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IJIE

http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

Internet of Vehicles Based On Cellular-Vehicle-To-Everything (C-V2X)

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DOI: https://doi.org/10.30880/ijie.2023.15.05.026
Received 1 August 2023; Accepted 15 August 2023; Available online 19 October 2023

Abstract: In line with the development of automotive and traffic systems, high mobility and density in different road topologies cause scalability and delay issues due to frequent disconnection between communication nodes. From a safety aspect, Cellular-V2X (C-V2X) wireless technology was introduced by the Third Generation Partnership Project Organization (3GPP) to realise the transmission of emergency messages at critical times, anywhere. Specifically, Mode 4 C-V2X supports side-link communication without relying on a base station to provide network coverage. However, Mode 4 is susceptible to several limitations, which include half-duplex transmission, packet collision, and propagation errors that will cause intermittent connectivity issues. It is also difficult to determine appropriate parameter configurations that can increase the spectrum efficiency of dense networks to facilitate reliable and low-latency networks. The objective of this paper is to investigate the effectiveness of a Mode 4 C-V2X system under different road topologies and traffic scenarios. The study adopts a Krauss vehicular mobility model based on SUMO software to model normal and dense networks in a highway and a road intersection scenario, then perform simulation using OMNET++ software to analyse the impact of different physical layer (PHY) configurations such as modulation and coding scheme, packet size, number of resource block allocation, as well as the probability of resource reservation. The results show that the optimal configuration of parameters depends on the scenario. For highway scenarios, a lower MCS and a higher number of RBs are recommended. For road intersection scenarios, a higher MCS and a lower number of RBs are recommended. The packet size should also be in accordance with the requirements of the application used. The findings of this study can be used to assist in the design of an optimal intelligent transportation system using adaptive C-V2X parameters that can be automatically adjusted under different scenarios and network conditions.

Keywords: Vehicle-to-everything (V2X), C-V2X, Mode 4, vehicle mobility, highway, intersection

1. Introduction

According to the statistics by the Ministry of Transport Malaysia [1], there are about 1.35 million fatalities in road accidents annually, representing an average of 3,700 loss of lives daily on the roads. Intelligent Transport System (ITS) provides multiple applications that contribute to road safety, traffic efficiency and infotainment services. For instance, in terms of safety, vehicles can reduce traffic problems and avoid the tragedy of road accidents by sending alerts and warning messages [2-4]. However, vehicle communications experience the constraint of delay in the transmission of emergency control messages between vehicles by several milliseconds [5]. High mobility and density of vehicles in

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complex road systems further worsen scalability and delay issues. For the past few years, Dedicated Short Range Communication (DSRC), also known as the IEEE 802.11p, has been proposed for wireless vehicular communication technology. Cellular-Vehicle-to-Everything (C-V2X) or Long-Term Evolution-Vehicular (LTE-V), on the other hand, is a comparatively new technology introduced by 3GPP in Release 14 [6], which extends the Proximity Services (ProSe) in 3GPP Release 12 [7] to another two new modes, namely Mode 3 and Mode 4 that supports the direct communication between vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I). Mode 3 works with an enhanced base station (eNB), where vehicles can only operate inside the coverage. Mode 4, on the other hand, enables communication without the dependency on eNB. However, Mode 4 suffers intermittent connectivity issues. It is also difficult to determine the most appropriate parameter configurations for efficient spectrum utilisation and low-latency networks.

C-V2X uses single carrier frequency division multiple access (SC-FDMA) in the uplink and orthogonal frequency division multiple access (OFDMA) in the downlink. It uses the 5.9 GHz band with a channel bandwidth of 10 MHz. The medium access method used is the semi-persistent scheduling (SPS) technique. In SPS, the vehicle transmits in a new subchannel for a period of selection window, known as resource reservation time interval (RRI), ranging from 20 ms to 100 ms based on the higher layer requirements [8]. In the selection window, each node consists of candidate single subframe resources (CSRs), which detects and stores slots located within the sensing period. The remaining unused CSRs must be at least 20% of the original total number of CSRs. Else, the process will be repeated with an increment of 3 dB RSRP threshold value. Then, the remaining 20% of the CSRs with the lowest average received signal strength indicator (RSSI) will be autonomously selected to reserve the channel. Thereafter, the vehicle reserves the selected subchannel for a random consecutive period determined by the packet reselection counter (PRC), which ranges from 5 to 15. After each transmission, it decreases by one. When PRC finally reaches zero, the vehicle will decide whether to continue to store the resource with a probability of (1-P), where P is the probability of resource reservation ranging between 0 to 0.8 as no specific value is given in [6]. If the size of the packet does not match the size of the stored subchannel that caused the packet collision to occur, then a new source will be re-elected.

