

An Efficient Mode Selection for improving Resource Utilization in Sidelink V2X Cellular Networks

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Abstract— Sidelink (SL) communication underlying cellular networks is a new paradigm that has been proposed to enhance the performance of cellular networks and support vehicle-to-everything (V2X) communications that enable vehicles to collaborate with other vehicles, devices, and infrastructures. In this way, vehicle-to-vehicle (V2V) communications can be performed using two communication modes, namely cellular communication based on uplink/downlink and direct V2V communications using sidelink. By properly selecting the operating mode according to the requirements of V2X services, significant operational benefits and efficient utilization of the spectrum can be achieved. In this paper, we propose a mode selection algorithm to avoid overload in the sidelink resources. A simulation-based analysis is presented to assess the performance of the proposed solution.

Keywords— Cellular networks, Sidelink , LTE-V2X, Vehicle-to-Vehicle (V2V), Mode selection.

I. INTRODUCTION

Recent progress in wireless technologies, as well as the development of automated connectivity for vehicles, bring new possibilities to improve traffic safety and efficiency. In order to deal with the exchange of safety information in complex road situations, vehicles will have to cooperate with each other and rely on information received from other vehicles. Recently, vehicle-to-everything communications (V2X) have attracted great attention because of the possibility of improving traffic safety. The connected vehicles will rely on V2X communications to deploy active safety services and enable vehicles to collaborate with each other to exchange information such as speed and direction in road safety, providing many traffic notifications and controlling traffic flow. The main goals of V2X are to improve road safety, increase traffic efficiency, passenger information services, and even reduce environmental impacts.

There is already a standardized system (LTE-V2X) that can operate in a wide geographical area and meet the requirements of V2X. In contrast to other approaches like IEEE 802.11p, LTE-V2X requires less additional investments in network infrastructure. The link performance of IEEE 802.11p could also be degraded due to the presence of the hidden node problem [1]. Despite its potential applicability in a vehicular environment, current cellular systems were originally designed for mobile broadband traffic (MBB) which has quite different requirements and properties than V2X traffic. Many works have been done to assess the suitability of cellular systems for traffic safety applications [2,3,4]. LTE-V2X has been designed for specific use cases, and they cover safety applications. Then,

5G V2X (eV2X) will address future use cases mainly dealing with autonomous driving. Integration of the sidelink (SL) (i.e. direct V2V communications) with cellular networks is a key technology to support V2V applications and to meet the requirements for V2X. Sidelink is an LTE feature that was first introduced in 3GPP Release 12 aiming at enabling device-to-device (D2D) communications within legacy cellular-based LTE radio access networks for commercial communication use-cases and public safety. Two transmission modes, namely mode 1 (D2D scheduled) and mode 2 (D2D UE-selected) have been introduced in 3GPP Release 12. SL has been enriched with various features in Release 14 since January 2016 to satisfy the V2X requirements in terms of low latency, high reliability, and network scalability. Release 14 introduced two new communication modes, namely mode 3 (V2V-scheduled) and mode 4 (V2V autonomous sensing) to support sidelink communications. In mode 3, the eNB selects and schedules the exact resources used by direct V2V communications. In mode 4, UEs autonomously select the radio resources for direct V2V transmission without interaction with the eNB.

Introducing sidelink communication between vehicles as an underlay to cellular networks will allow vehicles to operate in two transmission modes, namely cellular mode and sidelink mode. The sidelink mode refers to the direct V2V communication that allows nearby vehicles to communicate and transmit data directly over the PC5 interface and cellular mode indicates indirect transmission through the Uu interface with a two-hop transmission via a base station. In this work, we propose a mode selection algorithm to decide when it is appropriate to use one or the other mode for the involved vehicles. An efficient mode selection algorithm will result in different benefits: i) reducing the network traffic congestion handled by the eNB (cellular mode) or by direct V2V (sidelink mode), and ii) reducing the end-to-end transmission delay.

The rest of this paper is organized as follows. In Section II we present the relevant related works and summarize the contributions of the paper. Section III introduces the system model and assumptions. Section IV discusses the proposed algorithm for mode selection. Section V presents the performance evaluation followed by the conclusions in Section VI.

