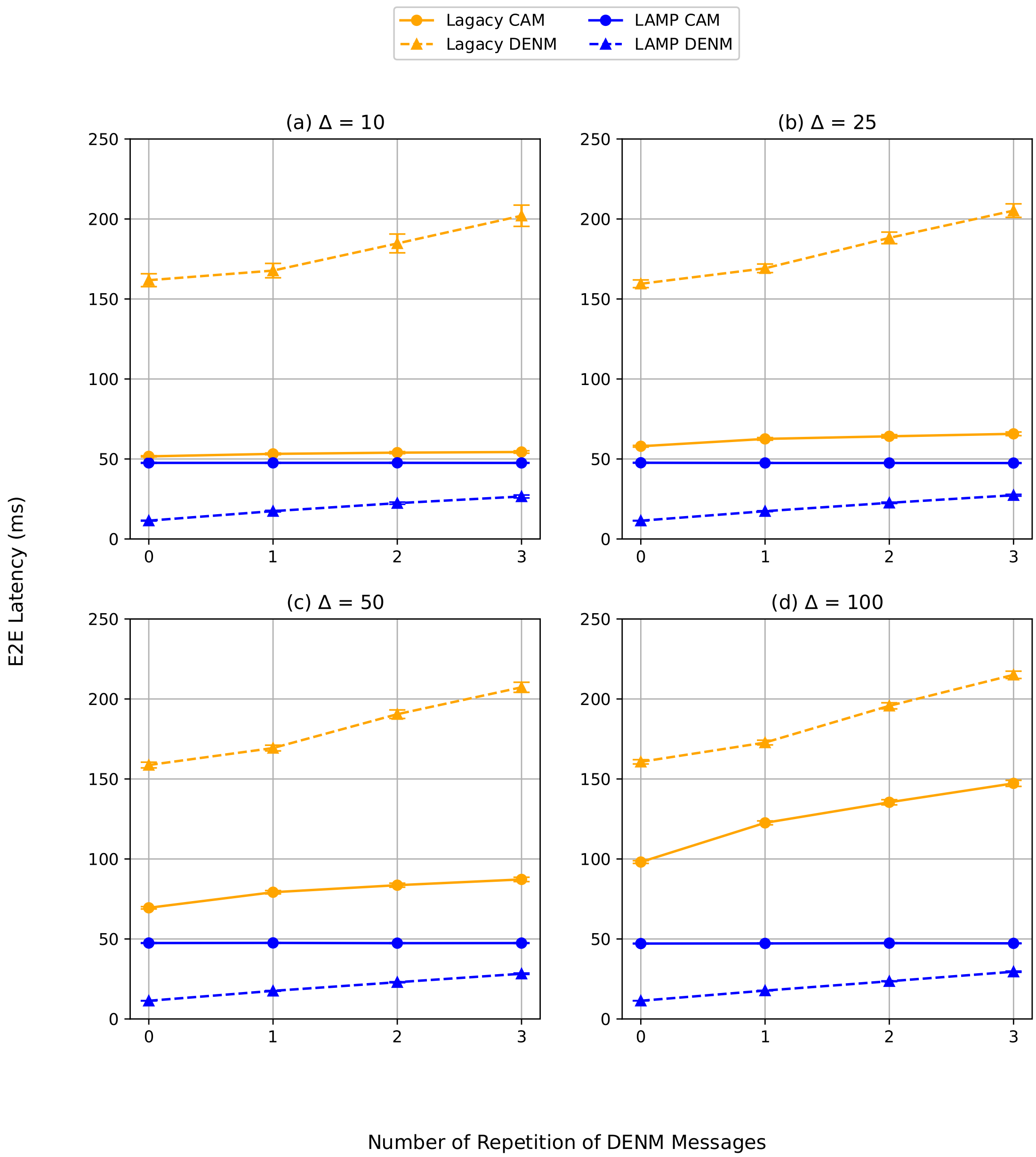

Fig. 7. Variation of E2E latency as a function of number of repetitions for varying % of VUEs sending out DENMs ($\sigma = Low$).

application layer of source VUE up to the point the application layer of receiving VUE correctly receives it. When multiple copies of DENM are sent to increase reliability, the reception of the first DENM packet is considered in calculating the E2E latency.

8. Experimental results

The Sections 8.1 and 8.3 analyze the effect on latency and PRR of *LAMP* versus the legacy system. The frequency analysis of E2E latency of CAM and DENM packets received in legacy versus LAMP is shown in Section 8.2. Section 8.4 validates the PRR results for different vehicular densities as a function of the distance between source VUE and receiving VUE. Next, we compare our LAMP with a recent work [26]. The last Section 8.6 tabularizes the results to highlight the superiority of *LAMP*.

