An Efficient Multi-Class Traffic Delivery Scheme in 5G Vehicle-to-Everything Communications

1st Eshita Rastogi
Department of Computer Science and Engineering
Sungkyunkwan University
Suwon, Republic of Korea.
Email: eshita@skku.edu

2nd Jaehoon (Paul) Jeong
Department of Computer Science and Engineering
Sungkyunkwan University
Suwon, Republic of Korea.
Email: pauljeong@skku.edu

3rd Abhishek Roy
MediaTek Inc.
USA.
Email: Abhishek.Roy@mediatek.com

4th Navrati Saxena
Department of Computer Science
San Jose State University
USA.
Email: navrati.saxena@sjsu.edu

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***Abstract*—5G and Beyond 5G (B5G) networks are regarded as effective solutions for serving numerous emerging applications through 5G Vehicle-to-Everything (V2X) communications, that is, 5G V2X. Vehicles experience several messages such as safety messages like Decentralized Environmental Notification Messages (DENMs) and non-safety messages like entertainment data packets having varied requirements. In this work, we consider the co-existence of DENMs along with background data traffic and explore the impact of DENMs on such low-priority background data traffic. We explore the multicast and broadcast techniques for robust 5G V2X communications. We consider the delivery of DENMs using the multicast of gNodeBs (gNBs) as Single-Cell Point-to-Multipoint (SC-PTM) over Vehicle-to-Infrastructure (V2I) links as well as the broadcast of the vehicles over Vehicle-to-Vehicle (V2V) links. User-specific data traffic is unicasted over a high-capacity V2I link. Next, we propose a joint V2I resource allocation algorithm for the two traffic classes. We mathematically model average DENM delivery delay, average DENM packet reception ratio, and average throughput of background data traffic. Our mathematical analysis is further validated by extensive simulations. Through these simulations, it is shown that our proposed scheme outperforms the existing schemes in terms of average DENM delivery delay.**

***Index Terms*—5G V2X, emergency message, DENM, queuing analysis, resource allocation.**

I. Introduction

In recent years, transportation systems have suffered from substantially reduced efficiency due to traffic congestion and the increasing number of road accidents [1], [2]. Consequently, the research community and automotive industry have shifted focus toward developing safer roads by incorporating intelligence and exploiting wireless communication technology. Vehicular communication strives to improve road safety and traffic conditions by reinventing parts of the transportation systems [3]. Especially, Software-Defined Vehicles (SDV) have emerged recently as vehicles with automotive operating systems (e.g., AUTOSAR [4]) and cloud-native systems (e.g., Eclipse SDV [5]) along with vehicular communication devices (e.g., 5G devices) [6], [7].

In 5G as New Radio (NR), the primary objective of Vehicle-to-Everything (V2X) communications (called 5G V2X) for the SDVs is to improve the connected autonomous driving experience including driving safety [8], [9]. 5G V2X comprises Vehicle-to-Vehicle (V2V), Vehicle-to-Pedestrian (V2P), Vehicle-to-Infrastructure (V2I), and Vehicle-to-Network (V2N) communications [10]. V2X connectivity envisions ubiquitous coverage, high reliability, and improved spectrum utilization [11]. Road safety relies on safety messages broadcasted within the vehicles' neighborhood to inform other vehicles of their immediate environment.

To support the wide range of applications having a diverse Quality of Service (QoS) in dense traffic scenarios, 3GPP further enhanced V2X communications in 5G New Radio (NR) in the Third Generation Partnership Project (3GPP) Release 16 [9]. 5G and Beyond 5G (B5G) networks are being proved as effective solutions for serving numerous emerging V2X applications. Knowing the inherent advantages of multicast and broadcast to cellular communications, 3GPP in Release 17 now supports Multimedia Broadcast Multicast Service (MBMS) [10], [12] in 5G V2X communications. In Downlink (DL), NR supports unicast, multicast, and broadcast transmission. DL based on multicast and broadcast can significantly reduce the resource utilization of V2I and V2V links compared to unicast transmission. Multicast and broadcast transmissions improve the system efficiency, enhance DL capacity, improve resource efficiency, etc. Here, the data packet is sent to multiple users through a common channel leading to an effective utilization of radio resources. MBMS supports two distinct transmission modes: MBMS Single Frequency Network (MBSFN)-based transmission and Single Cell Point-to-Multipoint (SC-PTM) transmission [14], [15] for

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V2X communications [16]. Unlike MBSFN, the SC-PTM transmission area is restricted to a 5G NR cell and its scheduling delay is lower since synchronization from multiple cells is avoided. Thus, SC-PTM is more efficient for distributing data to multiple receivers.

According to the European Telecommunications Standards Institute (ETSI), the common communication messages used in V2X, for the exchange of broadcast packets include Cooperative Awareness Messages (CAMs) and Decentralized Environmental Notification Messages (DENMs) [17], [18]. CAMs are periodically exchanged between vehicles to provide information on the presence, position, and basic status of the vehicles. DENMs are event-triggered safety messages that are broadcasted to alert other road users of hazardous events [19], [20]. Delay and loss of DENMs can cause serious consequences in vehicular communications.

