

Analysis of Packet drops and Channel Crowding in Vehicle Platooning using V2X communication

Nagacharan Teja Tangirala, Anuj Abraham, Apratim Choudhury, Pranjal Vyas, Rongkai Zhang and Justin Dauwels
School of Electrical and Electronic Engineering
Nanyang Technological University, Singapore
Singapore.

t.nagacharan@ntu.edu.sg, aabraham@ntu.edu.sg, choudhury.apratim@gmail.com, pranjal@ntu.edu.sg, rongkai001@e.ntu.edu.sg,
jdauwels@ntu.edu.sg

Abstract – With the increase in road fatalities and energy consumption, there is a need to improve road traffic in terms of safety and fuel efficiency. Vehicle platooning is one of the areas in road transportation that can be improved to reduce road freight operational costs. In this paper, an MPC (Model Predictive Control) algorithm is formulated based on the combination of Constant Distance (CD) and Headway Time (HT) topology. The simulations are carried out for platooning of Heavy Duty Vehicles (HDVs) using an integrated simulation platform, which combines VISSIM, MATLAB and Network Simulator (NS3). Deliberate communication failures are introduced through NS3 to study the platoon behavior. Further, a solution is proposed to avoid the channel crowding issue. Simulations of the platoon controller indicate that the vehicles follow a desired speed and maintain a desired intervehicular distance. It is also found that the platoon controller avoids collisions due to consecutive packet drops. Finally, an improvement in Packet Delivery Ratio (PDR) is observed with the proposed solution to avoid channel crowding issue.

Keywords— MPC, Platooning, CACC, V2V, WAVE, Channel crowding, Packet drop, Communication.

I. INTRODUCTION

Platooning of autonomous vehicles has the potential to significantly reduce the fuel consumption and human labor along with increasing the safety [6]. It enables a number of vehicles to drive within a short, acceptable inter-vehicular distance and act together as one unit [1]. The heavy duty truck platooning on highway road is analogous to railways. While platooning was originally designed for Automated Highway System (AHS), the improvements in wireless communication and vehicle control technology make it feasible to be used for semi-automated vehicles in the form of Cooperative Adaptive Cruise Control (CACC) [8].

CACC makes use of the Vehicle-to-Vehicle (V2V) wireless communication to share information among the vehicles. One of the protocol that can be used for V2X communication is Wireless Access for Vehicular Environments (WAVE) protocol [9]. WAVE protocol enables extremely low latency message exchange which is essential for safety critical applications such as platooning. On-Board Units (OBU) and Road-Side Units (RSU) are the two classes of WAVE devices. In a platoon, every vehicle is equipped with OBU to enable

V2V communication. Periodically, the vehicle is made to broadcast its state information through Dedicated Short Range Communications (DSRC) message [10]. This allows the vehicles to react faster to sudden changes in acceleration or velocity of the preceding vehicle.

On-field testing of platoon controller is often expensive and limited to a few traffic scenarios. Hence, a robust simulation environment is used to realistically replicate the conditions in which a platoon operates. A combination of VISSIM, MATLAB and the NS3 is used to test platooning. VISSIM is a widely used micro-simulator for traffic modeling. NS3 is used to simulate the communication between platoon vehicles since it supports WAVE architecture. MATLAB is used to coordinate and synchronize the simulations. This integrated simulator setup is developed in-house. The data exchange among the three tools is described in [3].

In this paper, an MPC is designed to control the movement of HDV platoons through a freeway scenario. With the help of the integrated simulator, platoon controller is tested for different antenna gains. Further, packet drop analysis is carried out and a solution is proposed for channel crowding issue.

II. PLATOON MODELLING

The terminology for the platoon is similar to the concept described in [4]. Here, the first vehicle in a platoon is termed as header. For any number of vehicles in the platoon, header will be fixed. The remaining vehicles are termed as the follower vehicles. For each follower vehicle, the immediate predecessor is termed as the leader.

