Cellular-V2X for Vulnerable Road User Protection in Cooperative ITS

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***Abstract*—Cooperative Intelligent Transport Systems (C-ITS) play a significant role in improving road traffic safety and efficiency. Primary use cases rely on vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. In C-ITS, the safety of vulnerable road users (VRUs) such as pedestrians, motorists and other users with reduced mobility is being increasingly considered. A warning system, where VRUs actively send and receive messages instead of being passively monitored as road traffic objects, can play an important role in detecting risky situations and allowing the warning of vehicle drivers. However, in a dense urban traffic scenario with closely moving vehicles and pedestrians, the communication network can face severe resource constraints. Considering Cellular-V2X communication systems, the user equipments (UEs) may have to use the unmanaged mode of the sidelink interface. This paper analyzes the limitations of the existing radio resource allocation mechanisms and proposes adaptive strategies to ensure fairness in the distribution of radio resources between vehicles and VRUs. In addition, this work addresses the question about the situations in which VRU safety, being subject to a resource-constrained Cellular-V2X network, can be ensured.**

***Index Terms*—Radio resource allocation in Cellular-V2X, VRU safety and protection, messaging services**

I. Introduction

The core vision of C-ITS revolves around an integrated communication and transportation network that promotes societal benefits and shapes a new era of advanced road safety, enhanced personal mobility, and environmental sustainability. To enable communication between different road traffic users, standardized communication techniques for use cases including cooperative awareness and sensing already exist: the first standards were based on WLAN (IEEE 802.11p); more recently cellular communication systems have been extended to incorporate direct communication between any two user equipments (UEs) using the sidelink (or PC 5) interface [1].

In order to address the aspect of VRU safety, Cellular-Vehicle-to-X (V2X) emphasizes the need to have a dedicated class of messaging service for VRUs with a new message type, the VRU awareness messages (VAMs). VRU messaging has some specific characteristics, i.e., *(i)* Flexibility of the VAM in length and content where the message containers are customized based on the class of VRU including pedestrian, cyclist etc. *(ii)* Adaptable periodicity of the messages depending on the location of the VRU on the road, and *(iii)* Irregularities in the VRUs' spatial distribution and unpredictable behavior, such as gathering up in crowds, stopping suddenly etc.

A typical urban traffic environment consists of stretches of roads within the built-up areas consisting of a large number of vehicles entering and exiting dynamically and an irregular distribution of different types of VRUs. Considering the varying nature of the data applications transmitted by different road traffic participants, it is not sustainable that all the participating nodes get an equal share of the available resources. Based on the availability of cellular coverage, the radio resource allocation is either managed by the base station (a.k.a eNodeB) or by the user equipment (UE) itself [2].

Having an established cellular infrastructure helps in adequate load balancing to ensure fair resource allocation among different users. In areas without cellular network coverage, the UE has to select its resources from a limited radio resource pool, which is referred to as unmanaged mode of operation. The present work aims to investigate the design challenges in this unmanaged mode of radio resource allocation for an urban traffic scenario consisting of vehicle and VRUs, particularly pedestrians, each having different requirements on the type of messaging service.

Approaches to mitigate resource congestion in Cellular-V2X sidelink has been carried out in [3], but the authors do not consider the heterogeneous message types. Taking into account the safety critical requirements of messaging service for vehicles and pedestrians, we propose an adaptive method called cooperative sensing-based decentralized resource management (CS-DRM) to achieve a fair distribution of radio resources among vehicles and pedestrians. The authors acknowledge that a joint Cellular-V2X based use-case study consisting of vehicles and pedestrians in a single simulation framework has not been carried out so far. Detailed investigation of channel characteristics based on vehicle and pedestrian mobility patterns, analysis of radio resource allocation mechanism in unmanaged mode and improving fairness in distribution of radio resources through the proposed CS-DRM method are the key contributions of the present work. The technical aspects of Cellular-V2X are further aligned with the vehicle kinematics in order to achieve suitable safety distances for vehicles, which can ensure pedestrian safety under normal and emergency braking situations.