The DENMs are treated as event-triggered safety messages with a higher priority upon occurrences. To ensure the reliability of DENM delivery, we leverage V2V links with ultra-reliable characteristics. Following this, we propose an alternative V2V communication link to disseminate DENMs using 5G NR V2V Mode 1 [21], [22]. In V2V Mode 1, the next generation NodeB (gNB) schedules V2V resources for vehicles and informs them of the resources allocated for communication. This means that the network coverage and connection to the gNB are always required [23]. Unlike DENM, which is intended for all vehicles, the background data traffic is a user-specific message and is transmitted through performing Proportional Fair (PF) scheduling using a V2I communication link with high-capacity characteristics. In this work, we consider the worst-case analysis, where the vehicles are susceptible to unwanted emergencies while downloading heavy data traffic. The main focus of this research is to study the multi-class traffic catering to diverse applications. Therefore, QoS becomes a crucial performance indicator.

In the absence of gNB coverage, V2V communication can still happen through Mode 2, but data transmission for infotainment traffic using the V2I link will be interrupted due to a lack of service continuity. The specific contributions of this article are three-fold:

1) We propose a joint V2I resource allocation scheme for DENMs and background data traffic simultaneously. The DENM transmission gets a higher edge in terms of priority. We also explore how the throughput of the background data traffic is affected by the DENM transmission.
2) We model DENM transmission over both V2I and V2V links to ensure better reliability. The DENM transmission is modeled using queuing theory and analytical expressions for average DENM delivery delay and for average DENM V2I Resource Block (RB) usage derived.
3) We derive an expression for the average user throughput of background data traffic. Next, we validate the proposed analytical model through extensive simulations and compare it with the existing scheme.

The remaining part of this paper is arranged as follows: we describe the background research describing the multicast in NR followed by the literature review in in Section II. We discuss the system model and the proposed scheme in detail in Section III, and we mathematically analyze the proposed scheme and derive the performance metrics in Section IV. We explain the numerical and simulation results in Section V. Finally, we conclude the paper along with future work in Section VI.

II. Related Work

In this section, we provide a detailed discussion of the existing research related to the work in this article. 5G NR infrastructure has been proven useful for classical V2X services, like CAM and DENM delivery through 5G NR MBMS capabilities. Moreover, 5G NR with MBMS as a provider shows significant advantages over unicast for supporting V2X services, in terms of latency, resource utilization, etc. [15].

The existing literature has mainly investigated the performance of DENMs over the cellular link, as well as background CAM traffic [18], [25]. The authors in [18] evaluate the Medium Access Control (MAC) performance of LTE-V2X Mode 4 and IEEE 802.11p in terms of average delay, collision probability, and channel utilization while considering both periodic CAMs and DENMs. Campolo et al. [25] analyze the performance of DENMs in terms of latency and reliability for both Mode 3 and Mode 4, in LTE-based V2X communications. However, these works did not consider the multi-class traffic scenario, which also includes the transmission of infotainment messages. Several works have considered the co-existence of messages, like CAMs and DENMs, each having different priorities [26], [27], but they have not analyzed how low-priority infotainment traffic and its associated demand on high throughput can affect the freshness and reliability of the DENMs.

The work in [26] evaluates the performance of different types of cellular connectivity to support ITS services like CAMs, DENMs, and platooning in a highway scenario. The authors in [28] propose a sensing scheme that can be used to simultaneously improve the packet delivery ratio of CAM and DENMs. However, this scheme does not consider the impact of high throughput traffic on the delivery of CAMs and DENMs. The authors in [41] analyze the End-to-End (E2E) delay for MBMS, SC-PTM, and V2V. Studies have also examined a number of machine learning-based spectrum sharing [30] and resource allocations [29] schemes in vehicular networks.

In our previous work [32], we have proposed resource allocations of the safety message dissemination in the presence of a non-safety message in the LTE-V2X framework. However, we did not consider the advantages of MBMS in terms of resource allocations,

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average delay, and Packet Reception Ratio (PRR). While the previous work has focused solely on resource allocation for the dissemination of either non-safety messages or safety messages, the present work, explores a scenario where vehicles on a highway are fetching infotainment services while, simultaneously encountering several emergency events, e.g., DENMs. Naturally, the DENMs generated due to such events have a higher priority than the background traffic.

As opposed to the previous work, in this work (i) we consider that the DENMs are multicasted using SC-PTM on the V2I link as well as broadcasted using the 5G NR V2V sidelink, while the background traffic is only unicasted using the V2I link; (ii) we study DENMs dissemination while intending to minimize the E2E delay, average DENM PRR, and average user throughput; and (iii) we verify the analytical results and simulations results together.