The mathematical modeling of the platoon for longitudinal movement of vehicles is explained in this section. A platoon of vehicles can be considered similar to a mass-spring-damper system [7].

$$m_i \ddot{x}_i + b_i \dot{x}_i = u_i, \quad (1)$$

where, the index i denotes the i^{th} vehicle of the platoon, m_i is the mass, b_i is the damping constant, x_i is the longitudinal position and u_i is the input information of the i^{th} vehicle of the platoon.

III. CONTROLLER IMPLEMENTATION

In this section, a kinematic model [11] for the design of MPC controller is given by Eq. 2.

$$\begin{aligned} x_{k+1}^i &= x_k^i + v_k^i T_s + \frac{1}{2} a_k^i T_s^2 \\ v_{k+1}^i &= v_k^i + a_k^i T_s \end{aligned} \quad (2)$$

where T_s is the sampling time.

The objective of the platoon vehicles is to track the desired speed of the header and maintain intervehicular distances based on the combination of CD and HT topology [12]. In this paper, state vector is formed with the information of three vehicles only. That is, the position and velocity of the header, the $(j-1)^{th}$ vehicle and j^{th} vehicle along with acceleration of the header. The input is the acceleration of $(j-1)^{th}$ vehicle and j^{th} vehicle. Now, considering a n -vehicles platoon, no extension is needed for the state vector or the input vector. The discrete-time model [13] is formed as in Eq. 3,

$$\begin{aligned} X_{k+1} &= AX_k + Bu_{k-1} + B\Delta u_k \\ Y_k &= \begin{bmatrix} x_1 - x_{j-1} \\ x_{j-1} - x_j \\ v_1 - v_{j-1} \\ v_{j-1} - v_j \end{bmatrix} = CX_k \end{aligned} \quad (3)$$

where

$$A = \begin{bmatrix} 1 & T_s & 0 & 0 & 0 & 0 & \frac{1}{2}T_s^2 \\ 0 & 1 & 0 & 0 & 0 & 0 & T_s \\ 0 & 0 & 1 & T_s & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & T_s & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{1}{2}T_s^2 & 0 \\ T_s & 0 \\ 0 & \frac{1}{2}T_s^2 \\ 0 & T_s \\ 0 & 0 \end{bmatrix} \quad C = \begin{bmatrix} 1 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & -1 & 0 & 0 \\ 0 & 1 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & -1 & 0 \end{bmatrix}$$

$$X = [x_1 \quad v_1 \quad x_{j-1} \quad v_{j-1} \quad x_j \quad v_j \quad a_1]^T$$

$$u = [a_{j-1} \quad a_j]^T \quad u_k = u_{k-1} + \Delta u_k$$

Using the formulated discrete time model, the predictions are made for N steps. N is called the prediction horizon. Here, only one step control is considered, that is $\Delta u_{k+n} = 0$ ($n > 0$). The prediction for N steps is given by Eq. 4,

$$\hat{Y} = \begin{bmatrix} Y_{k+1} \\ Y_{k+2} \\ \vdots \\ Y_{k+N} \end{bmatrix} = \Phi X_k + \Gamma u_{k-1} + \Gamma \Delta u_k \quad (4)$$

where,

$$\Phi = \begin{bmatrix} CA \\ CA^2 \\ \vdots \\ CA^N \end{bmatrix} \quad \Gamma = \begin{bmatrix} CB \\ CB + CAB \\ \vdots \\ \sum_{i=0}^N CA^i B \end{bmatrix}$$

The reference R can be generated using different topologies. For CD and HT topology, R is given by Eq. 5,

$$R = \begin{bmatrix} (hd + v_{j-1}T)(j-2) & (hd + v_jT) & 0 & 0 & \dots \\ \dots & (hd + v_{j-1}T)(j-2) & (hd + v_{j-1}T) & 0 & 0 \end{bmatrix}_{4 \times N \times 1}^T \quad (5)$$

According to the control goal in [2], a cost function is formed as shown by Eq. 6,

$$J = (\hat{Y} - R)^T (\hat{Y} - R) + \lambda \Delta u^T \Delta u. \quad (6)$$

where λ is the tuning parameter.

The optimal solution is obtained by minimizing the cost function J . The desired acceleration a_j is applied to the j^{th} vehicle and a_{j-1} is discarded.