Several studies [7-11] have shown that direct communications using C-V2X outperform 802.11p/DSRC in several aspects, including longer communications range, providing a better link budget, and allowing redundant transmission per packet. However, the study in [14] has shown that Mode 4 C-V2X in high vehicle densities is less effective than DSRC due to its higher end-to-end latency. Hence, the investigation of C-V2X Mode 4 is crucial to further improve its functionality and effectiveness. For studies focusing on C-V2X, [15] has investigated the performance of Mode 4 on highways with different channel loads. [16] analysed C-V2X in standardised linear power averaging procedure by evaluating P. Furthermore, the SPS access method based on the number of subchannels, resource reservation period and P in a highway scenario has been investigated [13]. In [15], the error rates of Mode 4 in urban scenarios have been investigated, where it was found that transmission blocks experience half-duplex errors, transmission errors, and no SCI issues. Though these papers have been investigating the impact of change of some parameters on the performance of mode 4 C-V2X and showed the types of transmission errors Mode 4 may suffer, those studies were solely focused on the investigation of highway scenarios. The number of packet sizes investigated is also small. Even when an urban scenario is considered [18, 19], the limitation of that approach is that the vehicles in the model are generated randomly, which does not reflect the real-world scenario.

To this aim, this study investigates the impact of SPS and physical layers parameters on Mode 4 C-V2X in two different Krauss vehicular mobility models, which are road intersections and highways in normal and dense scenarios. Five different configurations of parameters are investigated, which include modulation and coding scheme (MCS), packet size, number of resource blocks (RB), probability of resource reservation (P), and transmission power (PTx). Lastly, the optimal configuration of parameters is suggested. The rest of the paper is structured as follows. Section 2 explains the implementation methodology, where traffic model development, LTE framework in OMNet++ software, channel models and details of simulation parameters are outlined. Section 3 presents the simulation results and discussion, as well as the suggested optimal parameters configuration for different scenarios. Finally, Section 5 concludes the paper.

2. System Model

In this study, OMNet++ is used as a network simulator. In OMNet++, the framework model used includes INET 3.6.6, Veins 5.0, and Simulator & Simulation of LTE System Level [20]. Then, Simulation of Urban Mobility (SUMO) is used to develop a mobility model. The methodology of this study is divided into three phases, as shown in Figure 1. Firstly, the mobility model of both highway and intersection scenarios in normal and dense conditions is developed. Then, the configuration of the intended parameters to investigate is determined and coded in OMNet++. Lastly, statistical collection and analysis of the result obtained via packet delivery ratio (PDR) and throughput graph and propose the adaptive selection of parameters based on different scenarios.

2.1 Vehicular Mobility Model

In this study, a microscopic flow model is used to describe highway and road intersection mobility models. Different from [18] who develop the model via random car generation, traffic models used in this study were built manually based on the Krauss car model [21], which ensures a vehicle keeps a safety distance that adheres towards preventing vehicle collisions. The Krauss mobility model updates the position and velocity of each vehicle in the simulation at each time step. The acceleration of each vehicle is determined by several factors, including the traffic density, the speed of other vehicles, and the curvature of the road.

There are a few steps to develop the models. Firstly, the *node* file defines the end-to-end points on respective roads. Next, the *edge* file describes the connection from one node to another. Then, the *connection* file defines the connection between one edge to another. After that, the *netccfg* file, which contains information on the node, edge, and extension file is built. Then, a *net.xml* file is generated, which is a summary of traffic model features that contains information about traffic structure, width, lanes and connections. Next, the *route* file describes vehicle movement in the traffic model including acceleration, vehicle length, vehicle minimum distance and vehicle speed. The *Turndefs* defines the probability of turn points. Then, the *jttrouter* command generates vehicle flow file that includes all the features of each vehicle defined above with a specific departure and arrival time. Finally, the *configuration* file summarizes all the details about network files to allow OMNET ++ software to access the network model built to run the simulation. Figure 2 shows the vehicle mobility model construction flow chart while Table 1 summarizes the configuration of the vehicle mobility scenario used in the simulation.