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The remainder of the paper is structured as follows: Design considerations to model a V2V-V2P communication network using the OMNeT++ based simulator `Artery-C` are presented in Sec. II and Sec. III. Sec. IV provides results of the performance evaluation with an analysis of the limitations of the existing resource allocation mechanisms and aspects of pedestrian safety in subsections IV-A and IV-B. Sec. V concludes the paper with a summary and future prospects.

II. Radio resource allocation in Cellular V2X

This section explains selected aspects of radio resource allocation in 5G-NR V2X, which are relevant for the urban road traffic scenario considered in this work. The concept of fairness is further explained in the context of CV2X unmanaged mode of operation.

Sidelink bandwidth parts (SL-BWP)

In 5G-NR, gNBs are capable of supporting wide bandwidths, i.e., 100 MHz in the FRI and upto 400 MHz in the FR2 frequency bands [1]. However on the UE side, larger bandwidth implies higher power consumption from the radio frequency (RF) and base band signal processing perspectives. Therefore, the standards allow that an UE can configure a certain contiguous portion of the entire carrier bandwidth referred to as bandwidth part (BWP) and apply a selected numerology based on its power handling capabilities, which is particularly beneficial for power constrained VRU devices.

Need for radio resource management

In both LTE-V2X and 5G-NR V2X, only certain slots and a certain number of configurable subchannels are allowed for sidelink transmissions. In the time domain, the slots possible for sidelink transmission occur at a periodicity of 10240 ms and even within a slot, only a portion of the symbols are allowed to carry sidelink transport blocks. This leads to a situation of constrained resources when a large number of vehicles and pedestrians transmit different types of messages.

Some of the most intuitive approaches to reduce the resource occupancy is to adjust the periodicity of transmission for either vehicles or pedestrians and drop certain packets based on priority. Another approach is to adjust the modulation coding scheme (MCS), which in turn increases/decreases the data rate. The primary objective in this work is to find an approach that is able to reduce the resource collisions in unmanaged mode and at the same time ensures fairness for different types of traffic participants.

Fair distribution of radio resources

The two basic parameters to quantitatively analyse channel resource conditions are channel busy ratio (CBR) and channel occupancy ratio (CR). The channel busy ratio is defined as the ratio of the number of occupied subchannels to the total number of configured subchannels. A subchannel is considered occupied if the measured received signal strength indicator (RSSI) is higher than the prescribed threshold. The CR parameter is used to describe channel occupancy of the transmitting UE. The CR at a subframe n is measured as the number of subchannels used for transmissions in subframes in the interval $[n-a, n-1]$ and granted in subframes $[n, n+b]$, divided by the number of configured subchannels in the transmission pool over subframes in the interval $[n-a, n+b]$ subject to constraints $a, b \geq 0$, $a \geq 500$ and $a+b+1 = 1\,000$.

Uniformity in allocation of radio resources means that all the participating UEs in a communication network are allocated the same quantity of radio resources irrespective of the size of data they intend to transmit. However in a dynamic road traffic scenario consisting of UEs with different mobility profiles and message requirements, it is not sustainable that all the UEs are allocated the same share of resources. In order to improve the spectrum utilization and resource allocation, the concept of ”fairness” has been employed where resources are allocated to the UEs based on their transmission requirements. Additionally, a V2X communication system also faces the challenge that the number of nodes is not always constant at all times during the day. This further leads in the direction to define fairness as a parameter that depends on *(i)* node density (number of nodes per sq.m), *(ii)* message transmission rate λ and data size (in bytes), and *(iii)* communication range (in m), which helps us to get an idea of the number of neighbors.

In order to achieve fairness in the allocation of radio resources and at the same time balance the data traffic load, the present paper employs two strategies: *(i)* packet drop and *(ii)* cooperative sensing-based decentralized resource management (CS-DRM).

Packet drop: the aim of this strategy is to reduce the resource occupancy by dropping certain packets that cannot be transmitted due to unavailability of resources. In unmanaged mode, UEs are only partially aware about resource utilization of other UEs. This leads to overlapping of selection windows causing resource collisions especially at higher traffic densities. Dropping certain packets due to unavailability of resources is definitely an intuitive way to reduce the traffic load. Additionally, when an UE switches from managed mode to the unmanaged mode, it experiences larger synchronization delays as studied in [2], where it misses the allocations in its selection window. This leads to frequent re-allocations causing subsequent increase in the resource allocation latency (as studied in [2]). Hence dropping the packet in such a situation can also help to ease the flow of data traffic.