TABLE I
MAIN ABBREVIATIONS

Parameters	Description
m, M	Index/Number of gNBs
k, K	Index/Number of vehicles
λ_v, λ	DENM arrival rate per vehicle/gNB
S_m	Set of vehicles in coverage of gNB m
N_{V2I}	Number of available DL RBs on V2I link
W_{UL}	UL delay due to DENM processing time
W_{DL}, W_{SL-RX}	DL/SL processing time required to receive DENM
$W_{Q,V2I}, W_{Q,V2V}$	Average waiting time in V2I/V2V DENM queue
W_{V2I}, W_{V2V}	Average DENM Tx delay over V2I/V2V link
ρ	Utilization factor of V2I DENM queue
MSC_{V2I}^{min}	Min. MCS required to send 1 DENM in 1 TTI
A_{V2I}^{max}	Upper bound for V2I DENM multicast RB usage
p_j	Probability of having j DENMs in V2V queue
$PF_{kn}(t)$	PF metric of vehicle k at RB n at TTI t
$I_{kn}^{z}(t)$	1 if $PF_{kn}(t)$ is ranked z^{th} and 0, otherwise
$r_{kn}^{max}(t)$	Max. possible throughput of vehicle k
$r_{kn}(t)$	Instantaneous throughput of vehicle k
μ_{kn}, σ_{kn}^2	Mean/Variance of $r_{kn}(t)$
$R_k(t)$	Average throughput of vehicle k at TTI t

III. The System Model and Proposed Scheme

In this section, we discuss the system model and provide the details of the proposed scheme. We explain the transmission of DENMs and the background data traffic. After that, we discuss the proposed V2I resource allocation algorithm.

A. System Model

The system architecture for the message transmission is shown in Fig. 1. We consider a bi-directional multi-lane highway with m gNBs for $m = 1, 2, ..., M$. The gNBs are deployed at fixed distances along the highway so that there are no coverage holes. The gNBs are fully inter-connected through wired $X2$ links whose delays are assumed to be negligible. There are k vehicles for $k = 1, 2, ..., K$, which are distributed on the highway. The distribution of the vehicles is following a spatial Poisson process [31]. We assume that vehicles are moving with a random velocity, do not exit the highway, and do not change lanes. The vehicles can communicate with their serving gNBs over a high-capacity V2I communication link or with each other over a highly reliable V2V communication link using the same transceiver unit. For V2V communication, 5G NR V2V Mode 1 over sidelink is used. The vehicles periodically determine their position using a GPS device and report it to their serving gNBs. Each vehicle generates a DENM in response to any emergency event (e.g., accident, traffic condition warning, abnormal vehicle warning, road-work warning, and so on) it detects on the highway. We assume that these emergency events follow a Poisson arrival of rate λ_v per second for each vehicle [28]. For the sake of simplicity, our proposed schemes do not consider the repetition of DENMs [35]. To generate background data traffic, we consider that each vehicle downloads a video file and that the download of this file starts at a random time for each vehicle. Table I lists the symbols used in the paper.

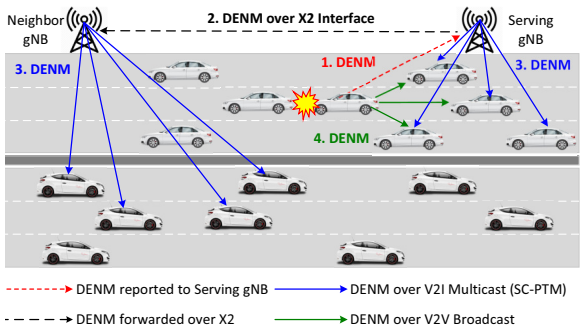

Fig. 1. A system architecture of DENM transmission on a highway using both V2V and V2I communication links

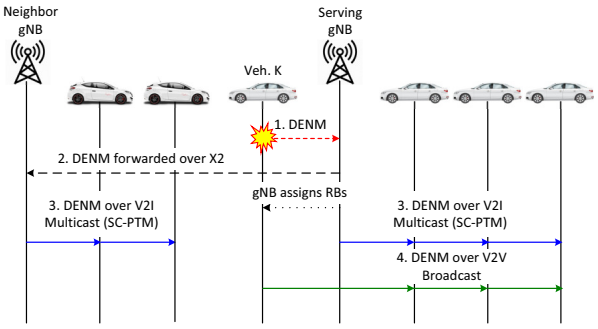

Fig. 2. Illustration of a flow diagram of DENM transmission

B. The Proposed Scheme

In this article, we consider a resource allocation scheme for multi-class data traffic scenarios having different QoS requirements. To ensure the reliability

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of DENM delivery, we consider an alternative path for disseminating DENMs over a V2V communication link using V2V Mode 1. Unlike DENM, which is intended for all vehicles, the other background data traffic is a dedicated message for each vehicle and is transmitted through PF scheduling. We consider a scenario, where the vehicles are vulnerable to unwanted emergency situations while downloading background traffic. The following section describes the scheme in detail.

1) Transmission of DENMs: In this section, we elaborate on the flow of vehicle k's DENM toward all the vehicles that intend to receive the DENM's copies, as shown in Fig. 1. The DENM generated by vehicle k is disseminated to other vehicles in the vicinity, as depicted in Fig. 2. Vehicle k sends the DENM to its serving gNB, which adds the DENM to its multicast queue. The gNB then forwards the DENM to its neighboring gNB using the $X2$ interface, as shown in Fig. 1. The DENM is forwarded to only those neighbors whose vehicles have not yet crossed the emergency event location. In other words, the serving gNB forwards to the neighbor gNB located to its left (or right) if vehicle k is moving from right to left (i.e., westbound) on the highway or vice versa (i.e., eastbound). For vehicles under the coverage of other neighbor gNBs, the DENM is no longer useful to them and therefore not sent to them. The DENM message is further broadcasted by vehicle k toward its adjacent vehicles using a Mode 1 V2V communication link. Based on a fixed V2V message size and a fixed Modulation and Coding Scheme (MCS), the serving gNB can schedule up to c vehicles to broadcast the same DENM in 1 Transmission Time Interval (TTI). Therefore, the grant includes the TTI and the RBs on which the DENM should be broadcasted on the V2V link. The serving gNB multicasts the DENM using SC-PTM from the multicast queue on a First-Come First-Served (FCFS) basis.