The purpose of the experimentation is to assess and validate the superiority of our scheme through performance analysis of the proposed framework and algorithm to support joint scheduling of CAM and DENM as opposed to the existing scheme. All the VUEs transmit CAM, and a certain percentage of VUEs also transmit DENMs, denoted by Δ. We analyze the performance by varying the number of repetitions (ϕ). It must be noted that each data point in the following graphical representation symbolizes the average of the metric taken over all vehicles with a 95% confidence interval.

8.1. Effect on latency of CAM and DENM

In Fig. 7(a) the legacy system having $\Delta = 10$, with VUEs sending single DENM packets (no repetition), the DENMs suffer a high latency of 153 ms violating the 3GPP latency constraints [30]. The MAC scheduler unable to differentiate CAM and DENM packets fails to satisfy the PDB_{DENM}. To increase the chances of reception of DENM packets, we increase ϕ, improving the reliability as in Fig. 9. The DENM packets which did not have successful reception in their first attempt were received after we sent multiple copies due to which the DENM E2E latency reached as high as 200 ms for $\phi = 3$.

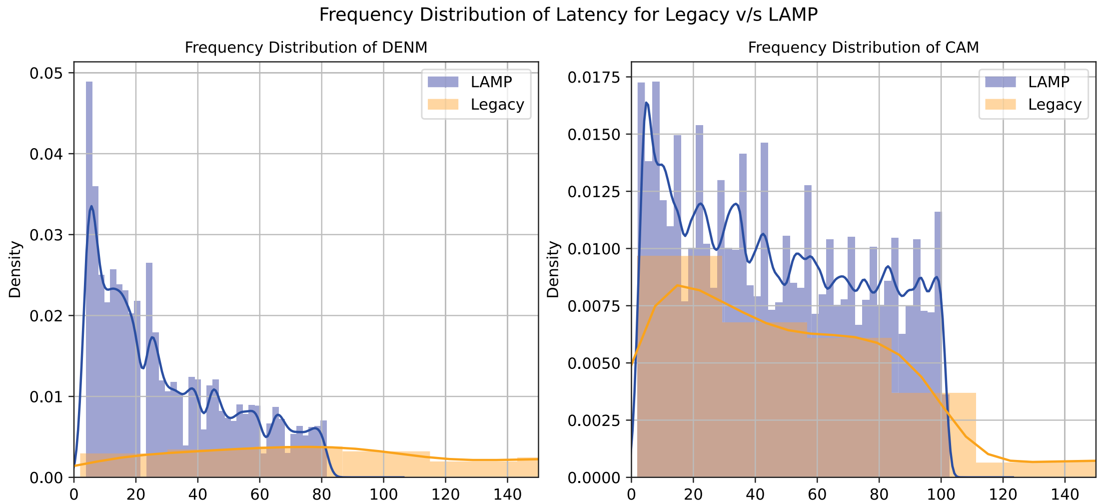

Fig. 8. Comparison of latency distribution for CAMs and DENMs in case of Legacy and LAMP.

The CAM incurs a latency of 50 ms. Interestingly, there is no significant effect on CAM E2E latency with increasing ϕ for $\Delta = 10\%$ *and* 25% as overall effect on CAM latency is suppressed owing to less % of VUEs sending out DENMs. But the increase in ϕ becomes significant when Δ increases to 50% and 100% as observed in Fig. 7(c) and (d), respectively. The aperiodic DENM arriving abruptly takes up the resources reserved for CAMs. This interferes with the smooth transmission of periodic packets whose transmission gets delayed. This phenomenon has also been explained in Section 5.

The Latency-Aware MAC Scheduler (*LAMP*) distinctly schedules DENM and CAM by taking care of their PDB constraint, $\text{PDB}_{DENM} < \text{PDB}_{CAM}$ through Buffer Selection Section 6.3. The resources reserved for CAM are never taken up by the DENMs and hence it maintains a constant latency of 50 ms throughout all the plots. However, noting from Fig. 9, the CAM PRR decreases gradually from 87% in case of $\Delta = 10$, to 78% in case of $\Delta = 100$ for $\phi = 0$, as more number of VUEs are sensing the channel simultaneously and attempts to transmit resulting in collisions. This reason is also valid for drop in CAM PRR as we increase the value of ϕ. Further explanation regarding Fig. 9 will be discussed in the following Section 8.3.

At the same time, the increase in ϕ improves the chances of DENM reception and hence its PRR increases from 63% to as high as 94% in case of $\Delta = 10$. The maximum value of PRR attained with $\phi = 3$ decreases with an increase in Δ due to greater channel load as more VUEs sense the channel simultaneously for transmission. The DENM E2E latency dropped drastically to 10 ms owing to the independent reservation of resources by DENM VUEs (as seen by other VUEs as RRI equals to Repetition Interval) along with the freedom to choose a better resource within the PDB and gets transmitted immediately by *LAMP* with the help of Semi-Reservation Scheme (SRS). Additionally, LAMP uses Random Fit Slot Selection that minimizes DENM fragmentation owing to further reduction in latency. The VUEs whose DENM transmission is unsuccessful in the first attempt receive it in the next successive repetitions, and hence the E2E latency incurred by DENM increases with ϕ reaching almost 30 ms which is within the PDB_{DENM}. Effectively in Fig. 7(d), *LAMP* could lower the latency by 100 ms in CAM and by 175 ms in the case of DENMs for $\phi = 3$ as compared to the legacy system.