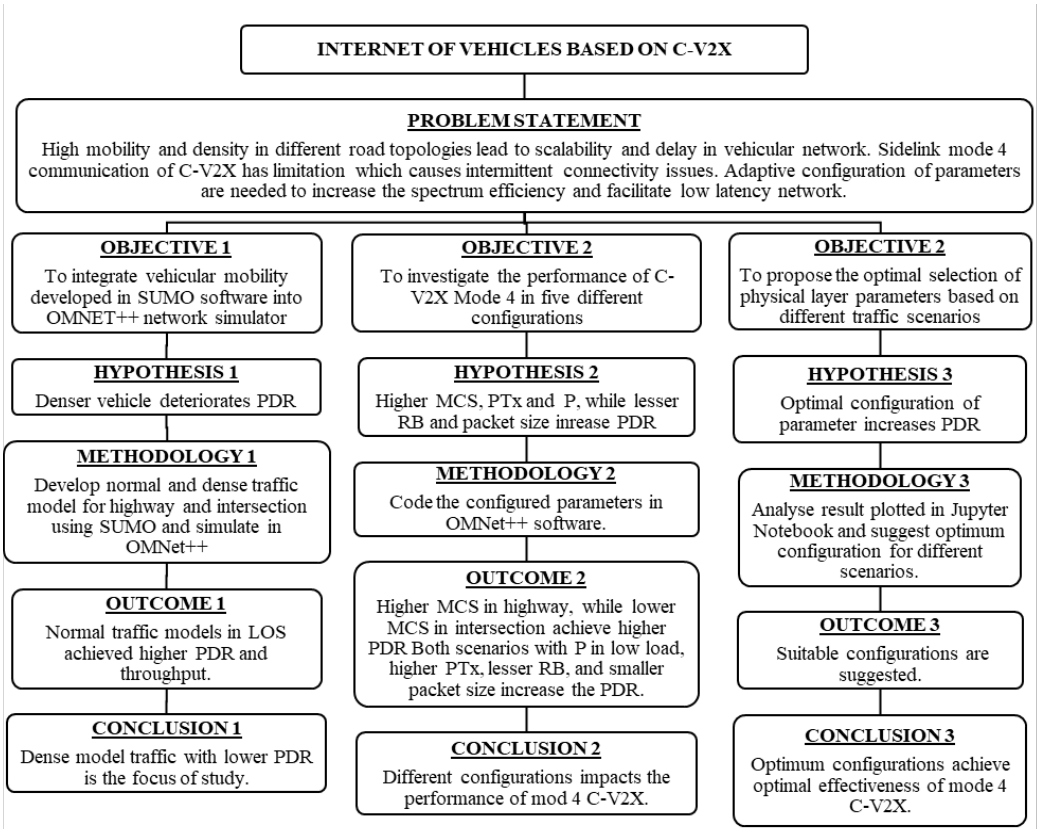


Fig. 1 - Methodology flow chart for this study

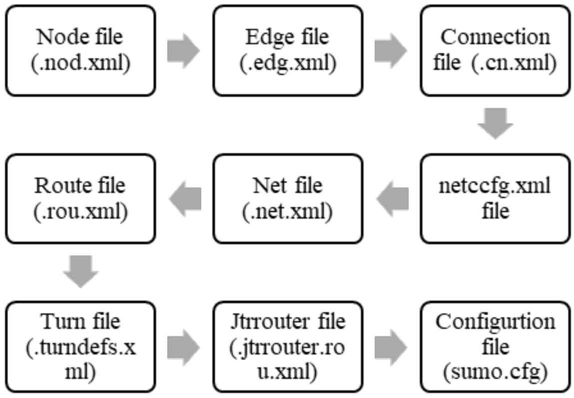


Fig. 2 - Structure of SIMULTE framework in OMNet++

Table 1 - Configuration of vehicle mobility scenarios

Scenario	Highway		Intersection	
	Normal	Congested	Normal	Congested
Number of roads and lanes	2 roads, 3 lanes each		4 roads, 2 lanes each	
Lane width (m)	4		4	
Road length (km)	2	0.6	0.4	0.4
Maximum speed (km/h)	140	35	60	35
Average number of vehicles	126	280	46	252
Vehicle density (cars/km)	10.5	77.78	14.38	78.75

2.2 LTE-V Physical Layer Model

In the SimuLTE framework model, file sources are classified according to the elements in the LTE architecture. For Mode 4, module *LteNicVUeMode4* contains files about the network interface card (NIC), where there are four submodules as follows:

i. *LteNicVUeMode4PdcP*: This is the topmost module, Packet Data Convergence Protocol- Radio Resource Control (PDCP-RRC) that manages the top layer of LTE and provides connectivity between the NIC and the LTE IP module.
ii. *LteNicVUeMode4Rrc*: This is the Radio Link Control (RLC) module, which performs multiplexing and demultiplexing of protocol unit data (PDU) and service unit data (SDU) from the MAC layer.
iii. *LteNicVUeMode4Mac*: This is a MAC module namely works to create packet buffering derived from RLC or PHY. Different parameters can be configured here including MCS, maximum latency and so on.
iv. *LteNicVUeMode4Phy*: The last layer is the PHY module which provides functions related to the physical layer such as packet transmission and reception, channel model type, and PHY layer parameters such as transmission power and antenna profile. The PHY layer will be connected to the outside of the NIC and connected to the radio media.