2) Transmission of Background Data Traffic: In this section, we describe the transmission of background data traffic, and how its transmission is affected by the high-priority DENMs. The background data traffic is transmitted uninterrupted using PF scheduling over a V2I communication link. However, for every TTI, if the DENM multicast queue is not empty, each gNB selects the first DENM in the queue for multicast using SC-PTM. The DENM multicast MCS is selected with the help of the following equation:

$$max\{min\{MCS\forall\ k\ \epsilon\ S_m\}, MCS_{V2I}^{min}\}, \quad (1)$$

where S_m is the set of all the vehicles under the coverage of serving gNB m and MCS_{V2I}^{min} is the minimum MCS required to allow the whole DENM to be sent in 1 TTI. Since we assume that the vehicles are randomly distributed in the network, some vehicles are likely to experience poor channel conditions. So, the MCS is determined based on the broadcast group member with the worst channel condition. Thus a very low MCS will be required for transmission. This implicitly means that transmission of 1 DENM will almost always use a large portion of RBs in a TTI. Due to this, there will not be enough remaining RBs to broadcast another DENM in the same TTI. Therefore, only 1 DENM per TTI is broadcasted even when there are multiple DENMs available in the queue.

Each gNB transmits background data traffic using PF scheduling to vehicles under its coverage [32] using a V2I link. The PF metric of vehicle k over RB n at TTI t is defined as:

$$PF_{kn}(t) = \frac{r_{kn}^{max}(t)}{R_k(t-1)}, \quad (2)$$

where $r_{kn}^{max}(t)$ is the maximum possible throughput of the vehicle over RB n at TTI t and $R_k(t-1)$ is the average throughput of the vehicle at TTI $(t-1)$. For each RB, the vehicles are ranked in decreasing order of their PF metrics, and the RB is assigned to the highest-ranked vehicle that does not have an empty buffer.

If at least 1 RB is assigned to a vehicle, gNB selects an MCS for the vehicle based on its reported Channel Quality Indicator (CQI) and then assigns Transport Block Size (TBS) to it based on the number of assigned RBs. The average throughput of vehicle k at TTI t is updated as:

$$R_k(t) = (1-\gamma)R_k(t-1) + \gamma \sum_{n=1}^{N_{V2I}} r_{kn}(t), \quad (3)$$

where $r_{kn}(t)$ is the actual throughput of the vehicle over RB n at TTI t, $0 < \gamma < 1$ is a smoothing factor, and N_{V2I} is the total number of DL RBs. If vehicle k is scheduled at TTI t, then $r_{kn}(t)$ is equal to the assigned transport block size (TBS) for RB n in units of kbps and $r_{kn}(t) = 0$, otherwise.

IV. Mathematical Analysis

In this section, we mathematically analyze the proposed scheme and derive the expressions used for the average delay and average V2I RB usage of DENM transmission as well as the average user throughput of background data traffic.

A. Analysis of DENM Transmission

We analyze the average End-to-End (E2E) delay experienced by DENMs when they are transmitted using the proposed scheme presented in section III-B1 and we also derive an upper bound on V2I RB usage for DENM transmission. First, we calculate the effective DENM arrival rate for each gNB. Since the highway is bi-directional and vehicle locations are uniformly distributed for a spatial Poisson process [33], there will be, on average, $K/2M$ vehicles traveling in one direction under the coverage of one gNB. Therefore, each gNB receives $2(K/2M)\lambda_v$ messages per second from the vehicles within its coverage. We consider that the gNBs are numbered as 1 to M from left to right. If the DENM-generating vehicle is traveling from left

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to right and is in the coverage of gNB m, then the vehicles in the coverage of gNB 1 to gNB $(m-1)$ are behind this vehicle. So, gNB m forwards the DENM to all gNBs from gNB 1 to gNB $(m-1)$. Similarly, if the DENM-generating vehicle is traveling from right to left, gNB m forwards the DENM to all gNBs from gNB $(m+1)$ to gNB M. As a result, the effective DENM arrival rate at gNB m is given as:

$$\lambda = \frac{(2+(m-1)+(M-m))K\lambda_v}{2M} = \frac{(M+1)K\lambda_v}{2M}. \tag{4}$$

After an emergency event occurs, there is a delay, W_{UL}, before the DENM is received by the gNB. This delay is comprised of message processing times in the vehicle and the gNB as well as delays due to the UL grant process, Scheduling Request transmissions, Buffer Status Report transmissions, etc. In this paper, we assume that W_{UL} is constant [25], [26]. As explained in Sections III-B1 and III-B2, DENM joins a queue from which it is transmitted in order of its arrival. This transmission is modeled using an M/D/1 queue with a deterministic serving time of $D = 1$ ms. In our proposed scheme, the DENMs are disseminated through the V2I broadcast, in which there is no feedback from the receivers. Because of this, the transmitter cannot know whether the DENM was received correctly or not. Note that there are no re-transmissions in broadcasting. In this way, the M/D/1 queue formulation for V2I transmission [34] is reasonable.