IV. PACKET DROP ANALYSIS

To ensure safety of the road users, the platoon movement should be properly constrained with no deviation from a defined set-point. This is achieved with the help of reliable V2V communication among the platoon members. However, communication failures can occur when the platoon vehicles are in motion. This may lead to collision among the platoon vehicles as well as other surrounding traffic. Hence, appropriate fail-safe measures are essential for the platoon controller. A clear understanding of the platoon behavior during communication failures is necessary to develop suitable fail-safe measures. In this paper, two types of communication failures are studied.

A. Interrupted communications

It is quite possible that a follower vehicle experiences a drop in communication for a certain period of time before it communicates again. Some of the reasons are hardware failures, bad weather, unexpected road conditions, intermittent software reboots etc. With the help of integrated simulator, irregular communication dropouts are deliberately introduced into certain follower vehicles to study the platoon behavior. The duration of the dropout is varied to determine the time at which collision occurs.

B. Channel crowding

Another form of communication failure is caused by channel crowding. WAVE protocol supports multi-channel operation. With the help of one radio or multiple radios, a WAVE device can communicate with other devices by switching channels. Various safety and non-safety applications can be supported over different channels. According to IEEE1609.4 standard, channel access can be configured in four ways as shown in Fig. 1.

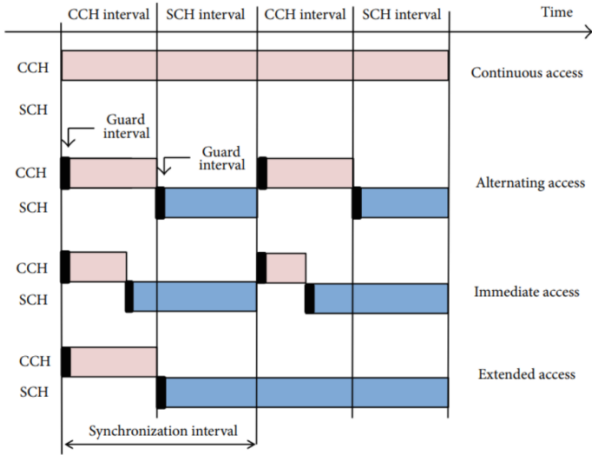


Fig. 1. Channel access configuration as described in IEEE1609.4 standard [5].

Safety applications broadcast in the CCH (Control Channel). All the WAVE devices must listen to CCH in every synchronization interval. Non-safety applications broadcast in SCH (Service Channel). However, devices can choose to skip SCH and prioritize listening to CCH channel alone. In *Continuous Access*, the WAVE device listens to CCH throughout the synchronization interval. However, in *Alternating Access*, the WAVE device switches to CCH and SCH in each synchronization interval. These CCH and SCH intervals can be adjusted as per the requirement. By default, the channel is configured with *Alternating Access*.

Since platoon application is safety-critical, vehicles communicate with each other over CCH channel. Hence, the packet transmissions must be scheduled within the CCH interval. However, the transmission time is set randomly in the application layer. Hence, some of the vehicles may get scheduled to transmit during SCH as shown in the Fig. 2. The red arrows indicate the vehicles that are scheduled during SCH.

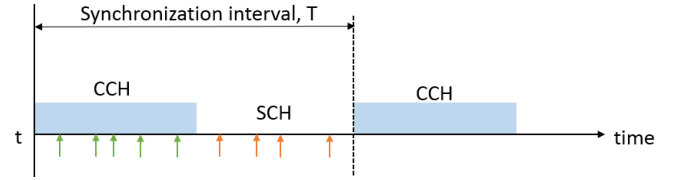


Fig. 2. Random packet transmission time allocation.

The packets scheduled during the SCH are not transmitted in the current time t . They are internally queued to transmit in the beginning of next CCH interval. Due to the presence of CSMA/CA, the packets are transmitted with a small delay between them as shown in the Fig. 3. This generates high traffic in the beginning of the CCH interval for all consecutive synchronization intervals causing channel crowding.