CS-DRM: combining the concepts of radio resource allocation in the unmanaged mode and practical aspects of pedestrian safety, we propose an approach to derive a relation between the transmit power and communication range in order to arrive at a suitable operational range for CBR for both V2V and V2P links. Two analytical approaches namely, linear memoryless range control (LMRC) and gradient descent range control (GRC) have been studied in literature [4]. The former approach targets towards achieving a suitable operational range for CBR while the latter aims in finding an optimal operating point.

The linear mapping between power and CBR utilizing the

LMRC approach can be expressed as,

$$P_{k+1} = P_k + \eta(f(U^k_{max}) - P_k) \tag{1}$$

where P_k is the previous measured value of power and P_{k+1} is the estimated power in the next cycle and η is the gain factor. The optimal CBR for each UE is to be maintained in the range of $[U_{min}, U_{max}]$. The mapping function $f(U^k)$ is defined as,

$$f(U^k) = \begin{cases} P_{max} & \text{if } U_k < U_{min} \\ P_{min} + \eta(P_{max} - P_{min}) & \text{if } U_{min} \leq U_k \leq U_{max} \\ P_{min} & \text{if } U_{max} \leq U_k \end{cases} \tag{2}$$

where $\eta = \frac{U_{max} - U_k}{U_{max} - U_{min}}$ is the gain factor. The CBR metric gives us an estimate of the number of neighbouring UEs and also how frequently can the channel get loaded due to the presence of such UEs.

Extending the concept of LMRC further, an adaptive approach called CS-DRM is proposed here. It helps the vehicles and the pedestrians to cooperatively share their measured CBR values and thereby make a decision on which UE (or groups of UEs) should be allocated the radio resources. For example, if a vehicle receives messages very frequently from a large number of pedestrians, the CBR for the vehicle exceeds a certain range, which in turn implies that a large number of pedestrians are overloading the channel. The vehicle then checks whether these pedestrians are within the collision range and decides about performing a braking manoeuvre. It shares its sensed CBR values with the pedestrian UEs and hence, the nodes will further adapt their transmit power in a certain way such that they cover only a suitable communication range. By employing such an approach, relevant pedestrian UEs (within the communication range) are granted the radio resources in a timely manner. In this work, a specific sensing window length is not defined for CBR but rather it is adjusted between $100 - 1\,000$ ms based on the real-time traffic density on that particular road. To keep the implementation simple, the CBR is appended as an additional field inside the cooperative awareness message (CAM) and VAM message formats for vehicles and pedestrians respectively. Further enhancements for cooperative sensing will involve sharing of vehicle/VRU density maps for the future work.

III. Cellular-V2X simulation framework

The OMNeT++ based discrete event simulation framework `Artery-C` has been further extended with 5G-NR features for sidelink communication. In addition to modeling vehicular movement using the microscopic traffic generator `SUMO`, this work also considers the movement of pedestrians in an urban traffic scenario at one of the busiest intersections in the city of Ingolstadt, Germany.

In order to incorporate a mixed V2X application scenario involving communication between vehicles and pedestrians, we have further introduced VAM broadcast services in the facilities layer in addition to the pre-existing CAM and DENM services. Comparing with the [5], the protocol stack has further undergone enhancements in the MAC layer and the physical layer to include selected 5G features such as variable numerologies, calculation of congestion control parameters and a revised radio resource allocation module based on 5G-NR for the sidelink interface (highlighted in red color in Fig. 1).