II. RELATED WORKS AND CONTRIBUTIONS OF THE PAPER

There have been different works carried out to investigate the D2D underlying LTE [5–7] and mode selection [8–16]. An optimal mode selection procedure for a multi-cell environment is proposed in [8] taking into account

the quality of the links for both cellular and D2D links. Further, it also takes into account the interference situation when sharing cellular uplink or downlink resources. The authors of [13] investigated the joint mode selection and channel assignment in a cellular network with underlying D2D communications, where multiple D2D links may share the same channel. Meanwhile, the QoS requirements for both D2D links and cellular users are guaranteed, in terms of Signal-to-Interference-Plus-Noise Ratio (SINR). The authors in [14] proposed an eNB scheduling algorithm to enable the eNB to perform joint scheduling on mode selection, radio resource allocation, and power coordination in D2D communication underlying cellular networks. A novel joint mode selection and channel resource allocation algorithms via the vertex coloring approach are proposed in [15]. Reference [16] proposed a network-assisted mode selection mechanism in a multi-cell scenario when taking into account the QoS requirements for cellular users and resource sharing as well as power optimization for D2D users. However the mode selection schemes in [8]–[16] are conducted for conventional D2D systems and not for V2X communications. In [9] it is assumed that the evolved Node B (eNB) is aware of the full instantaneous channel state information (CSI) of the cellular and D2D links, which might be possible when the D2D users are with slow mobility or static but it's not in fast-moving D2D-based V2X communication due to the rapid changes in vehicle channels status. Moreover, the network may have to perform the mode selection very frequently, resulting in a high computational process and significant cost. On the other hand, some researchers worked on maximizing the sum rate of all users [8,16]. Whereas V2X services are event triggered or periodic, the size of Basic Safety Message (BSM) / Cooperative Awareness Message (CAM) is usually small, so developing strategies to deliver the messages quickly, balancing the network load and offloading the network to avoid deterioration in the quality of services (QoS), and achieve significant system improvements in terms of resource consumption are important issues for V2X applications and need to be investigated to ensure that all the vehicles within the network will receive a high QoS evenly.

Based on all the above, the main contribution of this paper is the proposal and analysis of a novel algorithm for mode selection that takes into account the quality of the links between V2V users in sidelink mode and between eNB and vehicles in cellular mode, the available resources, and the network traffic load situation. Different from previous works, our proposed mode selection strategy targets to achieve the following objectives:

- (i) minimizing the consumption of radio resources
- (ii) reducing the network traffic congestion, and
- (iii) ensuring a high quality of signal for all users in the network.

III. SYSTEM MODEL AND ASSUMPTIONS

A. System model

We consider a scenario with a single cell consisting of a roadside unit (RSU) built within the eNB and a flow of several independent vehicles moving along a straight highway, as illustrated in Figure 1. The vehicles are required to send instantaneous safety information to their neighbor

vehicles using V2V. This can be done either through the sidelink technology enabled by the LTE PC5 interface or in cellular mode using the Uu interface through the eNB (in 2-hops). The RSU/eNB is located in the centre of the cell with distance (D) from a highway segment and communication range (R) defined in meters.

The eNB operates with an LTE channel. The frequency dimension is organized in Resource blocks (RBs) consisting of 12 subcarriers. Since subcarriers are separated by 15 kHz, the total bandwidth of a resource block is 180 kHz. The number of RBs depends on the channel bandwidth, which can range from 1.4 to 20 MHz. The time domain is organized in radio frames of length 10 ms. Each frame is then subdivided into 10 subframes, each one corresponding to a Transmission Time Interval (TTI) of 1 ms. The resource block (RB) is the smallest resource allocation unit that we consider in our model and can be used for data transmission. We assume FDD operation, meaning that there will be the same number of RBs for both UL and DL. In turn, the SL uses RBs from the set of RBs of the UL.