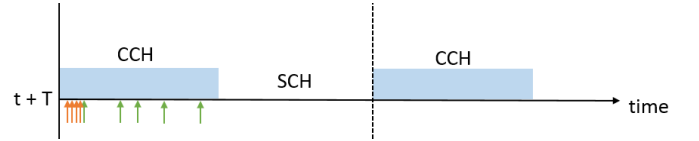


Fig. 3. Crowding of packets observed in the beginning of CCH.

Although CSMA/CA prevents collision, some of the packets fail to reach receivers if large number of vehicles are communicating in the channel. To overcome this issue, a random delay is added to the packet transmissions if they are scheduled in the beginning of the CCH. This avoids channel crowding and ensures that the channel is utilized efficiently as shown in Fig. 4. Simulations have shown improvement in the PDR with the proposed solution.

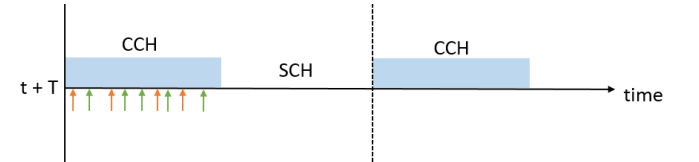


Fig. 4. Crowding issue avoided by adding random delay.

V. SIMULATION AND RESULTS

A. MPC algorithm validation

A layout of freeway road network is designed in VISSIM. A set of 14 vehicles are made to enter the network with an initial speed of 30 kmph. Once the MPC algorithm starts controlling the platoon, the intervehicular distance between the vehicles is corrected to 5.50 m and the speed of all the platoon vehicles settles to 30 kmph. At 100 s, a speed change command is given to the header to increase its speed to 60 kmph. Intervehicular distance is adjusted to 8 m accordingly. At 200 s, the header is asked to decrease its speed to 40 kmph. The intervehicular distances now settle at 6.33 m. Table I describes the various parameters used in the design of MPC algorithm.

TABLE I. PARAMETERS USED IN MPC ALGORITHM

Parameter	Symbol	Values
Sampling time	T_s	0.1 s
Constant inter vehicular gap	hd	3 m
Headway time	T	0.3 s
Tuning parameter	λ	0.1
Prediction horizon	N	70

With a constant distance of 3 m and a headway time of 0.3 s, the desired intervehicular distances which the vehicles should maintain during platooning are shown in Table II.

TABLE II. SPEEDS AND INTERVEHICULAR DISTANCE FOR A HEADWAY TIME OF 0.3 S

Speed (in kmph)	Desired Intervehicular Distances (in m)
30	5.50
40	6.33
50	7.17
60	8.00

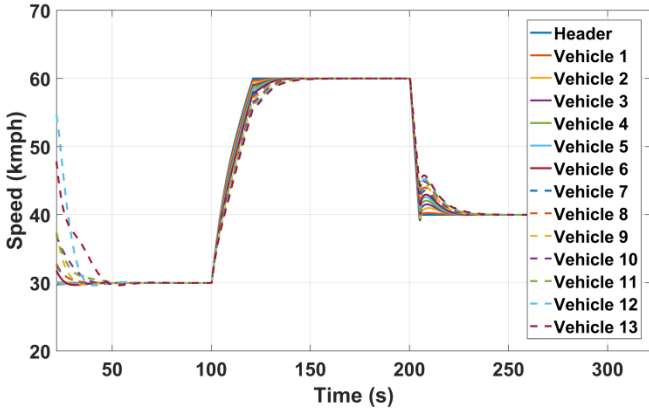


Fig. 5. Speed profile for 10 Hz communication frequency.

Since only platoon application has to be simulated, channel allocation is set to *Continuous Access*. The communication frequency is set to 10 Hz. The speed and intervehicular distance profiles of the platoon are shown in Fig. 5 and Fig. 6 respectively. It is observed that the controller maintains the desired intervehicular distance and tracks the speed of the header effectively. Further, simulation tests are carried out for 15 Hz and 20 Hz communication frequencies. Similar tracking performance is observed in platoon. There is a decrease in settling time with respect to increase in the communication frequency.