The average waiting time in a queue is given as:

$$W_{Q,V2I} = \frac{D\rho}{(2-2\rho)}, \tag{5}$$

where $\rho = \lambda D$ is the utilization factor [34]. After transmission, we assume that receiving vehicles require a constant processing time, W_{DL} to receive the message [25], [26]. Thus, the average V2I end-to-end delay is given as:

$$W_{V2I} = W_{UL} + W_{Q,V2I} + D + W_{DL}. \tag{6}$$

Based on DENM size, g RBs are used for DENM multicast with MCS = MCS_{V2I}^{min}, where g is derived using 3GPP 5G NR specifications [36]. Then, the RB usage for DENM multicast is upper-bounded by

$$A_{V2I}^{max} = \frac{\lambda g}{N_{V2I}}. \tag{7}$$

For DENM transmission using V2V, the initial delay, W_{UL}, is the same as that in the V2I case. The V2V DENM broadcast mechanism is explained in III-B1 and modeled using an M/D/c queue with a deterministic serving time of $D = 1$ ms. M/D/c queue modeling is considered appropriate as there is no re-transmission in broadcasting. However, the DENMs are broadcasted using low MCS to increase the probability of correct reception even by receivers experiencing poor channel conditions. To calculate the average waiting time in a queue, we first calculate the probability of having j messages in the queue as shown in (Eq. (9.6.1) in [37]):

$$p_j = e^{-\lambda D}\frac{(\lambda D)^j}{j!}\sum_{u=0}^{c} p_u + \sum_{u=c+1}^{c+j} p_u e^{-\lambda D}\frac{(\lambda D)^{j-u+c}}{(j-u+c)!}, \tag{8}$$

$j \geq 0$.

We also have the normalization equation as $\sum_{j=0}^{\infty} p_j = 1$. This is an infinite system of linear equations that is solved approximately by reducing it to a system of finite linear equations, as explained in [37]. Next, the CDF of the waiting time (WT) in the queue is given as (Eq. (9.6.9) in [37]):

$$\Pr\{\text{WT} \leq x\} = \sum_{j=0}^{\nu c-1} \Omega_{\nu c-1-j} e^{-\lambda(\nu D-x)}\frac{(\lambda(\nu D-x))^j}{j!}, \tag{9}$$

where $(\nu-1)D \leq x \leq \nu D$ for $\nu = 1, 2, ...$, and $\Omega_j = \sum_{i=0}^{c+j} p_i$ for $j = \{0, 1, ...\}$. The average WT in the queue is given by Eq. (10):

$$W_{Q,V2V} = \nu_{max} D - \sum_{\nu=1}^{\nu_{max}}\sum_{j=0}^{\nu c-1}\frac{\Omega_{\nu c-1-j}}{\lambda} \left(1 - \sum_{s=0}^{j} e^{-\lambda D}\frac{(\lambda D)^s}{s!}\right), \tag{10}$$

where ν_{max} is selected such that $1 - \Pr\{\text{WT} \leq x\} < \epsilon$ when $(\nu_{max}-1)D \leq x \leq \nu_{max} D$ and ϵ is a small number. The transmitting vehicle requires W_{DL} processing time to receive gNB's V2V grant whereas the receiving vehicles require a constant processing time, W_{SL-RX}, to receive V2V DENM [25], [26]. Thus, the average V2V E2E delay is given as:

$$W_{V2V} = W_{UL} + W_{Q,V2V} + W_{DL} + D + W_{SL-RX}. \tag{11}$$

When both V2I and V2V links are used to send DENMs to vehicles, the delay for each message is given by the minimum of the delays over the V2I link and over the V2V link. As can be seen by comparing Eq. (6) and Eq. (11), on average, the delay over the V2I link is expected to be lower than the delay over V2V the link. This is because, in 5G NR V2V Mode 1, the vehicle requires a V2V grant from its gNB before it can broadcast DENM on V2V. So, when a DENM is received over the V2I link, its delay is expected to be the same as the delay over V2I link, irrespective of whether it is received through the V2V link or not. Moreover, some DENMs might be received by a vehicle through the V2V link only because of a V2I multicast reception failure. In this case, their delay will be the same as the delay over V2V link. So, the average delay for DENM transmission over both V2I and V2V links is given as:

$$W_{V2I+V2V} = \alpha W_{V2I} + (1-\alpha)W_{V2V}, \tag{12}$$

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where $0 \leq \alpha \leq 1$ is the fraction of messages received over the V2I link. The average value of α can be estimated from the simulation.