B. Key Assumptions for the proposed Model

- 1- In the specified scenario, the highway segment is divided into sub-segments (clusters) by sectioning the road into smaller zones according to the length of the road. It is assumed that each vehicle communicates with the rest of vehicles in the same cluster. Clusters are numbered as $j \in \{1, \dots, C\}$, and the vehicles in the j -th cluster are numbered as $i \in \{1, \dots, V(j)\}$. The association between clusters and vehicles is managed and maintained by the RSU based on different metrics (e.g. position, direction, speed and link quality) through a periodic exchange of status information.
- 2- The vehicles in the highway are assumed to enter the cell coverage following a Poisson process with arrival rate (λ_v).
- 3- Each vehicle is assumed to generate safety packets randomly with rate (λ_m) according to Poisson arrival model. The length of the messages is S_m .
- 4- We assume that all sidelink UEs get the resource blocks from the resource pools allocated for sidelink V2V and these resources are a subset of available subframes in the UL resources, which are organized based on a periodical subframe pool. We assume that the vehicles transmit packets in a completely interference-free manner, i.e. resources used by a given vehicle are not concurrently selected by any other vehicles within its transmission range or within other cells.
- 5- In cellular mode, the RSU will be utilized to multicast the V2V safety messages to the member vehicles within the same network using eMBMS (one-to-all) communication technology. We assume that when LTE broadcast transmission is utilized, every member vehicle can communicate with the RSU directly as in following steps, where i denotes the i -th vehicle in the cluster j , for $1 \leq i \leq V(j)$ and $1 \leq j \leq C$.
 - o Each member vehicle i transmits the safety information to the RSU through the uplink;

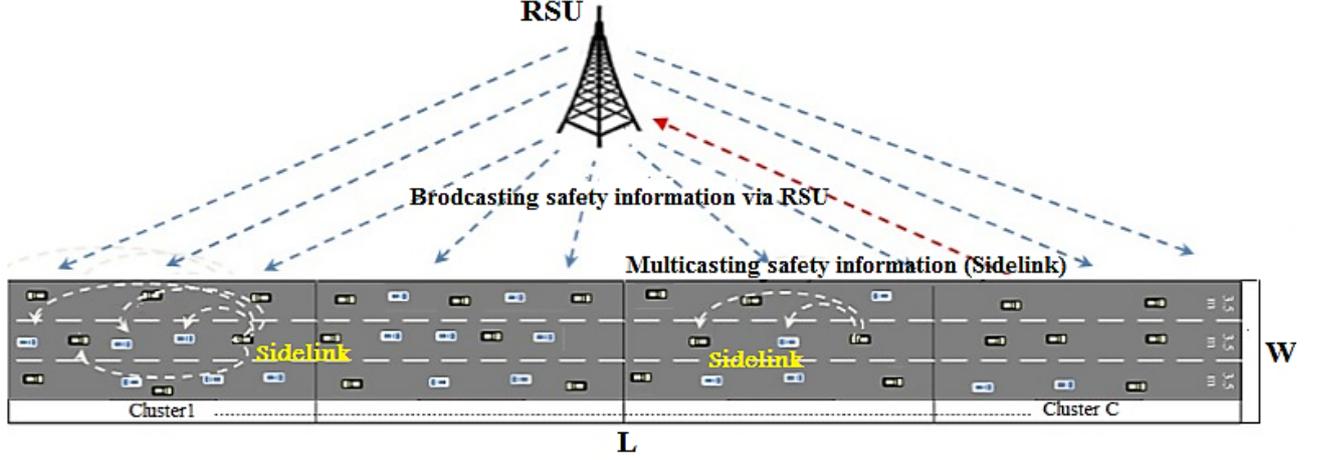


Figure 1 Illustration of the considered scenario and V2X communication models

- o The RSU multicasts this safety information to the other vehicles within the cluster for $1 \leq i' \leq V(j)$, $i' \neq i$
- 6- In sidelink mode, direct V2V communications can be established to share the information of vehicles. We assume that when sidelink transmissions are utilized, every member vehicle can multicast the V2V messages directly to multiple member vehicles of the same cluster $1 \leq i \leq V(j)$ using one-to-many technology, thus reducing the number of required transmission hops.
- 7- The received power signal at each V2V receiver is calculated according to

$$P_{R,i} \text{ (dBm)} = P_{t,i} \text{ (dBm)} - L \text{ (dB)} \quad (1)$$

Where $P_{t,i}$ and L are the transmission power and the propagation loss in dBm and dB, respectively. The propagation loss L includes both shadowing and path loss.