By default, Tx and Rx antenna gains are set to ideal value of 0 dB in NS3. The controller is tested for variation in antenna gains. The gains are set to half power (-3 dB) and double power (3 dB) values. PDR of the header vehicle is determined

and compared for 10 Hz communication frequency as shown in Fig. 7. It is seen that PDR drops significantly when the antenna gains are set to -3 dB and improves when the antenna gains are set to 3 dB. Similar results are obtained for 15 Hz and 20 Hz communication frequencies.

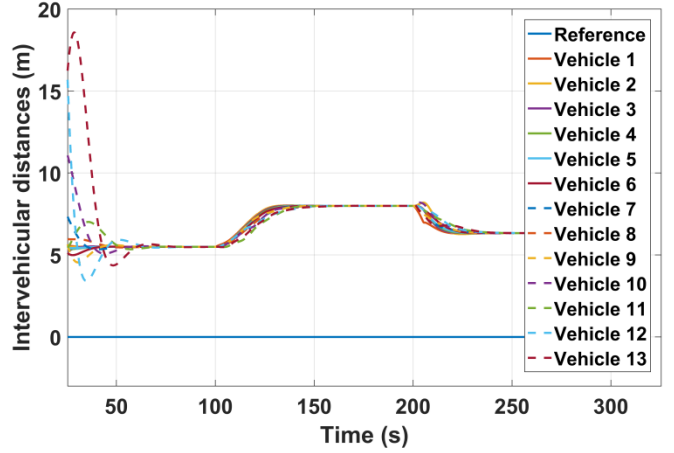


Fig. 6. Intervehicular distance profile for 10 Hz communication frequency.

From these observations, it can be concluded that communication frequency of ≥ 10 Hz is suitable for platoon. Hence, all further tests are carried out with 10 Hz communication frequency and ideal antenna gain of 0 dB.

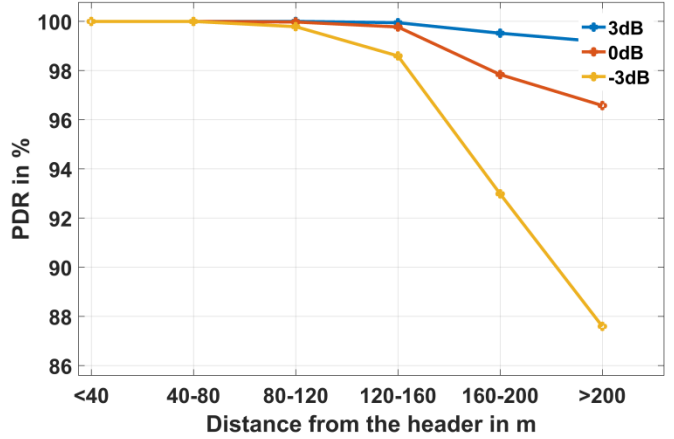


Fig. 7. Comparison of PDR for 10 Hz with different antenna gains.

B. Simulations for packet drops

A set of 14 vehicles enter the freeway road network at a certain speed. The vehicles are given a speed input to accelerate and decelerate within a time interval of 50 s. Communication failures are deliberately introduced in vehicle 5 of the platoon. Initially, the time duration for communication failure is set to 1 s and gradually increased in steps of 0.5 s. In Figures 8, 9 and 10, blue lines indicate the data obtained without deliberate communication failures while the red lines indicate the data obtained with communication failures. The bold red line and the dotted red line indicate the intervehicular distances of vehicles 5 and 6 respectively.

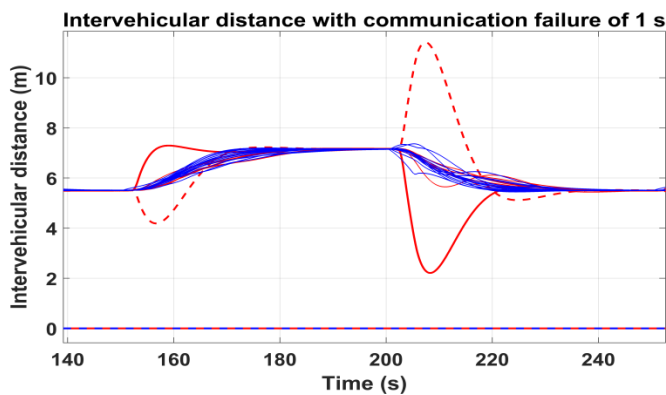


Fig. 8. Intervehicular distance with and without communication failure of 1 s for a speed change of 20 kmph.