8.2. Frequency distribution of latency incurred by CAMs and DENMs in legacy versus LAMP

The significant reduction in E2E latency (L) of the ITS messages, specially DENMs using LAMP scheduler for inter-vehicular distance of 75 m is reflected in Fig. 8. The performance of legacy and LAMP scheduler has been compared through a frequency distribution of E2E latency of each packet. Based on the observations, Table 6 showcases the probability distribution for L. It describes the percentage (%) of packets received within certain latency ranges across different schemes. The key observation from this Table 6 is $\simeq 70\%$ of the DENM packets are received within 40 ms using LAMP. This reduction is achieved by minimizing DENM fragmentation using random fit slot selection scheme with prioritized scheduling of DENMs owing to buffer selection and SRS. Using legacy scheme, $\simeq 75\%$ of DENM packets are received beyond 80 ms with some packets even reaching 1200 ms (not shown in Fig. 8) for transmission. About 98.22% of CAM packets were received within E2E latency of 100 ms whereas for legacy $\simeq 30\%$ of CAMs exceeded the PDB_{CAM} and were received beyond 100 ms of latency. Traffic segregation at the RLC layer contributes to the latency improvement in CAMs by preventing DENMs from disrupting the scheduled CAM transmissions through the LAMP scheduler, thereby minimizing queuing delay.

Table 6
Probability distribution of latency (L) for IVD = 75 m, $\Delta = 100$ and $\phi = 3$.

Probability distribution of E2E latency (L)	Legacy		LAMP	
	CAM	DENM	CAM	DENM
$P(0 \text{ ms} \le L < 20 \text{ ms})$	18.82%	5.6%	23.44%	43.54%
$P(20 \text{ ms} \le L < 40 \text{ ms})$	15.41%	5.9%	21.82%	25.99%
$P(40 \text{ ms} \le L < 60 \text{ ms})$	12.34%	6.8%	18.97%	16.99%
$P(60 \text{ ms} \le L < 80 \text{ ms})$	12.47%	7.3%	16.92%	12.10%
$P(80 \text{ ms} \le L < 100 \text{ ms})$	11.1%	8.2%	17.04%	1.36%
$P(L \ge 100 \text{ ms})$	29.8%	65.9%	1.78%	0.02%

8.3. Effect on PRR of CAM and DENM

In the case of the legacy system for $\Delta = 10$ and $\phi = 0$ in Fig. 9(a), the DENM PRR achieves a PRR of 75% which is lesser than the PRR of CAM, i.e., 85%. The MAC scheduler unable to distinguish between CAM and DENM treats them evenly and sends the large-sized DENM packets in chunks using the CAM resources. If among those multiple chunks, any one of them faces collision; then the entire transmission becomes unsuccessful. Thus, the PRR of DENM is much lower than that of CAM in the first repetition. A surge of PRR is observed with an increase in ϕ and surpasses the CAM PRR across all four plots - Fig. 9(a), (b), (c), (d), as the chances of all the chunks transmitted successfully increase whereas CAMs have a single chance for successful transmission. As more VUEs re-transmit, there is a serious drop in CAM PRR as channel load increases and chances of collision also increase proportionately. In