- 8- Let $\gamma_{V2V,i}^{DL}$, $\gamma_{V2V,i}^{UL}$ and $\gamma_{V2V,i}^{SL}$ denote the measured signal-to-noise ratio (SINR) for all the vehicles $1 \leq i \leq V(j)$ in the downlink of cellular mode, uplink of cellular mode, and sidelink mode, respectively. It is assumed that when vehicles get the resource blocks from the resource pools that are allocated for sidelink V2X services, these resources are not used by any other user, no interference between cellular and sidelink users will occur. The number of required RBs for transmitting safety-critical messages in the UL, DL and SL of one cluster, denoted respectively as ρ_{UL} , ρ_{DL} , and ρ_{SL} , can be estimated as follows:

$$\rho_X = \frac{\sum_{i=1}^{V(j)} m(j,i,t) * S_m}{SP_{eff,X} * B * F_d} \quad (2)$$

Where $X \in \text{SL, DL, and UL}$. $m(j,i,t)$ is the number of transmitted safety messages by the vehicles of the j -th cluster in the t -th TTI. $S_{eff,X}$ is the spectral efficiency and B the

bandwidth per RB. F_d is the TTI duration which is 0.1 ms. S_m represents the size of safety message, and $V(j)$ is the number of vehicles within the j -th cluster that transmit safety messages.

IV. MODE SELECTION ALGORITHM

In this section, we introduce the key steps for our proposed mode selection algorithm in detail. In our proposed mode selection strategy, two different aspects are considered. First, it must ensure that the amount of required RBs that vehicles will need to transmit their safety messages is less than the number of available RBs in the network that are allocated for the mode in which the vehicles are to be switched and operated. Second, ensure reliable connection by switching all the vehicles within the cluster to be served by the mode that has a higher link quality. In this algorithm, each vehicle transmits the information about the location and the received SINR from the RSU and other transmitting vehicles respectively to the eNB and the eNB will decide whether the vehicle must switch to another mode or stay in the same mode as it operates. The algorithm steps are shown in Algorithm 1. Starting from $j = 1$, the outer loop iterates through all the clusters and the inner loop is initiated to iterate vehicles to decide the optimal mode of operation for each cluster. Each vehicle i -th in each cluster estimates the SINR received from the eNB and other vehicles in the inner loop (lines 5-8). The average of SINR for all the UEs within each cluster is calculated for each mode to decide whether the vehicles within each cluster must switch to another mode or stay at the same mode in which it operates. The average of SINR is measured within a time window T . First the average SINR for each cluster of vehicles is computed for each mode of operation and compared to each other (lines 9-11). The algorithm will keep track about the available RBs and check the capacity to avoid the network congestion and to ensure that the cell has sufficient physical resources at each mode to be used for serving the V2V links before taking the decision for switching.

If the average values of SINR for both uplink and downlink in the j -th cluster are higher than the average value of sidelink SINR, i.e. $\text{Min}(\gamma_{V2V,i}^{DL}, \gamma_{V2V,i}^{UL}) > \gamma_{V2V,i}^{SL}$, and the number of available RBs at the cell (Φ) for cellular users

is higher than the RBs required by V2V links within the cluster, then it is switched to the cellular mode, otherwise the V2V will stay in sidelink mode as line (12-24) shows

Algorithm 1: Mode selection scheme

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1 Input:  $V(j)$ ' vehicles in cluster  $j$ ,  $C$ : number of clusters.
2 Initialization: All the clusters are in sidelink mode
3 begin
4   For  $j \leftarrow 1$  to  $C$  do
5     For  $i \leftarrow 1$  to  $V(j)$  do
6       measure the  $\gamma_{V2V,i}^{SL}$  &&  $\gamma_{V2V,i}^{DL}$ ,  $\gamma_{V2V,i}^{UL}$  for vehicle  $i$ 
7     End
8     Find the average value of  $\gamma_{V2V,i}^{SL}$ , among all vehicles
       within cluster  $j$ 
9     Find the average value of  $\gamma_{V2V,i}^{DL}$  and  $\gamma_{V2V,i}^{UL}$  among all vehicles
       within cluster  $j$ 
10
11    If  $\text{Min}[\gamma_{V2V,j}^{UL}, \gamma_{V2V,j}^{UL}] > \gamma_{V2V,j}^{SL}$ ,
12      Check the availability of RBs for each mode
13      If RBs required by V2V links  $< \Phi$ 
14        V2V transmit via cellular mode
15      else
16        V2V transmit via Sidelink mode
17      End
18    else
19      V2V transmit via Sidelink mode
20    End
21  End
22 End
23 End
24 End