From the Fig. 8, platoon accelerates from 30 kmph to 50 kmph (20 kmph speed change) at 150 s. Due to the communication failure of 1 s introduced, vehicle 5 does not receive the information from the header to accelerate. This causes the vehicle 6 to move closer to vehicle 5 and the vehicle 5 moves away from vehicle 4. At 200 s, platoon decelerates from 50 kmph to 30 kmph. In this case, the vehicle 5 does not receive the information from the header to decelerate. This causes the vehicle 5 to move closer to vehicle 4 and the vehicle 6 moves away from vehicle 5. This is evident in Fig. 8.

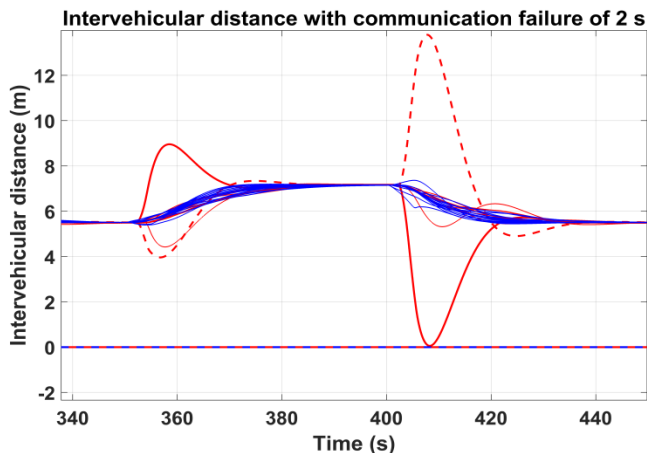


Fig. 9. Intervehicular distance with and without communication failure of 2 s for a speed change of 20 kmph

Similar speed change input is given to the header vehicle with increase in communication failure duration. For a duration of 2 s and more, collision is observed between vehicles 4 and 5 while decelerating. This is seen in Fig. 9. When the platoon accelerates, no collisions were observed even when the duration of the failure was increased to 4 s. The only difference noticed is that the time to reach the set-point speed increases with increase in the communication failure duration.

Similar tests were carried out for a speed change of 40 kmph (10 → 50 kmph and 50 → 10 kmph). From the Fig. 10, it

can be seen that vehicle 5 collided with vehicle 4. Collision is observed with 1 s of communication failure when compared to 2 s for 20 kmph speed change.

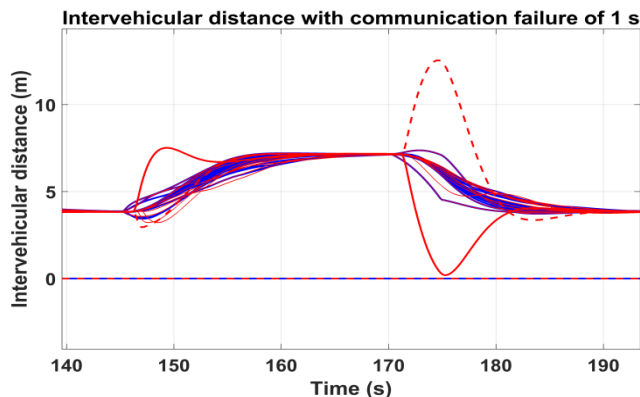


Fig. 10. Intervehicular distance with and without communication failures of 1 s for a speed change of 40 kmph.

To simulate channel crowding, the channel allocation is set to *Alternating Access* mode with default values for CCH, SCH and Guard Interval as shown in Fig. 11 for 10 Hz communication frequency. The default value for SCH is 50 ms while the guard interval is set to 4 ms. The remaining 46 ms is set for CCH.