2.3 Wireless Channel Model

In this study, the WINNER+ B1 channel model [22] was selected as the channel model. It is a statistical model, and the focus of this project is on path loss and fading. The path loss equation in (1) is used for a highway scenario, where feasibility of line-of-sight (LOS) V2V transmission is high. For road intersections, both (2) and (3) are used depending on LOS V2V transmission, or non-line-of-sight (NLOS) conditions due to obstruction of buildings and other objects. Meanwhile, a shadowing factor of 3 dB and 4 dB is used for LOS and NLOS, respectively. The simulation parameters for different scope of studies are shown in Table 2, while other default parameter values used in this paper is shown in Table 3.

LOS Pathloss (dB) [4]

For 3m < d < d'_{BP} :

$$PL_{LOS,hw} = 22.7\log_{10}(d) + 27.0 + 20.0\log_{10}(f_c) \quad (1)$$

For d > d'_{BP} :

$$PL_{LOS,is} = 40.0\log_{10}(d) + 7.56 - 17.3\log_{10}(h'_{Bs}) - 17.3\log_{10}(h'_{Ms}) + 2.7\log_{10}(f_c) \quad (2)$$

NLOS Pathloss (dB) [4]

3m < d < 2000 m :

$$PL_{NLOS,is} = (44.9 - 6.55\log_{10}(h_{Bs}))\log_{10}(d) + 5.83\log_{10}(h_{Bs}) + 18.38 + 23\log_{10}(f_c) \quad (3)$$

Table 2 - Simulation parameters by scope of study

Scope of Study	Parameters	Values					
MCS	MCS	9		14		20	
	Coding Rate	0.518		0.432		0.432	
	Subchannel Size	12		8		6	
	No. of Subchannel	4		6		8	
	TBS Bits	1544		1544		1544	
RB	No. of RB	12		16		24	
	Subchannel Size	4		3		2	
	TBS Bits	1544		2219		3496	
Packet Size	Packet Size (Bytes)	190		300		600	
	MCS	9		9		9	
	Number of RB	48		48		32	
	TBS Bits	2470		2024		2344	
P	P	0		0.4		0.8	
	Transmission frequency (pps)	10	20	10	20	10	20
PTx	PTx (dBm)	20		23		26	
	Transmission frequency (pps)	10	20	10	20	10	20

Table 3 - Default simulation parameter values

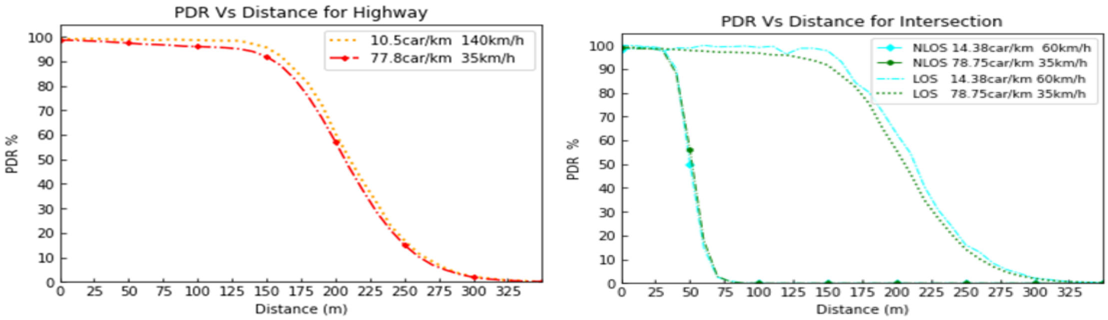
Parameter	Value
Carrier Frequency (fc)	5.91 GHz
Bandwidth (BW)	10 MHz
Thermal Noise (Nt)	-105 dBm
Antenna Gain (Gt, Gr)	3 dBi
Noise Figure	9 dB
MCS	7
Packet Size	190 Bytes
Transmission Power (PTx)	23 dBm
Probability of Resource Reservation (P)	0.4

3. Results and Discussions

3.1 Effect of Vehicle Density

Figure 3 shows the impact of vehicle density on PDR. Normal scenario is used as a comparison standard for dense scenario. Figures 3(a) and 3(b) show that both the highway (10.5 cars/km) and line of sight (LOS) road intersection (14.38 cars/km) model in congested condition achieved lower PDR. The reason is because a higher number of vehicles contributes to higher competition for subchannel resources to transmit data and increases the risk of packet loss, thus lowering the PDR. Hence, dense model traffic will be the focus of this study.