B. Analysis of Background Data Traffic Transmission

The average throughput of background traffic for vehicle k at TTI t is given by Eq. (3). With the approach in [38], we derive an expression for steady state average throughput for the case when resources for background traffic are assigned. The resources for background traffic are assigned in a TTI only if that TTI is not used for DENM broadcasting with the probability of $1-\rho$. Thus, Eq. (3) is modified as [38]:

$$R_k(t) = (1-\gamma)R_k(t-1) + (1-\rho)\gamma\phi \sum_{z=1}^{|S_m|}\sum_{n=1}^{N_{V2I}} (1-\phi)^{z-1} I_{kn}^{z}(t) r_{kn}(t), \quad (13)$$

where ϕ is the probability that the buffer of vehicle k is not empty, S_m is the set of all vehicles under the coverage of serving gNB m, and $I_{kn}^{z}(t), z \in 1, 2, ...|S_m|$, is an indicator that equals 1 if vehicle k is ranked z^{th} on RB n and equals 0, otherwise. In a steady-state,

$$\mathbb{E}\left[R_k(t-1)\right] = \mathbb{E}\left[R_k(t)\right] = \mathbb{E}\left[R_k\right]. \quad (14)$$

Thus, by Eq. (13), the steady-state average throughput is:

$$\mathbb{E}\left[R_k\right] = (1-\rho)\phi \sum_{z=1}^{|S_m|}\sum_{n=1}^{N_{V2I}} (1-\phi)^{z-1} \mathbb{E}\left[I_{kn}^{z}(t) r_{kn}(t)\right]. \quad (15)$$

Note that a Gaussian approximation for an instantaneous data rate is good for a wide range of channel conditions [38], [39]. We assume that $r_{kn}(t)$ is Gaussian-distributed with mean μ_{kn} and variance σ_{kn}^2. Further, assuming that a proportional relationship exists between the mean and variance of all vehicles under the coverage of gNB m [38], Eq. (15) is expressed as Eq. (17) (given on next page) [38], where $F_{(0,1)}(y)$ denotes the standard Gaussian CDF and $\mathbf{B}(a,b)$ denotes the beta function, which is given as:

$$\mathbf{B}(a,b) = \frac{(a-1)!(b-1)!}{(a+b-1)!}, \quad (16)$$

where a and b are positive integers. Eq. (17) can be solved numerically to obtain $\mathbb{E}\left[R_k\right], k = 1, 2, ...K$.

$$\mathbb{E}\left[R_k\right] = (1-\rho)\sum_{u=1}^{K}\sum_{n=1}^{N_{V2I}} \frac{\lambda}{\mathbb{E}\left[R_i\right]}\left(1-\frac{\lambda}{\mathbb{E}\left[R_i\right]}\right)^{u-1} \left(\mu_{kn}\mathbf{B}(u, K-u+1) + \sigma_{kn}\int_{-\infty}^{\infty} y \frac{e^{-y^2/2}}{\sqrt{2\gamma}}\left(1-F_{(0,1)}(y)\right)^{u-1} F_{(0,1)}^{K-u}(y)\, dy\right). \quad (17)$$

TABLE II
SIMULATION PARAMETERS

Parameters	Values
Simulated area - Highway	10 km long
Number of lanes	3 + 3 lanes
Lane Width	4 m
Number of gNBs (M)	6
Distance between gNBs	1732 m
Number of vehicles	$200 \sim 1,200$
Average speed [31]	$70 \sim 140$ kmph
SINR threshold	0 dB
Transmission Bandwidth [40]	20 MHz
Number of RBs	100
Carrier frequency V2I link [40]	2 GHz
Carrier frequency V2V link	5.9 GHz
V2V transmission range [32]	250 m
Uplink delay (W_{UL}) [25], [26]	14.5 ms
Vehicle's msg. reception time (W_{DL})	4.5 ms
W_{SL-RX} = W_{DL} + vehicle's msg. processing	5.5 ms
V2I log-normal shadowing parameters	Mean=0 dB, SD=8 dB
V2V log-normal shadowing parameters	Mean=0 dB, SD=3 dB
Thermal noise power [31], [40]	-174 dBm/Hz
gNB TX power (P_{gNB})	46 dBm
Vehicle TX power (P_{veh})	23 dBm
Size of DENM	800 B
Video file size (F)	30 MB
DENM arrival rate (λ)	$\{0.1, 0.5, 1\}$ msg./s

V. RESULTS AND DISCUSSIONS

In this section, the specific simulation parameters, simulation settings, performance metrics, and performance evaluation are explained. The MATLAB-based simulation is performed to verify the proposed algorithm. We also compare the proposed scheme with the work presented in [41]. The parameters adopted in the work are listed in Table II and are discussed hereafter.

A. Performance Evaluation

We consider a 10 km - long highway with 6 lanes, 6 gNBs, and $200 \sim 1,200$ vehicles, with speeds varying from $70 \sim 140$ kmph [31]. The inter-gNB distance is $1,732$ m and the vehicles are handed over from one gNB to another as they move on the highway. We follow the V2I and V2V channel models described in [31]. Fast fading is considered while calculating the path loss for both V2I and V2V links. We follow the 3GPP recommendations outlined in 3GPP TR 36.885 for modeling fast fading [31]. The Inter-cell interference (ICI) is calculated for each vehicle from all the neighboring gNBs in the simulation (i.e., all gNBs except the serving gNB of the vehicle). The ICI is calculated on a per-RB basis. For each RB assigned to the vehicle by the serving gNB, only ICI from those neighboring gNBs that also have that RB scheduled for one of the vehicles in their coverage is included. ICI is used in calculating the SINR for the vehicle while evaluating whether or not the data sent to the vehicle has been successful. The SINR threshold for signal detection is 0 dB. For the V2I and V2V links, the carrier frequencies are 2 GHz and 5.9 GHz, respectively, and the transmission bandwidths are 20