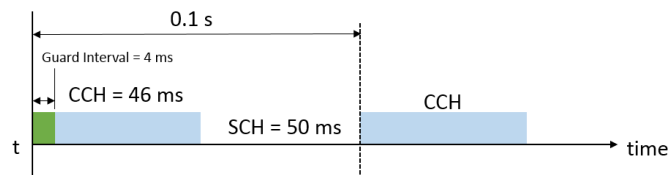


Fig. 11. Default channel access for 10 Hz communication frequency.

TABLE III. PACKET TRANSMISSION TIMES HIGHLIGHTING CROWDING ISSUE AND THE PROPOSED SOLUTION

Initial schedule (a)		Crowding (b)		No Crowding (c)	
Veh	Time	Veh	Time	Veh	Time
6	90.0037	12	90.1041	6	90.1041
5	90.0062	3	90.1049	5	90.1062
8	90.0072	6	90.1057	8	90.1072
1	90.0083	9	90.1065	1	90.1083
11	90.0094	2	90.1065	2	90.1092
7	90.0103	8	90.1074	11	90.11
4	90.0138	5	90.1082	7	90.1109
14	90.0316	1	90.1091	4	90.1138
10	90.0352	11	90.1099	3	90.1149
13	90.0377	7	90.1108	14	90.1316
2	90.0554	4	90.1138	10	90.1352
3	90.0648	14	90.1316	13	90.1377
9	90.0918	10	90.1352	9	90.143
12	90.0985	13	90.1377	12	90.149

Table III lists out the packet transmission times of the 14 vehicle platoon highlighting the crowding issue and the proposed solution to avoid crowding. For the simulation time interval of [90, 90.1], the vehicles are set to broadcast at random time instants as shown in column (a). The vehicles 2, 3, 9 and 12 are unable to transmit in the interval [90, 90.1] since their transmission time is scheduled during SCH.

In the next time interval [90.1, 90.2], the vehicles 2, 3, 9 and 12 are scheduled to transmit in the beginning of the CCH. It can be observed from the column (b) that 8 vehicles are transmitting in the first 7 ms while 6 vehicles are allocated over the remaining 39 ms of CCH interval. As the header vehicle is also transmitting in the crowded 7 ms duration, its PDR is affected as shown in Fig. 12.

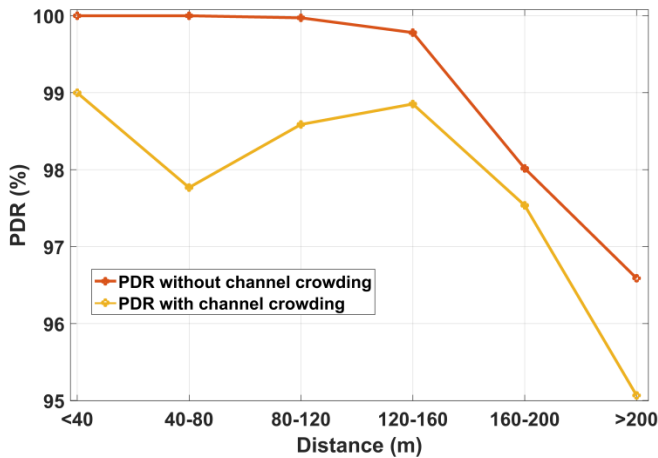


Fig. 12. PDR comparison for Channel crowding issue.

Simulation is repeated with the proposed solution for crowding issue as described in the earlier section. Packet transmission times for time interval [90, 90.1] are scheduled as shown in column (a). However, for the next time interval [90.1, 90.2], it can be observed that crowding is avoided. Instead of allocating vehicles 2, 3, 9 and 12 in the beginning of CCH, they are scheduled with a randomly generated delay as highlighted in column (c). This avoids channel crowding and the PDR is significantly improved as shown in Fig. 12.