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V. PERFORMANCE ANALYSIS

In order to demonstrate the feasibility of the proposed mode selection algorithm, a single LTE cell is simulated in MATLAB. All relevant system and simulation parameters are summarized in Table I. Simulations were conducted for different critical-safety message sizes S_m : 300 bytes, 800 bytes, and 1200 bytes. Similarly, different offered loads are imulated by varying the rate of vehicles λ_v (vehicles/s) arriving to the highway.

The main characteristic of the proposed mode selection algorithm is to reduce the channel congestion due to an increase in demands for the RBs and achieve an efficient usage of the available RBs at the cell. Then, in order to get a vision and check the behavior of the algorithm, different performance metrics such as offered load, required resource blocks (RBs), and traffic congestion are evaluated. The proposed approach is compared against a reference scheme in which the vehicles always operate in sidelink mode. Figure 2 depicts the data traffic load delivered in Kbits/sec for the sidelink communications with the proposed algorithm and with the reference scheme. The figure illustrates with three lines the behavior for different message sizes S_m

(300,800, and 1200) bytes. Here, we can clearly observe that when vehicle arrival rate λ_v is increased, more vehicles will use the network and request RBs to be used for the transmissions. For all the assumed arrival rates under consideration, the figure shows that there is a marked decrease in data traffic load for sidelink direct V2V system. This occurs because, with the proposed approach, some users switch to operate and send the safety information through the cellular mode instead of through the sidelink mode. Fig.3 presents the RB utilisation for the sidelink (i.e. the number of used RBs normalized to the number of total available RBs for the SL). It shows that the proposed algorithm is able to reduce resource consumption. In the proposed algorithm, the required RBs for SL transmission are reduced when the arrival rate and thus the number of vehicles transmitting critical safety messages is reduced and when the messages sizes are small. By switching the vehicles who receive a high SINR from the eNB to operate in cellular mode, we keep some proportion of RBs to be utilized by the vehicles that do not receive a good quality of service from the eNB and are able to operate in SL mode only. From Fig. 3, it is observed that our proposed algorithm saves up to 20 % of the SL resources with respect to the reference scheme. This turns into an increase in the RB utilisation for cellular mode in both UL and DL, as shown in Fig. 4 and Fig.5. In this case, the algorithm ensures that all the vehicles within the network will receive a high QoS evenly, offloading the network and avoiding the outage of service due to the lack of resources.

Table I - Simulation parameters

Parameter	Values	
Number of RBs per cell	100 RBs For uplink pool	50% for sidelink transmission (sidelink mode)
		50% for uplink transmission (cellular mode)
	100 RBs for downlink broadcast (cellular mode)	
Number of lanes	3 in one direction (one is considered in the freeway)	
Length of the street	Freeway length = 1 Km	
Lane width	4 m	
Size of cluster	250m	
Number of clusters	4	
Vehicular UE height	1.5m	
safety message size (S_m)	{300,800,1200} bytes	
Number of safety packets	1 [packets/s]	
Path loss model	The path loss and the LOS probability for cellular mode are modeled as in [17]. In sidelink mode, all V2V links are modeled based on freeway case (WINNER+B1) with hexagonal layout [ITU-R] [18].	
Spectral efficiency model to map SINR.	Model in section A.1 of [19]. The maximum spectral efficiency is 4.4 b/s/Hz.	
Base station antenna gain	5 dB	
Shadowing standard deviation	3 dB in LOS and 4 dB in NLOS.	
Frequency	2.6 GHz	
Time window T	3s	
vehicle speed	80 Km/h	
vehicle arrival rate (λ_v).	Poisson model. Different average values considered in the simulations to simulate different loads.	