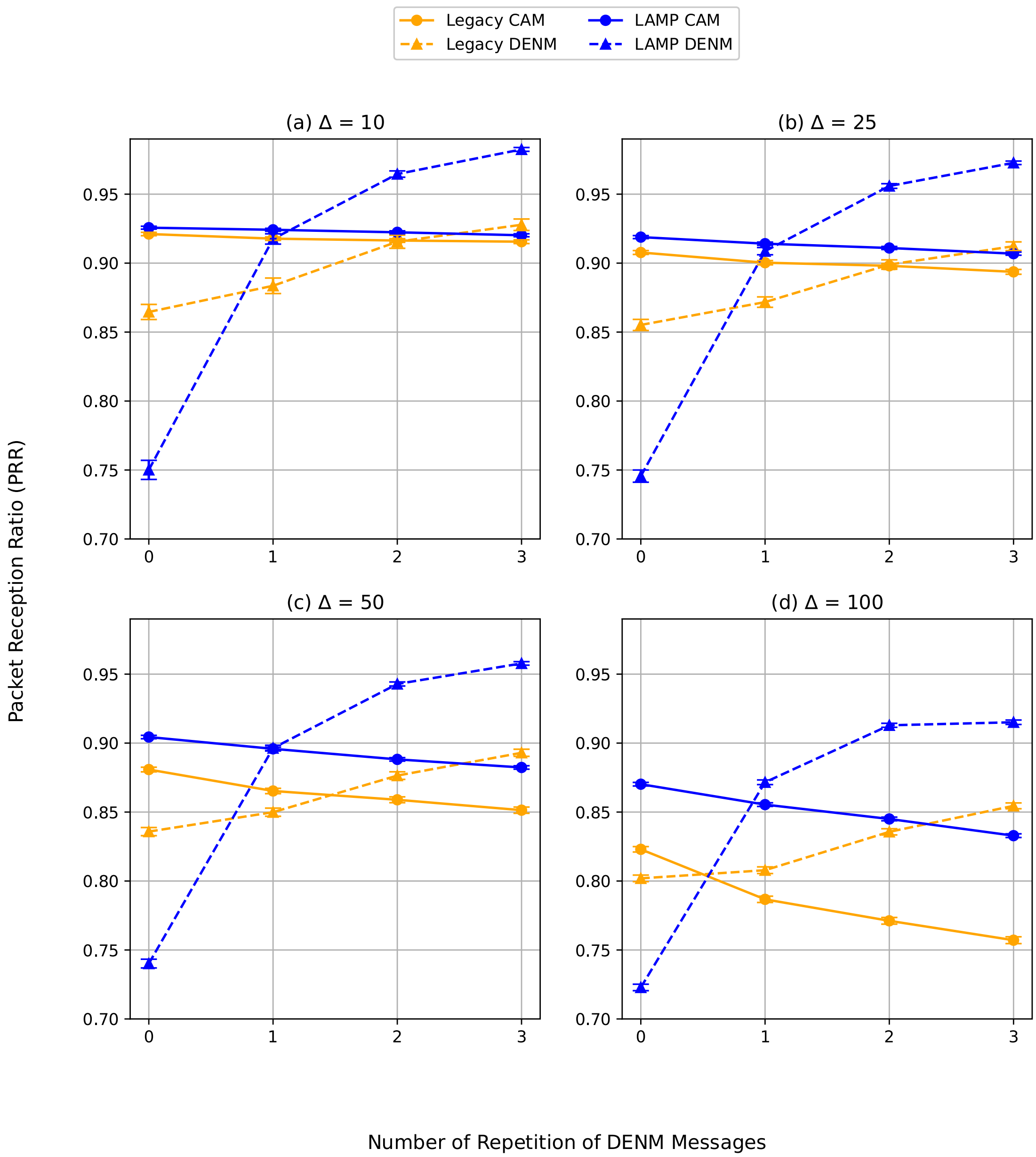

Fig. 9. Variation of PRR as a function of number of repetitions for varying % of VUEs sending out DENMs (σ = *Low*).

LAMP, DENM does not occupy resources reserved for CAM. Thus, there is no hindrance in resource usage by CAMs which can be validated with a higher CAM PRR as we increase the channel load by increasing Δ than the PRR achieved for CAMs in the legacy system. On the other hand, for all of the four plots, the DENM PRR for $\phi = 0$ is much lower because when DENM arrives unexpectedly with no history, it negatively affects its own performance through collision with other VUEs which sense the channel to be free at that time. Repetitions help increase the PRR as once a DENM is sent off with RRI set as the Repetition Interval, no other neighboring VUE occupies it. So, it is definite that a resource would be secured by SRS for future DENM re-transmission after RRI time. Thus there is a boost in PRR when we repeat the DENM packets; also with ϕ the chances of successful reception increase. In Fig. 9(d), the maximum achieved DENM PRR with $\Delta = 100$ is 92%, with the original DENM packet being repeated twice. This is quite impressive in case of high channel load where the DENMs in the legacy system could achieve a PRR of about 85%. *LAMP* could boost up the PRR by 7%.

8.4. Impact on PRR at different vehicular density levels over an extended range

In the low-density scenario, Fig. 10(a), the PRR achieved by DENMs is highest using *LAMP*. The PRR of both CAM and DENM turns out to be better than the legacy system. As distance increases, there is a gradual drop in PRR till we encounter a cross-over point after which the performance of the PRR of CAM dominates the PRR of DENMs. Though we have enough resources, vehicular communication gets harder as according to the inverse-square law of electromagnetic propagation radio signal strength weakens by the square of the distance. The cross channel interference is high. It is more likely for the received transport block to be erroneous, and hence PRR drops. DENM packets with greater resource requirements find acquiring a good quality resource more difficult. As vehicular density increases as in Figs. 10(b) and (c), in addition to the above reasoning, the competition is high owing to heavy traffic at the network as well as vehicular level over the given geographical region. This worsens the situation leading to an upward