VI. CONCLUSION

This paper addresses the problem of packet drops and channel crowding in vehicle platooning with respect to both control and communication aspects. An MPC algorithm is tested for freeway road network using an integrated simulator developed in-house. It is seen that the controller is able to maintain the vehicles at a desired speed with the intervehicular distances proportional to the speeds of the vehicles. Further, packet drops are introduced into the platoon communication to study the controller performance in detail. The possibility of

collision during communication failure depends on the speed change magnitude. The analysis helps to determine the additional sensors required to provide fail-safe alternatives in case of communication failures. In addition to that, the proposed solution for crowding issue shows improvement in the packet delivery ratio and channel utilization.

ACKNOWLEDGMENT

The authors gratefully acknowledge the contribution of Dr. Hong Li, NXP Semiconductors Eindhoven, Netherlands and Mr. Chetan B. Math, Department of Electrical Engineering, Eindhoven University of Technology (TU/e), Eindhoven, Netherlands for their timely guidance.

REFERENCES

- [1] D. Swaroop, J.K. Hedrick, C. C. Chien, P. Ioannou, "A Comparison of Spacing and Headway Control Laws for Automatically Controlled Vehicles", *Vehicle System Dynamics*, vol.23, pp.597-625, 1994.
- [2] Abraham, A., Pappa, N., Honc, D., Rahul Sharma, Reduced order modelling and predictive control of multivariable nonlinear process, *Sadhana*, vol.43(41), pp.1-18, 2018.
- [3] A. Choudhury, T. Maszczyk, M. T. Asif, N. Mitrovic, C. B. Math, Hong Li and J. Dauwels, "An integrated V2X simulator with applications in vehicle platooning", *IEEE 19th International Conference on Intelligent Transportation Systems (ITSC)*, Rio de Janeiro, pp. 1017-1022, 2016.
- [4] S. Dasgupta, V. Raghuraman, A. Choudhury, T. N. Teja and J. Dauwels, "Merging and splitting maneuver of platoons by means of a novel PID controller", *IEEE Symposium Series on Computational Intelligence (SSCI)*, Honolulu, HI, USA, pp. 1-8, 2017.
- [5] H. Yoo and D. Kim, "Dynamic Channel Coordination Schemes for IEEE 802.11p/1609 Vehicular Networks: A Survey", *International Journal of Distributed Sensor Networks*, vol. 9, no. 10, pp. 1-8, 2013.
- [6] S. Tsugawa, S. Jeschke and S. E. Shladover, "A Review of Truck Platooning Projects for Energy Savings", in *IEEE Transactions on Intelligent Vehicles*, vol. 1, no. 1, pp. 68-77, March 2016.
- [7] Z. Gacovski and S. Deskovski, "Different control algorithms for a platoon of autonomous vehicles", *International Journal of Robotics and Automation* vol. 3 pp. 151-160, 2014.
- [8] M. Amoozadeh, H. Deng, C. Chuah, H. M. Zhang and D. Ghosal, "Platoon management with cooperative adaptive cruise control enabled by VANET", *Vehicular Communications*, vol. 2, no.2, pp.110-123, 2015.
- [9] A. Choudhury, T. Maszczyk, C. B. Math, H. Li, and J. Dauwels, "An integrated simulation environment for testing V2X protocols and applications", *Procedia Computer Science*, vol. 80, pp. 2042-2052, 2016.
- [10] Y. J. Li, "An overview of the dsrc/wave technology," in *Quality, Reliability, Security and Robustness in Heterogeneous Networks*, Springer, pp. 544-55, 2010.
- [11] A. Galip Ulsoy, Huei Peng, Melih Cakmakk, *Automotive Control Systems*, Cambridge University Press, Cambridge, 2012.
- [12] Shengling Shi, Mircea Lazar, On distributed model predictive control for vehicle platooning with a recursive feasibility guarantee, *IFAC PapersOnLine*, vol.50(1), pp.7193-7198, 2017.
- [13] Honc D, Sharma R, Abraham A, Dusek F and Pappa N, Teaching and practicing model predictive control. In *Proceedings of the 11th IFAC Symposium on Advances in Control Education (ACE)*, Bratislava-Slovakia, IFAC-PapersOnline, vol.49(6), pp.34-39, 2016.