Then in Figure 3(b), the NLOS condition of road intersection achieved shorter communication range compared to its LOS condition, because the loss is higher when there are obstacles between V2V in NLOS. However, for this NLOS condition, the PDR is nearly constant even when the density of vehicle changes, because the communication coverage in this road intersection model is small. Due to this reason, the following simulations for road intersection will not analyse the NLOS condition. Lastly, the communication range do not change even when the speed of vehicle is different at two different densities. This is because the WINNER B1+ channel model implemented in this simulation is merely focusing on pathloss and slow fading that are impacted by distance and shadowing of large objects only. Since it does not depend on frequency, the Doppler shift has a small effect causing the increase in vehicle speed to have no significant effect in the bandwidth difference of the Doppler distribution. Hence, the packet transmission distance does not change even if the vehicle speed changes.



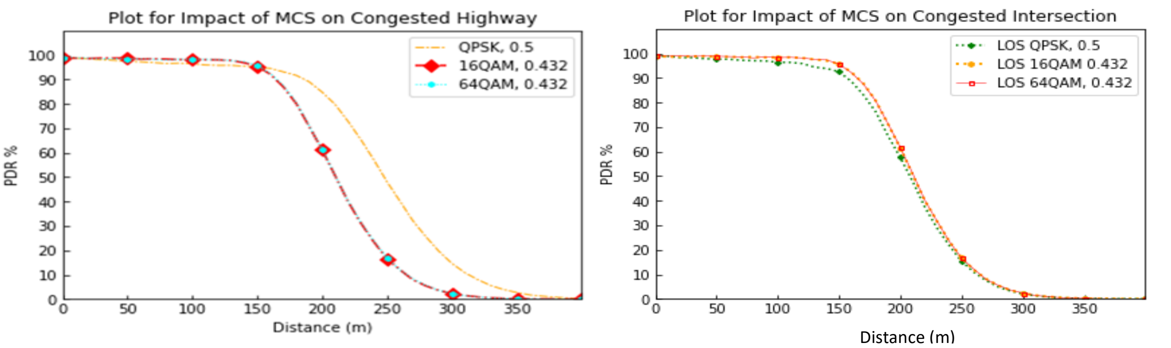
(a) (b)

Fig. 3 - Impact of vehicular density on (a) highway and; (b) road intersection

3.2 Effect of Modulation and Coding Scheme

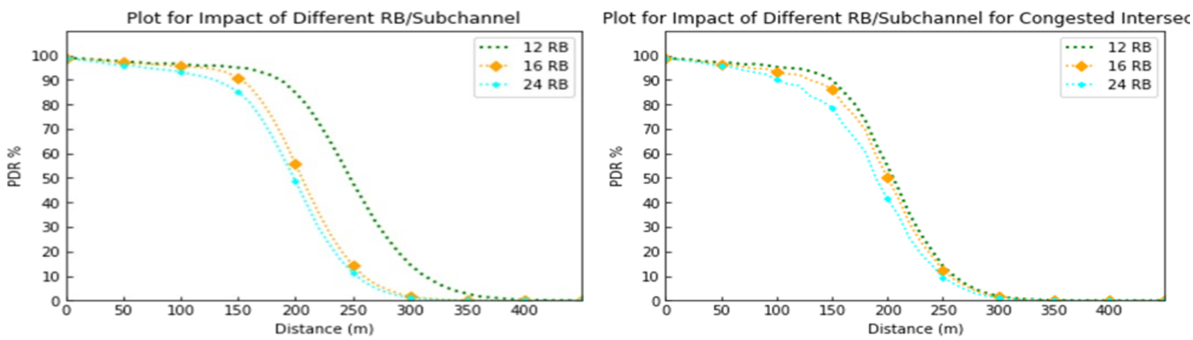
This study investigates the impact of three different modulations and coding schemes (MCS), namely QPSK, 16QAM and 64QAM in congested scenarios. As shown in Figure 4(a), for congested highways, initially, when the communication distance is less than 150m, a higher MCS, which is 16 QAM or 64 QAM has a higher PDR. However, as the distance increases, PDR with high MCS drops significantly. This is due to the increased probability of channel symbol error in higher MCS. Each modulation scheme sent a specific number of bits/symbols in one source element (RE), namely 2 bits/symbols for QPSK, 4 bits/symbols for 16 QAM, and 6 bits/symbols for 64 QAM. Higher order MCS has ability to transmit higher data rates, and this increases the channel capacity, but this reduces the encoding rate where less useful data can be transmitted when more redundant bits are being added to send data. Therefore, as the communication distance increases, high MCS usage is more susceptible to noise interference and will reduce PDR.

In congested road intersection as shown in Figure 4(b), result is opposite of congested highway. Higher MCS now has the higher PDR compared to QPSK. This is because in a congested road intersection, vehicles communicate at a closer distance. So, higher MCS will contribute to higher spectrum efficiency and data rates thus improving the PDR.