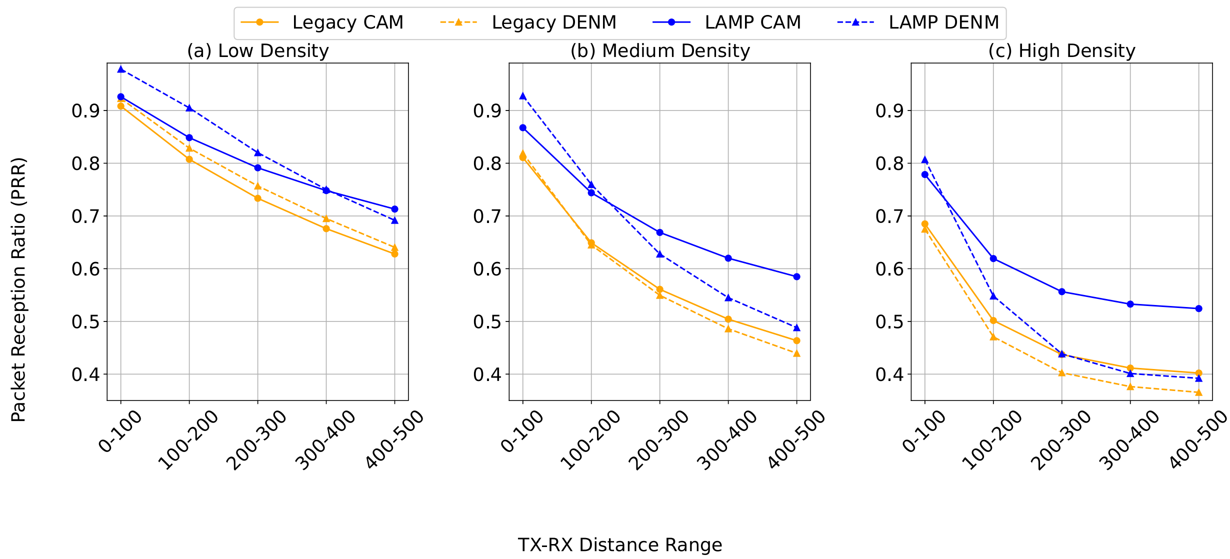

Fig. 10. Variation of PRR as a function of Tx-Rx distance for different traffic density levels (σ) with $\Delta = 50$ and $\phi = 2$.

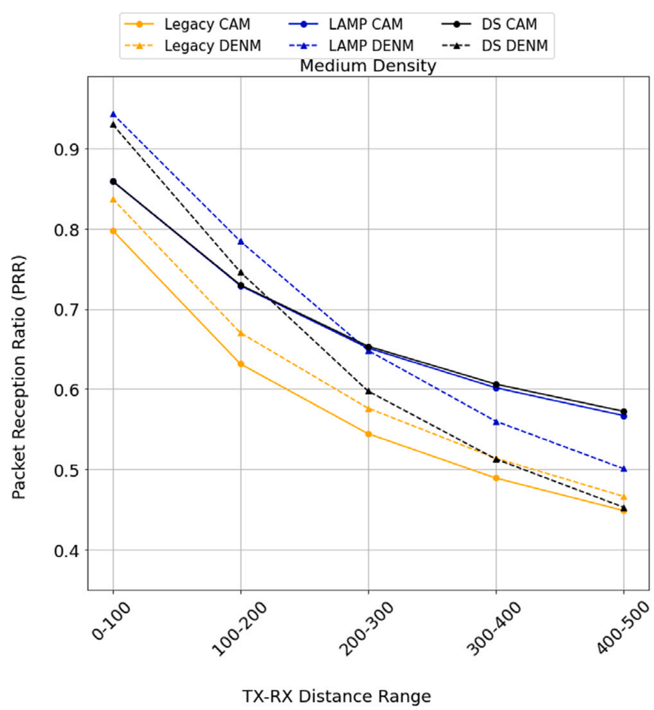

Fig. 11. Variation of PRR as a function of Tx-Rx distance for different schemes under σ = Medium with $\Delta = 50$ and $\phi = 3$.

shift of cross-over points as we move from low density to a high-density scenario as DENMs are less tolerant of poor channel conditions. However, in all the cases, *LAMP* shows a clear-cut performance boost of 12% increase in CAM PRR and 7% increase in DENM PRR over legacy system in extreme congestion at a range of 400–500 m between sender VUE and receiver VUE.

8.5. Comparison between legacy SPS, LAMP, and Dynamic Scheduling (DS)

We have tested the performance of LAMP with respect to the legacy SPS and Dynamic Scheduling (DS) which the authors in [26] claim to have best performance in case of aperiodic mixed traffic scenario. For DENM packets, it is seen from Fig. 11 that LAMP performs better than DS across Tx-Rx distance of 100-500 m. This improvement is due to our Semi-Reservation Scheme (SRS) 6.1 which allows a DENM packet to acquire a radio resource as soon as it finds an unoccupied slot and also reserves a resource for the next DENM packets. In the worst case, if there are no free resources that can be used immediately to transmit DENM, it can use the reserved resource. Thus in this way, a resource is always guaranteed by SRS within PDB of DENMs. This benefit magnifies when the number of repetitions for DENMs increases. Also, the performance trend in PRR for CAM and DENM gets reversed in DS at 100–200 meters Tx-Rx distance whereas for LAMP, the CAM packets outperform the DENM packets PRR at a greater distance of 200-300 m. As Tx-Rx distance increases, the drop in PRR for DENM packets more than CAM packets in both DS and LAMP schemes. This is due to the aperiodic nature of DENM packets and the pronounced hidden node problem with increased TX-RX distances. This effect cannot be seen in legacy SPS where both DENM and CAM are treated as periodically arriving packets for scheduling purposes.