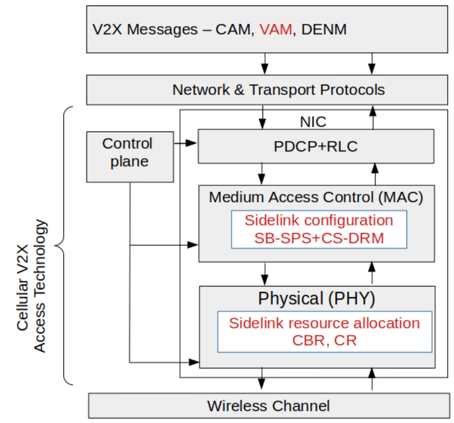


Fig. 1: Cellular-V2X protocol stack

Channel characteristics

Link-level simulations normally deploy same multipath propagation characteristics for all the nodes in a communication network. In our considered urban road traffic scenario, the channel propagation characteristics for vehicle-to-vehicle (V2V) and vehicle-to-pedestrian (V2P) considerably differ owing to different mobility patterns.

Two types of geometry-based channel models have been widely studied in the literature, namely the geometry-based deterministic channel model (GBDCM) [6] and the geometry-based stochastic channel model (GBSCM). The former approach is more detailed for the fact that it models very closely the geometry of all the features such as street width, building, foilage etc. Owing to greater computation complexity of GBDCM, we have adopted the GBSCM approach to model V2V channel propagation characteristics. The Winner II model is discussed for various types of environments in [7]. For the V2V links, we have adopted the Winner II C2 variant [7]. Similar to the studies in [7], the European Telecommunications Standards Institute (ETSI) has also carried out similar studies on Winner II and recommends certain Non-line-of-sight (NLOS) path loss characteristics, which have been considered to model our V2V-NLOS links.

In order to model V2P channels, we have adopted the log-distance path loss models as defined in [8]. Scientific studies on pedestrian mobility have categorized the path loss models into three groups - (i) Static pedestrian, (ii) Moving pedestrian with a speed of 5-7 km/h and (iii) Crowded groups of pedestrians that move slowly (3-4 km/h). Considering the busy intersection and fast movements of pedestrians, we have considered V2P channels of the latter two categories in our implementation.

Urban road traffic model

For the simulation we have chosen the *InTAS* [9], a realistic traffic scenario for the city of Ingolstadt based on *SUMO* [10] which models finer details of a city such as real traffic lights phases, zebra crossings locations, bus stops, parking areas, buildings. For this paper, we have refined pedestrian demands *InTAS* and extrapolated to generate different pedestrians densities using the `striping` model.

In order to develop a Cellular-V2X based vehicle-pedestrian road traffic scenario, we have chosen a certain section in *InTAS* based on the following criteria - *(i)* vehicle/pedestrian traffic density (based on real traffic data collected from the city of Ingolstadt), *(ii)* number of pedestrian accidents during a certain time of the day and *(iii)* availability of cellular network infrastructure. Another point to note is that the chosen section of the urban traffic scenario does not lie within the range of good cellular network coverage and both the vehicles and pedestrians cross the intersections in accordance with the traffic rules since traffic lights are not present. Hence, the UEs operate in the unmanaged mode most of the time. This leads us to the research question - how well can we ensure pedestrian safety outside the regions of cellular network coverage.

IV. Evaluation

The first part of evaluation aims towards analyzing the limitations of the existing resource allocation mechanism in unmanaged mode and further demonstrate how the proposed CS-DRM strategy aims to achieve fairness in distribution of radio resources and eventually control the network congestion caused by simultaneous transmission of messages from vehicle and pedestrian UEs that have a variable message generation frequency (λ) between 1 to $10\,$Hz.

The second part of the evaluation section aims to analyze to what extent a VAM service can ensure pedestrian safety in a crowded urban traffic scenario. By measuring the mean end-to-end (E2E) latency for VAMs, it is possible to verify whether VAMs have arrived within the correct time so that a vehicle is able to brake normally by maintaining a safe front distance to the pedestrian. Also, through simulations, a certain margin of E2E latency is measured where it is still possible to ensure pedestrian safety but the vehicle has to perform an emergency braking manoeuvre.

A. Radio resource allocation

Considering the half duplex (HD) nature of the sidelink, we have already analyzed the probability of packet reception P_r metric in [2] for unmanaged mode of operation. In the present work, P_r is studied in the context of varying CBR conditions to understand *(i)* Cellular-V2X awareness range, *(ii)* P_r for V2V and V2P links in resource constrained situations and *(iii)* Operational CBR range for both vehicle and pedestrian users.