(a) (b)

Fig. 4 - Impact of MCS in (a) congested highway; (b) congested road intersection



(a) (b)

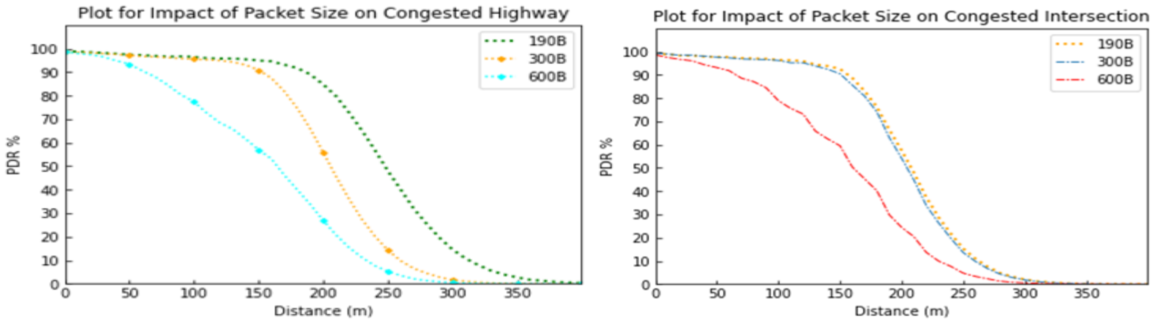
Fig. 5 - Impact of number of RB in (a) congested highway; (b) congested road intersection

3.3 Effect of Number of Resource Block

This study investigates the impact of three different numbers of RB, which is 12, 16 and 24 with a fixed MCS 9 and packet size of 190 Bytes on the performance of Mode 4 C-V2X. Based on Figure 5(a) and 5(b), in both scenarios, it can be seen that the highest PDR is achieved when the number of RBs used is the lowest which is 12. As the number of RBs increased, the PDR achieved decreased because the size of the transmission block determines the number of bits that will be sent from the MAC layer to the PHY layer. So, the increase in number of RBs increases the number of transmission blocks (TBs). Therefore, the capacity to transmit data increases, causing PDR to decrease.

3.4 Effect of Packet Size

Next, study of impact of packet sizes in 190 Bytes, 200 Bytes and 600 Bytes. MCS 9 has been used to send different packet sizes. Results obtained in Figure 6(a) and 6(b) showed that the largest packet size of 600 Bytes has the lowest PDR in both scenarios because increase in packet size cause load in shared wire channel to increase thus lowering the PDR. Not only that, it can be seen that the larger packet also results in shorter communication distances.



(a) (b)

Fig. 6 - Impact of packet size in (a) congested highway; (b) congested Road intersection

3.5 Effect of Probability of Resource Reservation

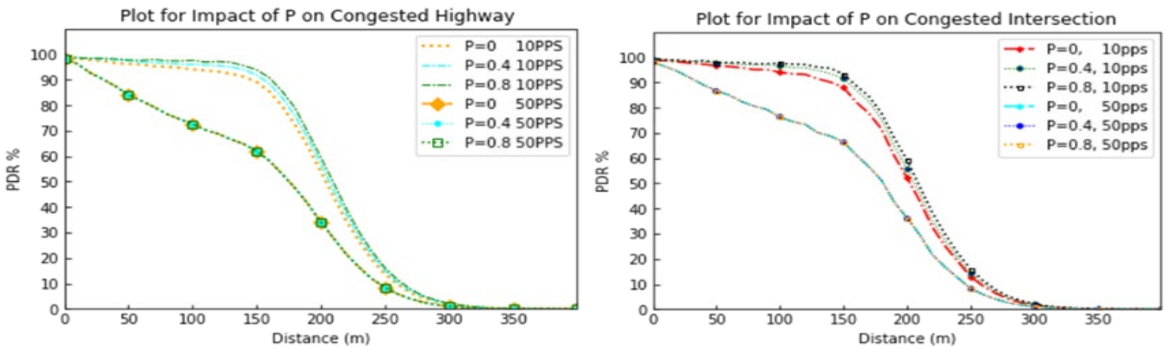
The probability of resource reservation, P is the probability of the vehicle continuing to store the old resource in the channel sensing process using SPS of Mode 4. Although (Luis F. Abanto-Leon 2018; Alessandro Bazzi 2018) have proven that P addition can achieve higher PDRs, their study only focused on low loads. As for the study (Gonzalez-Martin 2019), the high data load studied was limited to randomly generated highway scenarios. Therefore, this study examined the impact of P values of 0, 0.4 and 0.8 on the PDR of Mode 4 C-V2X in highway and road intersection scenarios. Two transmission frequencies were used, where 10 packets per second (pps) represents vehicle communication applications that require low data load, and 50 pps represents vehicle communication applications that want to send high data load were studied. The values of other parameters are according to the default values of this study.