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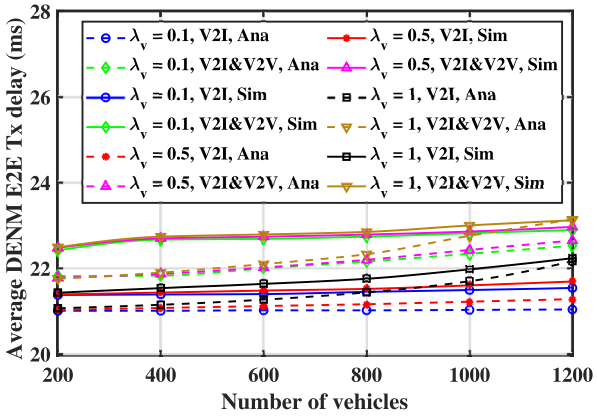

Fig. 3. Average DENM End-to-End (E2E) transmission delay with varying the number of vehicles

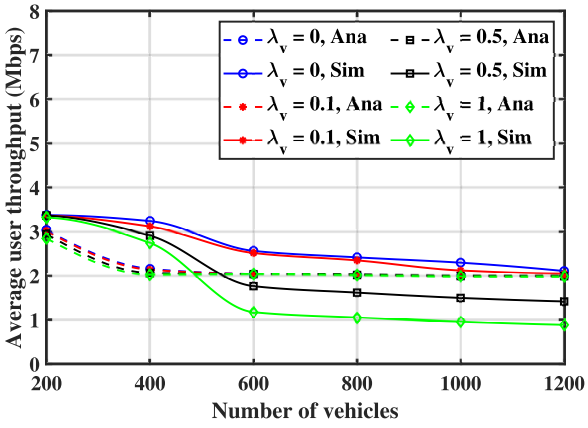

Fig. 5. Average user throughput of background data traffic with varying the number of vehicles

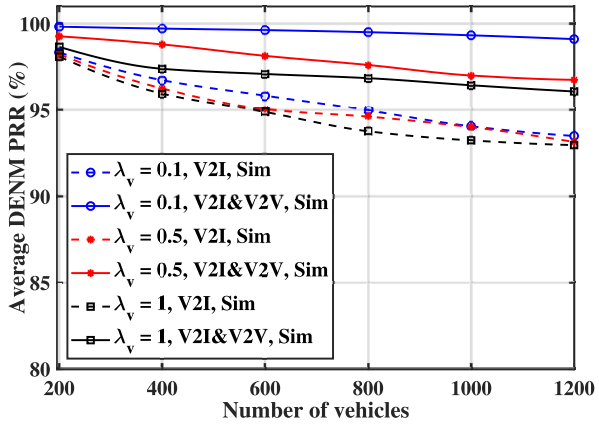

Fig. 4. Average DENM Packet Reception Ratio (PRR) with varying the number of vehicles

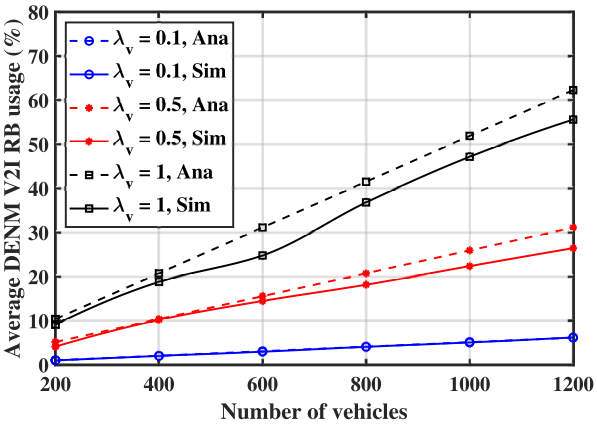

Fig. 6. Average DENM V2I Resource Block (RB) usage with varying the number of vehicles

MHz (100 RBs) for both the links [31]. We assume that the vehicles send the information of their position to the gNB after every 100 ms.

Since the focus of our work is on the DL data transmission, we assume a deterministic value of uplink (UL) delay, W_{UL} [25], [26]. W_{UL} is 14.5 ms and consists of time alignment (1 ms), vehicle's message processing time in upper layers (1 ms), scheduling request time (1 ms), buffer status report time (4 ms), UL grant process time (4 ms), UL DENM transmission time (1 ms), gNB's message reception time in lower layers (1.5 ms), and gNB's message processing time in upper layers (1 ms) [25], [26]. Similarly, the vehicle's message reception time in lower layers (W_{DL}) = 4.5 ms and W_{SL-RX} = W_{DL} + vehicle's message processing time in upper layers = 5.5 ms. For background traffic, each vehicle's serving gNB receives a 30 MB video file at a data rate of 4 Mbps from the 5G NR core network and transmits it to the vehicle over V2I link using PF scheduling [32].

B. Performance Metrics

The following performance metrics are used for the evaluation of the proposed scheme:

1) Average DENM E2E transmission delay, which is the average time required for DENMs to reach destination vehicles after DENM generation.
2) Average DENM Packet Reception Ratio (PRR), which is the ratio of the number of DENMs received by a vehicle to those sent to the vehicle over V2I and/or V2V links.
3) Average DENM V2I RB usage.
4) Average user throughput of background traffic with and without DENM transmission.