Cellular-V2X awareness range: The permissible distance between the transmitter and receiver UE that guarantees reliable packet reception and SINR above threshold limits is referred to as Cellular-V2X awareness range or sidelink broadcast range. This variable is calculated depending on the measured V2V/V2P SINR for a given distance d between the transmitter and receiver UEs taking into account all propagation conditions listed in Table I. Similar studies have been carried out in [11] and [12] but these studies do not consider varying propagation conditions for different V2X situations.

TABLE I: Cellular-V2X parameters for vehicle and pedestrians users

Parameter	Road user type	
	Vehicle	Pedestrian
Velocity [km/h]	30–50	0–7
Message size [bytes]	300-1500	300-600
Modulation scheme	QPSK	
Channel bandwidth [MHz]	10	
Carrier frequency (f_c) [GHz]	5.9	
Transmit power [Watt] ($P_{r,TX}$)	0.4	0.2
Height of Transmitter antenna [m]	1.5	0.9–1.2
Noise power [dBm] (P_N)	-174	
Doppler shift ($I_{Doppler}$)	yes	no
Penetration loss (L) [dB]	10	0
Shadowing	log-normal	

The sidelink SINR is calculated as follows:

$$SINR|_{dB} = 10log_{10}(\frac{P_{r,TX}}{N_{r,TX}}) - P_L(d) - L - I_{Doppler} \quad (3)$$

Here, the transmit power is calculated as the power distributed over the number of allocated resource blocks $N_{r,TX}$. The value of $N_{r,TX}$ depends on the size of the transport block (TB).

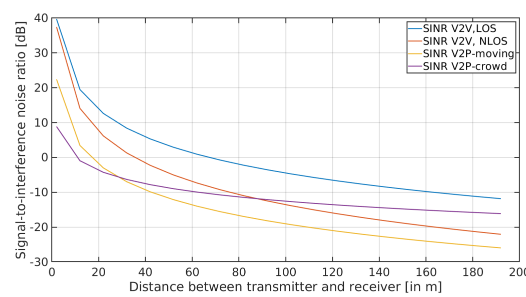
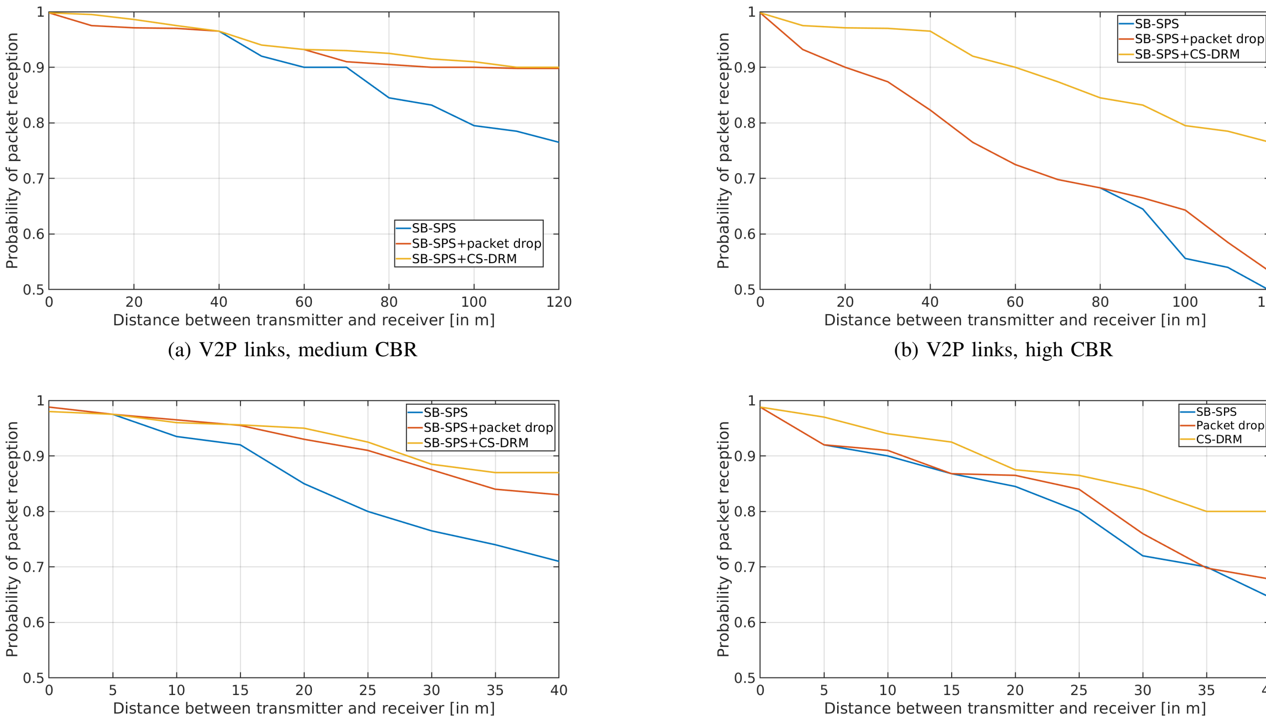