8.6. Comparative report on performance of LAMP highlighting latency and PRR gains

Tables 7 and 8 give a consolidated performance check on our proposed *LAMP* system across low, medium and high-density scenarios (σ) and the number of repetitions (ϕ) when the number of VUEs sending out DENMs (Δ) is 50%. The PRR performance for DENM in the case of ϕ = 0 lags behind. The drop against legacy system is indicated in red color. Rest for both CAM and DENM across all other repetitions the *LAMP* guarantees an increase in PRR by at least 2% and a maximum of 10% indicated in green color. Table 8 summarizes the E2E latency enhancements with a noticeable maximum drop of 200 ms in the case of DENMs at high density against the legacy system. The drop in DENM latency is at least 150 ms across all cases. The latency of CAM on the other hand is decreased by at least 22 ms.

9. Limitations and practical challenges

The proposed LAMP scheme enables vehicles to have low latency contextual and situational traffic awareness with a high degree of reliability but there are some practical challenges pertaining to the deployment and implementation of this solution in real-world ITS environments.

The proposed LAMP scheduler checks for the presence of DENM messages in the RLC buffer and schedules the DENM packet using

Table 7
Comparison table for PRR ($\Delta = 50$) with respect to traffic density (σ) and number of repetitions (ϕ).

σ	ϕ							
	0		1		2		3	
	CAM	DENM	CAM	DENM	CAM	DENM	CAM	DENM
Low	90.43 (+2.35)	74.02 (−9.56)	89.58 (+3.06)	89.63 (+4.64)	88.82 (+2.94)	94.28 (+6.64)	88.23 (+3.1)	95.77 (+6.48)
Medium	82.84 (+5.53)	60.57 (−8.56)	81.75 (+7.49)	77.97 (+8.22)	80.69 (+7.53)	84.49 (+11.14)	79.53 (+7.91)	86.49 (+10.98)
High	73.92 (+8.17)	45.59 (−9.49)	72.09 (+10.19)	61.67 (+6.79)	70..45 (+10.46)	68.68 (+10.66)	69.37 (+10.94)	70.16 (+9.85)

Table 8
Comparison table for latency ($\Delta = 50$) (in ms) with respect to traffic density (σ) and number of repetitions (ϕ).

σ	ϕ							
	0		1		2		3	
	CAM	DENM	CAM	DENM	CAM	DENM	CAM	DENM
Low	47.46 (−22.01)	11.37 (−147.34)	47.54 (−31.67)	17.56 (−151.76)	47.38 (−36.23)	22.96 (−167.52)	47.43 (−39.79)	28.27 (−179.04)
Medium	46.96 (−23.31)	11.33 (−154.59)	46.94 (−32.88)	18.18 (−162.94)	47.21 (−34.61)	24.29 (−180.91)	47.11 (−36.30)	30.45 (−194.93)
High	46.94 (−24.87)	11.35 (−160.07)	46.81 (−33.94	18.46 (−166.42)	46.83 (−34.21)	24.97 (−184.74)	46.69 (−34.88)	31.50 (−199.34)

CSSR with a capacity greater than or equal to the DENM packet size. But in case of network congestion the LAMP scheduler might fail to allocate a CSSR which can satisfy the DENM packet size, resulting in fragmentation of DENM packet, leading to higher latency and possible packet corruption at the receivers end.

Another practical challenge would be, to implement the improved SPS scheduler in the hardware, which now scans for the presence of DENM and CAM in the RLC buffers at every TTI, thus it might be necessary to have hardware support which can handle high computational workloads in the On Board Unit (OBU) of the vehicle.

A possible deployment challenge would be to ensure consensus among ITS operators on DENM packet generation interval and duration of DENM transmission.