Figure 7(a) shows the impact of the probability of resource reservation (P) on a congested highway, and Figure 7(b) for congested intersection scenarios. After conducting the study, the results of the highway scenario study obtained showed that the P configuration had the same effect in both scenarios. When the transmission frequency is as much as 10 pps, the highest P (i.e., P = 0.8) reaches the highest PDR. This is because when P is high, the previously booked subchannel will continue the booking to send data. As the resource reservation period increases, then the vehicle can use the allocated subchannel more stably without being affected by nearby vehicles. Therefore, data transmission can be sent with less competition thus causing the ratio of successfully sent packets to increase. For 50 pps, the vehicle has to send more packets thus the overall PDR is also reduced. Yet different P values in this high transmission frequency do not affect the PDR. This is because in high load conditions, the risk of packet loss is high regardless of P.

3.6 Mode 4 V2V Parameters Recommendation

For MCS, highway scenarios that generally have a longer transmission distance are desirable to use a lower MCS. This is because low MCS has higher encoding rates and can guarantee more useful data to be transmitted over longer distances with lower redundant bits. Conversely, in a road intersection scenario, higher MCS such as 16 QAM or 64 QAM should be used because the short communication distance in the road intersection requires higher data rates to achieve spectrum efficiency. As for the number of RBs, in both these scenarios, the optimal number of RBs should be selected where it should have sufficient capacity to accommodate the data to be sent but not excessively, which may reduce the efficiency of data transmission. The selected packet size should also be in accordance with the requirements of the application used because the increase in packet size lowers the PDR performance. For example, packet sizes vary when sending Cooperative Awareness Messages (CAM) or Distributed Environment Notification Messages (DENMs).

In addition, the probability of resource reservation (P) needs to be configured according to the data load. In highways as well as congested road intersections, applications that require a lower data load per second are recommended to use higher P values to increase efficiency by achieving higher PDRs. However, the selection of P should consider the density of the scenario. This is because, despite the fact that an increase in P can ensure that more packets are delivered successfully, in situations where there is a high vehicle density and many vehicles compete for a single channel, it may become problematic if a vehicle accidentally chooses a channel that has already been assigned to another vehicle. This is because a high value of P will result in the incorrectly allocated channels continuing to store for a long time, which will cause a packet collision between two approaching vehicles. In high data load applications such as platoon applications, however, due to the P configuration does not contribute to higher efficiency, therefore, in this case, the P value can be selected between the range of [0,0.8]. Table 4 summarises the parameters recommendation under different road scenario.



(a) (b)

Fig. 7 - Impact of P in (a) congested highway; (b) congested road intersection

Table 4 - Parameters recommendation for Mode 4 V2V scenarios

Highway	**Intersection**
Low MCS due to higher vehicle speed	High MCS due to lower vehicle speed
Low traffic load in normal traffic	High traffic load due to many approaching vehicles
High P value	Moderate P value
Mostly near LOS giving higher average communication coverage	Lower average communication coverage due to combination of LOS and NLOS propagation conditions
Setting on number of RBs and packet size is dependent on vehicular applications. Traffic prioritisation at the MAC layer can defined.	

4. Conclusions

In this work, the effectiveness of different configurations of parameters on Mode 4 C-V2X in different scenarios and traffic loads has been studied. Furthermore, an adaptive selection of configuration for each scenario has been proposed. After analysing the impact of different MCS on highways and road intersections, it has been concluded that MCS contributes to opposite outcomes in a congested highway, which need lower order MCS and road junction scenario, which need higher order MCS. The study of the impact of the number of RBs and packet size shows that an increase in RBs only increases the data capacity, thus lowering the PDR. Bigger packet size also has a similar effect in burdening the channel. Therefore, when designing a Mode 4 C-V2X V2V communication network, the optimal number of RBs and packet size should be selected where it should have sufficient capacity to transmit data according to the application. Lastly, this study also evaluated that P improves effectiveness of C-V2X only in low traffic load conditions.

Acknowledgement

This work is partly supported by the research fund provided by the Malaysian Ministry of Higher Education and Universiti Kebangsaan Malaysia under grant codes DPK-2023-004 and GUP-2021-023.

References

[1] Kementerian Pengangkutan Malaysia (2022). Indeks Kematian Jalan Raya. https://www.mot.gov.my/my/land/safety/malaysia-road-fatalities-index.

[2] Sheikh, M. S., Liang, J., & Wang, W. (2020). Security and privacy in vehicular ad hoc network and vehicle cloud computing: a survey. Wireless Communications and Mobile Computing, 2020, 1-25.

[3] Altahrawi, M. A., Abdullah, N. F., Nordin, R., & Ismail, M. (2021). Multi-radio access software-defined vehicular network. IEEE Transactions on Intelligent Transportation Systems, 23(8), 10030-10048.