Fig. 2: Sidelink SINR for V2V and V2P scenarios

Fig. 2 illustrates the variation of SINR as a function of distance d between the transmitter and receiver. In order to get an estimate of the awareness range (R_{aw}), we consider a medium level of channel occupancy where the CBR varies within a range of $[0.4, 0.65]$. For V2V situations under good LOS conditions, the awareness range is around $100 - 120\,$m. In case of V2V-NLOS conditions, the penetration and shadowing effects due to buildings and trees deteriorate the SINR beyond $70\,$m. Considering that the transmit power of pedestrian UEs are much smaller than vehicles, the V2P SINR values are in general lower. The V2P awareness range between a single vehicle and a single moving pedestrian is between $30 - 40\,$m and the V2P awareness range between a vehicle and a crowded



(a) V2P links, medium CBR

(b) V2P links, high CBR

(c) V2V links, medium CBR

(d) V2V links, high CBR

Fig. 3: Probability of packet reception vs. awareness range for V2V links (top) and V2P links (bottom)

group of moving pedestrians is between $20 - 30\,\mathrm{m}$. When groups of pedestrians move in a crowd, higher path losses are encountered due to shadowing. The propagation losses due to pedestrian movement are calculated in the simulator in accordance to the studies carried out in [8].

Probability of packet reception: after obtaining the permissible awareness range values for V2V and V2P links as shown in the plots, we study the probability of packet reception (P_r) under two types of channel busy ratio (CBR) conditions, namely medium ($0.4 < CBR < 0.65$) and high ($CBR > 0.7$). The plots in Fig. 3 illustrate how the P_r deteriorates when the distance between transmitter and receiver increases for V2P and V2V links. It can be observed that for a medium CBR range, the packet drop policy is effective in reducing the congestion by nearly $20\,\%$ in V2V links and nearly $15\,\%$ in V2P links respectively. However, under the high CBR conditions, the packet drop policy performs almost similar to the situation where there is no congestion control employed. These cases refer to scenarios of high vehicular and pedestrian traffic density (especially caused by a large number of new vehicles and pedestrians entering the communication range and waiting to be synchronized) and high synchronization latencies (T_{Syn} in [2]). We note that under low CBR conditions, both vehicle and pedestrian are able to successfully utilize $90\,\%$ of the available resources and hence there is no need for active data congestion control.

When packet drop is employed in unmanaged mode of operation, the SB-SPS grant for subsequent transmissions is still maintained, hence no updated SCI is transmitted. This leads to poor resource selection decision for other UEs because they expect that the message will arrive and hence assume that the resource is not free yet. As a consequence, P_r deteriorates to almost $50\,\%$ under high CBR conditions in both V2V and V2P links. Under such a situation, the vehicle will not receive VAMs from the pedestrians within the stipulated latency period and hence will not be able to successfully perform a braking manoeuvre, thereby endangering the life of the pedestrian.

Operational CBR range: in order to ensure a fair distribution of radio resources based on the transmission needs of vehicles and pedestrians, the CS-DRM approach converges at a certain operating range of average CBRs for both V2V and V2P links, see Fig. 4. As illustrated in the figure, with increasing data traffic load from CAMs and VAMs (normalized traffic load) the CBR values for the V2V and the V2P links start growing exponentially.