10. Conclusion and future directions

This work has investigated the feasibility of joint sidelink scheduling of CAM and DENM traffic through our proposed enhancements in MAC layer protocol, *LAMP*. The LAMP scheduler scans for the presence of CAM and DENM packets in their respective RLC buffers at every subframe and chooses to schedule the transmission following the Buffer Selection Scheme giving high priority to the DENM messages. Next, when the DENM packet is being transmitted the SCI field in the PSCCH is configured to inform other vehicles to stay clear of the current CSSR in their future transmissions thus minimizing packet collisions, as per the Semi-Reservation Scheme (SRS). All these help to ensure that DENM packets are received with a high degree of reliability, improving the PRR and are transmitted as soon as the packet arrives in the RLC layer thus providing low E2E latency. The proposed LAMP scheme enables the delivery of time-critical DENM alert messages within 31.5 ms (note the rightmost-lower corner of Table 8) at extreme congestion with repetitions resulting in an overall drop of 89.36% across all scenarios. It has been built on top of NR V2X Mode-2 to guarantee a reliability boost of 12% for out-of-coverage delivery with repetitions. In light of the results presented above, the effectiveness of delivering DENM messages has been analyzed in all kinds of realistic scenarios with no compromise but rather an improvement in the performance of CAM. The CAM latency has been reduced by 40%, and the PRR has been increased by 9.74%. This shows that our proposed LAMP scheme can significantly improve the reliability and reduce latency in V2X communication services thus enabling time critical safety applications to function properly and saving lives.

The impressive drop in E2E latency, worth appreciating paves the way for latency modeling of CAM and DENM across the layers of the protocol stack of source and receiver VUE including the probable delay incurred in the air interface based on the channel conditions for an in-depth analysis. Secondly, there can be different levels of prioritization of a DENM message based on the proximity of the event occurrence or age of the DENM message, such as a VUE disseminating about the occurrence of a nearby roadside accident is of utmost importance than broadcasting a DENM message received from far-away VUEs. Also, the number of repetitions of a DENM message can be controlled dynamically based on the priority level and channel conditions preferring less number of repetitions if the availability of resources is less. Third, we can dynamically tune the MCS used for DENM to improve the reception of DENMs by vehicles farther away from the source VUE. Lastly, in light of the Federal Communications Commission (FCC)'s decision to permit unlicensed NR (NR-U) and Wi-Fi operations over lower 45MHz of ITS spectrum in 2020 to meet the growing bandwidth demands of Wi-Fi and next-generation communications, there will be a need for fair coexistence of NR-U, Wi-Fi, and ITS devices in the unlicensed spectrum. Techniques to achieve greater spectrum efficiency, minimizing channel congestion, and fair resource allocation can be studied in future works.

CRediT authorship contribution statement

Suranjan Daw: Conceptualization, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. **Anwesha Kar:** Conceptualization, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. **Venkatarami Reddy Chintapalli:** Supervision, Writing – original draft, Writing – review & editing. **Bheemarjuna Reddy Tamma:** Conceptualization, Supervision, Writing – original draft, Writing – review & editing. **Siva Ram Murthy C.:** Conceptualization, Funding acquisition, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: C. Siva Ram Murthy reports financial support was provided by Science and Engineering Research Board.

Data availability

Data will be made available on request.

References

[1] 3GPP, Service requirements for V2X services, Technical Specification (TS) 22.185 v16.0.0 Release 14, 3rd Generation Partnership Project (3GPP), 2020.

[2] 3GPP, Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2, Technical Specification (TS) 36.300 (v15.7.0, Release 15), 3rd Generation Partnership Project (3GPP), 2019.

[3] 3GPP, Release 16 Description; Summary of Rel-16 Work Items, Technical Report (TR) 21.916 (v1.0.0 , release 16), 3rd Generation Partnership Project (3GPP), 2020.

[4] ETSI, Intelligent transport systems (ITS);vehicular communications; basic set of applications; part 2: Specification of cooperative awareness basic service, 2014, (EN 302 637-2 V1.3.1 (2014-09)).

[5] ETSI, Intelligent Transport Systems (ITS);Vehicular Communications; Basic Set of Applications; Part 3: Specifications of Decentralized Environmental Notification Basic Service, 2014, (EN 302 637-3 V1.2.2).

[6] Zoraze Ali, Sandra Lagén, Lorenza Giupponi, Richard Rouil, 3GPP NR V2X mode 2: Overview, models and system-level evaluation, IEEE Access 9 (2021) 89554–89579.

[7] 3GPP, Study on evaluation methodology of new Vehicle-to-Everything (V2X) use cases for LTE and NR, Technical Report (TR) 37.885 (v15.3.0, Release 15), 3rd Generation Partnership Project (3GPP), 2019.

[8] Brian McCarthy, Andres Burbano-Abril, Víctor Rangel-Licea, Aisling O'Driscoll, OpenCV2X: Modelling of the V2X cellular sidelink and performance evaluation for aperiodic traffic, 2021, CoRR, abs/2103.13212.

[9] 3GPP, Architecture enhancements for 5G System (5GS) to support Vehicle-to-Everything (V2X) services, Technical Specification (TS) 23.287, 3rd Generation Partnership Project (3GPP), 2016.

[10] 3GPP, NR; Radio Resource Control (RRC); Protocol specification, Technical Specification (TS) 38.331, 3rd Generation Partnership Project (3GPP), 2017.

[11] 3GPP, NR; Medium Access Control (MAC) protocol specification , Technical Specification (TS) 38.321 (v16.7.0 Release 16), 3rd Generation Partnership Project (3GPP), 2017.