[4] Al-Mayouf, Y. R. B., Ismail, M., Abdullah, N. F., Al-Qaraawi, S. M., & Mahdi, O. A. (2016). Survey on VANET technologies and simulation models. ARPN Journal of Engineering and Applied Sciences, 11(15), 9414-9427.

[5] Ni, Y., Cai, L., He, J., Vinel, A., Li, Y., Mosavat-Jahromi, H., & Pan, J. (2019). Toward reliable and scalable internet of vehicles: Performance analysis and resource management. Proceedings of the IEEE, 108(2), 324-340.

[6] TR 33.885, 3rd Generation Partnership Project (3GPP) (2017). Study on LTE-based V2X Services; (Release 14). Technical Specification Group Radio Access Network: 1-460.

[7] TS36101, 3rd Generation Partnership Project (3GPP) (2014). Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception: 1-538.

[8] Mansouri, A., Martinez, V., & Härri, J. (2019, January). A first investigation of congestion control for LTE-V2X mode 4. 15th IEEE Annual Conference on Wireless On-demand Network Systems and Services (WONS) (pp. 56-63).

[9] Molina-Masegosa, R., & Gozalvez, J. (2017, June). System level evaluation of LTE-V2V mode 4 communications and its distributed scheduling. IEEE 85th Vehicular Technology Conference (VTC Spring) (pp. 1-5).

[10] Thota, J., Abdullah, N. F., Doufexi, A., & Armour, S. (2018, June). Performance of car-to-car safety broadcast using cellular V2V and IEEE 802.11 P. In 2018 IEEE 87th Vehicular Technology Conference (VTC Spring) (pp. 1-5). IEEE.

[11] Bazzi, A., Cecchini, G., Zanella, A., & Masini, B. M. (2018). Study of the impact of PHY and MAC parameters in 3GPP C-V2V mode 4. IEEE Access, 6, 71685-71698.

[12] Thota, J., Abdullah, N. F., Doufexi, A., & Armour, S. (2019). V2V for vehicular safety applications. IEEE Transactions on Intelligent Transportation Systems, 21(6), 2571-2585

[13] Nguyen, T. V., Shailesh, P., Sudhir, B., Kapil, G., Jiang, L., Wu, Z., & Li, J. (2017, November). A comparison of cellular vehicle-to-everything and dedicated short range communication. IEEE Vehicular Networking Conference (VNC) (pp. 101-108).

[14] Shimizu, T., Lu, H., Kenney, J., & Nakamura, S. (2019, October). Comparison of DSRC and LTE-V2X PC5 mode 4 performance in high vehicle density scenarios. Proceedings of the ITS World Congress (pp. 1-7).

[15] Gonzalez-Martín, M., Sepulcre, M., Molina-Masegosa, R., & Gozalvez, J. (2018). Analytical models of the performance of C-V2X mode 4 vehicular communications. IEEE Transactions on Vehicular Technology, 68(2), 1155-1166.

[16] Abanto-Leon, L. F., Koppelaar, A., & de Groot, S. H. (2018, August). Enhanced C-V2X mode-4 subchannel selection. IEEE 88th Vehicular Technology Conference (VTC-Fall) (pp. 1-5).

[17] Nabil, A., Kaur, K., Dietrich, C., & Marojevic, V. (2018, August). Performance analysis of sensing-based semi-persistent scheduling in C-V2X networks. IEEE 88th vehicular technology conference (VTC-Fall) (pp. 1-5).

[18] Molina-Masegosa, R., & Gozalvez, J. (2017). LTE-V for sidelink 5G V2X vehicular communications: A new 5G technology for short-range vehicle-to-everything communications. IEEE Vehicular Technology Magazine, 12(4), 30-39.

[19] Al-Mayouf, Y. R. B., Abdullah, N. F., Mahdi, O. A., Khan, S., Ismail, M., Guizani, M., & Ahmed, S. H. (2018). Real-time intersection-based segment aware routing algorithm for urban vehicular networks. IEEE Transactions on Intelligent Transportation Systems, 19(7), 2125-2141.

[20] SimuLTE - LTE System Level Simulation Model and Simulator for INET & OMNeT++. https://github.com/inet-framework/simulte.

[21] Song, J., Wu, Y., Xu, Z., & Lin, X. (2014, November). Research on car-following model based on SUMO. 7th IEEE International Conference on Advanced Infocomm Technology (pp. 47-55).

[22] Meinilä, J., Kyösti, P., Hentilä, L., Jämsä, T., Suikkanen, E., Kunnari, E., & Narandžić, M. (2010). Document title: D5. 3: WINNER+ final channel models. IST-4-027756 WINNER II. V1. 0. D5(107):1-107.