However, the CS-DRM algorithm controls the transmit power based on the reported CBR values and the chosen value for the gain parameter ($\eta < 1$) in eq. II. When the transmit power is controlled in a certain range, it further limits the transmission range in such a way that when pedestrians are located close to the vehicles (at a distance of $d = 40\,\mathrm{m}$), the reliability of VAM reception can be ensured. Additionally, this approach provides robustness in a sense that even when the vehicular/pedestrian data traffic load dynamically increases, it converges to a certain operational range of average CBR values that both vehicles and pedestrians are able to obtain the required radio resources in a timely manner. This in turn guarantees a P_r of above $80\ \%$ even under high CBR

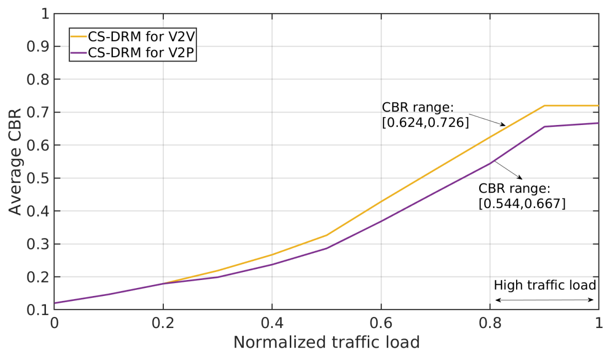


Fig. 4: CBR operational range

conditions (as depicted in Fig. 3b and 3d). The convergence property of the algorithm verifies fairness in distribution of resources and at the same time prevents resource congestion.

B. VRU safety

The stopping distance for the vehicles gets directly affected by the measured E2E latency because a vehicle starts to decelerate only after the successful reception of a VAM. Table II contains information about the mean E2E latency and the recorded stopping distances for vehicles for three different speeds.

TABLE II: Vehicle stopping distance under normal braking

Mean E2E latency [ms]	Vehicle speed [km/h]		
	30	40	50
60 - 80	6.5 - 7.5	13	22.5 - 24
80 - 140	9	15.5 - 16	25 - 26
>140	15	20	30

The values in Table II correspond to the scenario where the distance between the vehicle and the pedestrian is roughly $40 - 45$ m in which normal braking is feasible for the vehicles. The mean E2E latencies in Table II correspond to the 5G-NR V2X technology employing SCS of 15 kHz. The periodic transmission of VAMs by VRUs increases the awareness for the vehicle about the location and movement of the pedestrians. From the simulations we can see that when a vehicle and a pedestrian are approximately $40 - 45$ m apart and the vehicle receives a VAM from a pedestrian, it begins to apply brakes and start decelerating. Under normal braking situations, for a mean E2E latency in the range of $60 - 80$ ms, vehicles in the simulation are successfully able to stop within their specified stopping distances thereby ensuring pedestrian safety.

When the mean E2E latency for VAM further increases in the range of $80 - 140$ ms, in some situations, the vehicle's stopping distances are increased. When VAMs experience mean E2E latencies higher than 140 ms owing to delays in synchronization or resource allocations, the vehicles are unable to meet the stopping deadlines even at speeds of 30 km/h. Hence, in such situations an emergency braking has to be initiated. A more detailed analysis on time-to-collision based on pedestrian mobility and vehicular kinematics will be carried out in future work.

V. Conclusion

The paper has presented a simulation framework to co-simulate vehicle and pedestrian users in a Cellular-V2X environment with detailed modeling of the V2V-V2P channel characteristics. We have analyzed the radio resource allocation mechanism in Cellular-V2X unmanaged mode and identified the situations that lead to bottlenecks and constraints. To improve fairness in the distribution of radio resources, we have investigated the feasibility of the packet drop strategy and further proposed a power adaptive strategy "CS-DRM". Both strategies have been studied for V2V-V2P links in various types of congested road traffic environments. By utilizing Cellular-V2X as an enabling technology, we have further analyzed pedestrian safety from a practical perspective.

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