[12] 3GPP, Final Report of 3GPP TSG RAN WG1 100bis-e v1.0.0, Technical Report (TR) TSG RAN WG1 100bis-e v1.0.0, 3rd Generation Partnership Project (3GPP), 2020.

[13] 3GPP, NR; Physical layer procedures for data, Technical Specification (TS) 38.214 (v16.4.0 Release 16), 3rd Generation Partnership Project (3GPP), 2017.

[14] 3GPP, NR; Services provided by the physical layer, Technical Specification (TS) 38.202 (v16.2.0 Release 16), 3rd Generation Partnership Project (3GPP), 2017.

[15] 3GPP, Service requirements for enhanced V2X scenarios, Technical Specification (TS) 22.186, 3rd Generation Partnership Project (3GPP), 2017.

[16] Ahmad Alalewi, Iyad Dayoub, Soumaya Cherkaoui, On 5G-V2X use cases and enabling technologies: A comprehensive survey, IEEE Access 9 (2021) 107710–107737.

[17] Lorenzo Gibellini, Maria Luisa Merani, Out-of-coverage multi-hop road safety message distribution via LTE-A cellular V2V (C-V2V), in: 2018 IEEE 88th Vehicular Technology Conference (VTC-Fall), 2018, pp. 1–6.

[18] Luca Lusvarghi, Maria Luisa Merani, On the coexistence of aperiodic and periodic traffic in cellular vehicle-to-everything, IEEE Access 8 (2020) 207076–207088.

[19] Malik Muhammad Saad, Muhammad Ashar Tariq, Junho Seo, Mahnoor Ajmal, Dongkyun Kim, Age-of-information aware intelligent MAC for congestion control in NR-V2X, in: 2023 Fourteenth International Conference on Ubiquitous and Future Networks, ICUFN, 2023, pp. 265–270.

[20] Claudia Campolo, Antonella Molinaro, Antoine O. Berthet, Alexey Vinel, On latency and reliability of road hazard warnings over the cellular V2X sidelink interface, IEEE Commun. Lett. 23 (11) (2019) 2135–2138.

[21] Francesco Romeo, Claudia Campolo, Antonella Molinaro, Antoine O. Berthet, Asynchronous traffic on the sidelink of 5G V2x, in: 2020 IEEE International Conference on Communications Workshops (ICC Workshops), 2020, pp. 1–6.

[22] Francesco Romeo, Claudia Campolo, Antonella Molinaro, Antoine O. Berthet, DENM repetitions to enhance reliability of the autonomous mode in nr V2X sidelink, in: 2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring), 2020, pp. 1–5.

[23] Francesco Romeo, Claudia Campolo, Antonella Molinaro, Antoine O. Berthet, Alessandro Bazzi, Supporting sporadic DENM traffic over 5G-v2x sidelink in the autonomous mode, in: 2021 IEEE 94th Vehicular Technology Conference (VTC2021-Fall), 2021, pp. 1–5.

[24] Francesco Romeo, Claudia Campolo, Antoine O. Berthet, Antonella Molinaro, Improving the DENM reliability over 5G-v2x sidelink through repetitions and diversity combining, in: 2021 IEEE 4th 5G World Forum (5GWF), 2021, pp. 352–357.

[25] Alejandro Molina-Galan, Baldomero Coll-Perales, Luca Lusvarghi, Javier Gozalvez, Maria Luisa Merani, How does 5G NR V2X mode 2 handle aperiodic packets and variable packet sizes? in: 2022 IEEE 23rd International Conference on High Performance Switching and Routing, HPSR, 2022, pp. 183–188.

[26] Luca Lusvarghi, Alejandro Molina-Galan, Baldomero Coll-Perales, Javier Gozalvez, Maria Luisa Merani, A comparative analysis of the semi-persistent and dynamic scheduling schemes in NR-V2X mode 2, Veh. Commun. 42 (2023) 100628.

[27] José Santa, Fernando Pereñíguez, Antonio Moragón, Antonio F. Skarmeta, Experimental evaluation of CAM and DENM messaging services in vehicular communications, Transp. Res. C 46 (2014) 98–120.

[28] Suranjan Daw, Anwesha Kar, Bheemarjuna Reddy Tamma, On enhancing semi-persistent scheduling in 5G NR V2X to support emergency communication services in highly congested scenarios, in: Proceedings of the 24th International Conference on Distributed Computing and Networking, ICDCN '23, Association for Computing Machinery, New York, NY, USA, 2023, pp. 245–253.

[29] CTTC, NR V2X Module. URL https://gitlab.com/cttc-lena/ns-3-dev/-/tree/v2x-lte-dev.

[30] Mario H. Castañeda Garcia, Alejandro Molina-Galan, Mate Boban, Javier Gozalvez, Baldomero Coll-Perales, Taylan Şahin, Apostolos Kousaridas, A tutorial on 5G NR V2X communications, IEEE Commun. Surv. Tutor. 23 (3) (2021) 1972–2026.