In turn, from Fig. 4 it is observed that the maximum RB utilization in the uplink is about 48% when the vehicles arrival rate is 5 vehicles/s and the message size is 1200 bytes, while for downlink transmission (see Fig. 5), the maximum RB utilization is only about 24% when the vehicles arrival rate is 5 vehicles/s and the message size is 1200 bytes. It is worth mentioning that Fig. 4 and Fig. 5 only depict the case of the proposed algorithm because with the reference scheme there are no vehicles transmitting in cellular mode. Another relevant aspect is that the proposed algorithm can reduce the network traffic congestion result due to the increase in demands for the RBs. This is observed in Fig. 6, which depicts the congestion probability (i.e. the probability that there are not sufficient RBs to serve all the transmission requests). Results are presented for message size 1200 bytes. It is observed that the proposed approach can substantially reduce the congestion probability in relation to the reference scheme.

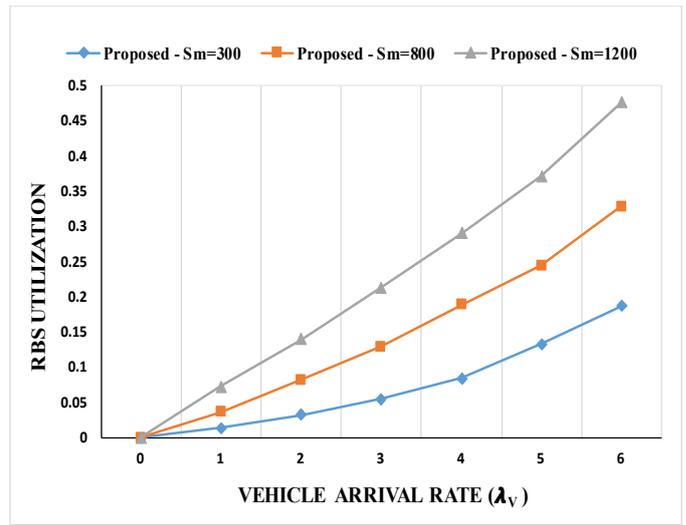


Fig.4 Resource Blocks Utilization for uplink transmissions vs Vehicle Arrival Rate λ_v (vehicles/s)

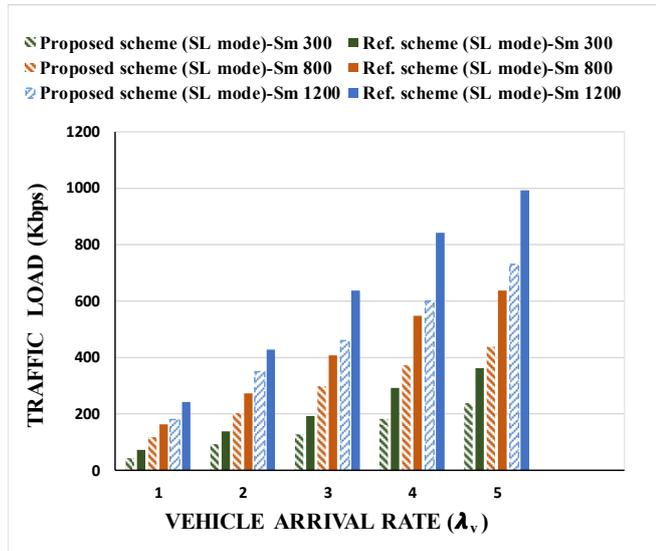


Fig.2 Network Traffic Load for sidelink V2V communications vs Vehicle Arrival Rate λ_v (vehicles/s).

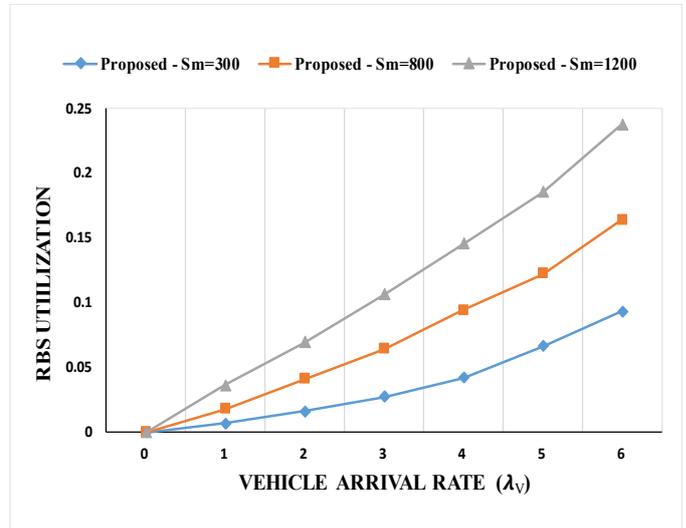


Fig.5 Resource Blocks Utilization for downlink transmissions vs Vehicle Arrival Rate λ_v (vehicles/s)