C. Simulation Results

Fig. 3 shows the average E2E delay of DENM transmission through multicast using the V2I link as well as, using both V2I and V2V links with varying numbers of vehicles for different λ_v values. The average delay increases with an increasing number of vehicles and arrival rate due to an increase in the

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queuing delay. The average delay when only the V2I link is used is lower than that when both the V2I and V2V links are used. Fig. 4 depicts the DENM PRR for a varying number of vehicles and for different λ_v values. The PRR decreases with an increase in the number of vehicles as well as with an increase in the arrival rate due to the increase in inter-cell interference at the cell edge. As the number of vehicles or arrival rate increases, the gNBs perform DENM scheduling more frequently. This increases the probability that two neighboring gNBs will schedule a DENM in the same TTI, thus increasing inter-cell interference at a cell edge. It can be seen that when a DENM is sent through both links, PRR is higher because the probability of transmission failure of a DENM sent through both V2I and V2V links is lower than that sent through the V2I link alone. For example, for $\lambda_v = 1$ msg/s and 400 vehicles, the average delay using the V2I link only (21.54 ms) is lower than that using both V2I and V2V links (22.79 ms) but PRR using the V2I link only (95.95%) is also lower than that using both the V2I and V2V links (97.39%) Thus, the addition of the V2V link slightly increases the average delay but it simultaneously also increases the DENM transmission reliability.

Fig. 5 shows the average user throughput of background traffic for a varying number of vehicles and different λ_v values. The average throughput decreases with an increase in the number of vehicles because the same amount of resources is shared by a larger number of vehicles. Since the number of DENMs to be multicasted increases with an increase in the arrival rate, the background traffic transmission is delayed, leading to a decrease in average throughput. For example, for 600 vehicles, average throughput decreases from 2.57 Mbps when no DENMs are generated to 1.18 Mbps when DENMs are generated with $\lambda_v = 1$ msg/s. We follow the approach used in [38] to calculate the average throughput of the background traffic transmission. We note that deriving a mathematical expression for throughput under PF scheduling is generally a difficult problem and the only approximate solutions are available in the existing literature. Eq. 17 provides an approximation to the mathematical expression for background traffic throughput, and it is based on a Gaussian distribution approximation for the instantaneous throughput of each vehicle over each RB. This approximation is widely used in the existing literature to analyze throughput under PF scheduling. According to this approximate analysis, there is a discrepancy between the results calculated using Eq. 17 and the simulation results based on PF scheduling. However, we note that the analysis and the simulation curves show the same trend, i.e., a decrease in average throughput with an increasing number of vehicles.

Fig. 6 shows the DENM V2I RB usage for a varying number of vehicles. The RB usage increases with an increase in the number of vehicles and an increase in the arrival rate because more TTIs are used to multicast

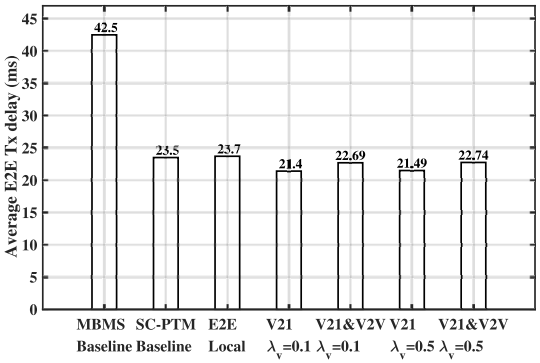

Fig. 7. Comparison of average E2E transmission delay

the DENMs. To validate the proposed scheme, we compare the simulation (Sim) and analytical results (Ana) and note that they match well for the average delay, average user throughput, and DENM V2I RB usage.

The authors in [41] analyze the E2E delay for MBMS, SC-PTM, and V2V. Fig. 7 shows that the average E2E delay achieved by our proposed schemes is very similar to the baseline [41], despite the fact that we simulate multiple vehicles and various DENM arrival rates. We note that the authors in [41] have considered Core Network latency (20ms). Since our proposed schemes do not involve the Core Network, we have removed the Core Network delay from the analysis results of [41] in Fig. 7. We would also like to mention that Figs. 5 and 6 are new performance metrics since we have analyzed the impact of multi-class traffic when DENM is being broadcasted. Therefore, these metrics are not available for comparison in the existing literature.

VI. Conclusion

In this work, we analyze DENM delivery using SC-PTM-based multicast over a V2I link and 5G NR V2V Mode 1-based broadcast over a V2V link in the presence of high throughput background traffic. The analytical results are verified through simulation and they are also compared with the baseline approach. We analyze the performance of the proposed scheme in terms of average E2E delay, PRR, V2I RB usage, and the throughput background traffic. We find that, with our proposed scheme, average E2E delay and average PRR only slightly increase and decrease, respectively, as the number of vehicles increases. Similarly, the average throughput of background traffic shows only a slight decrease with an increasing number of vehicles. The analysis proposed in this work motivates us to explore DENM dissemination in directional mmWave 5G networks, which supports shorter TTI capable of increasing the probability of timely DENM delivery. As future work, we will consider more realistic scenarios by considering lane changes, an urban scenario,

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and the variable speed of vehicles. Especially, we will use Artificial Intelligence (AI)-based techniques (e.g., graph neural networks) for the urban scenario. Also, we will consider security issues to provide secure and safe V2X communications to our DENM delivery.

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