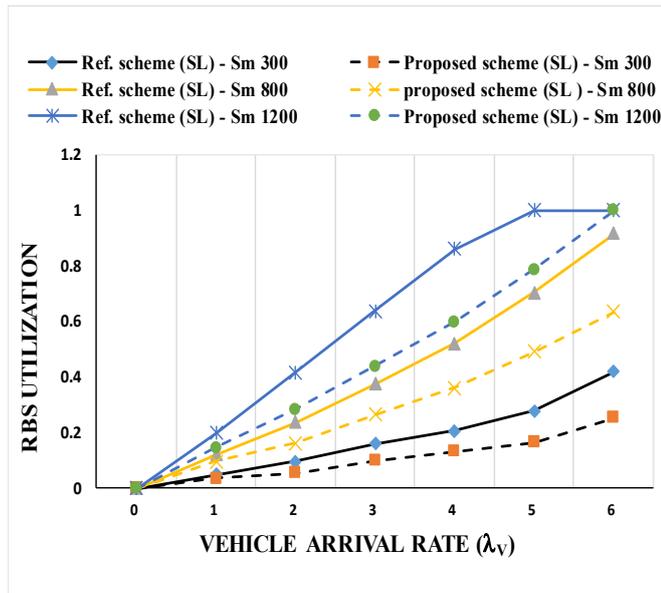


Fig.3 Utilization of Resource Blocks in sidelink mode vs Vehicle Arrival Rate λ_v (vehicles/s).

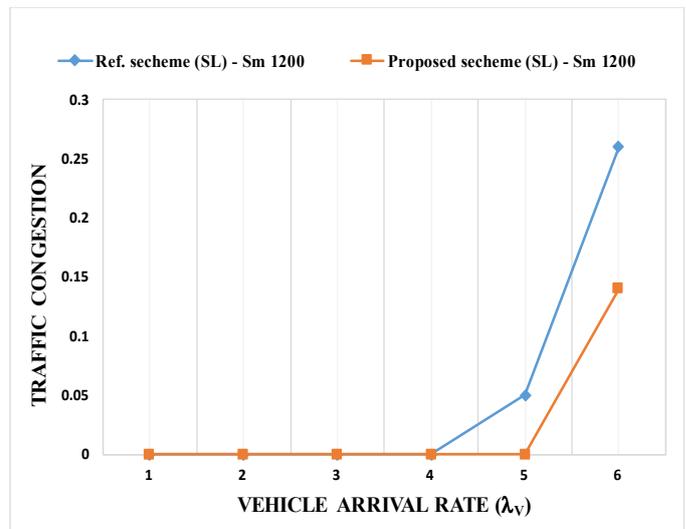


Fig.6 Traffic congestion for Sidelink vs Vehicle Arrival Rate λ_v (vehicles/s)

VI. CONCLUSIONS AND FUTURE WORK

In this paper, we have investigated the mode selection in direct V2V communications underlying cellular network. Specifically, a new mode selection algorithm has been proposed to decide the adequate mode of operation (i.e. cellular or sidelink) for transmitting V2V messages. The proposed mode selection algorithm is introduced with a main focus on optimizing the system performance for sidelink (direct V2V) communication in terms of network capacity, data traffic load and network congestion. For this purpose, the proposed mode selection algorithm checks the received signal by the users from the eNB and other transmitting vehicles, respectively, and switches the user to operate in the mode with highest SINR after checking that there are enough resources to be utilized for transmitting the safety messages. The evaluation of the performance is achieved through simulations in a realistic highway scenario. Simulation results have shown that the proposed algorithm improves the network performance for sidelink communication in terms of network capacity and network congestion without causing significant harm to the cellular network. Based on the current work, future work intends to introduce other aspects in the model to assess the performance in terms of packet delays. Similarly, applying the current V2V mode selection algorithm in a multi-cell scenario can be considered as a relevant direction for future works.

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