

Modelling the packet delivery of V2V messages based on the macroscopic traffic parameters

Aashik Chandramohan, Geert Heijenk

Department of Computer Science, University of Twente, The Netherlands

{a.chandramohan, geert.heijenk}@utwente.nl

Abstract—In this paper, we present an analytical model for estimating the Packet Delivery Ratio (PDR) in vehicular communication using IEEE 802.11p protocol for a highway scenario based on the macroscopic traffic parameters. We also consider the effects of Decentralised Congestion Control (DCC) based on Transmit Rate in improving the PDR. The model is validated using a simulation environment based on Artery and its estimation of the PDR is found to be within 1 % deviation of the PDR calculated from the simulation environment. We also show a use case of our model in identifying the correct DCC parameters at which the DCC will be activated based on the macroscopic traffic parameters.

Index Terms—Vehicular communication, IEEE 802.11p, Cooperative Awareness Message, Decentralized Congestion Control, Packet Delivery Ratio, Artery, Macroscopic traffic parameters.

I. INTRODUCTION

Vehicle to Vehicle (V2V) communication will play an important role in improving road safety and traffic efficiency as vehicles connected together will have more information about each other and therefore can give better feedback to the driver or, in case of autonomous driving, take better decisions. However, just like in any kind of wireless communication, channel bandwidth plays an important role in vehicular communication. There is currently only a limited bandwidth available for vehicular communication and with higher number of vehicles being equipped for vehicular communication, the strain on the communication channel can increase.

One of the basic type of message in V2V communication is the Cooperative Awareness Message (CAM) which is a broadcast message with the sender vehicle's parameters so that the vehicles around it within the communication range can be aware of this vehicle. This is a safety related message and is generated based on the change in certain vehicle parameters like position, speed and direction as given in its specification document in [1]. These vehicle parameters based on which the CAM message is generated are known as microscopic traffic parameters. Hence, to find the message generation based on the microscopic traffic parameters, we need to know the vehicle parameters like, speed and position of each individual vehicle within the communication range. Macroscopic traffic parameters on the other hand reflect the average state of the road traffic using just three parameters, traffic flow rate, vehicle density and the average speed. Hence finding a method to estimate the communication load or the Packet Delivery Ratio (PDR) based on the macroscopic parameters will allow us to estimate for different traffic states easily without needing

the information of each individual vehicle. Even though CAM does not have a large packet size which can lead to congestion in the channel, it is still an important event driven message that can be used to show how traffic scenarios can play a role on the communication channel load. Hence we have considered the CAM message as the type of message to be modelled. The same concept can be used to also model other types of new messages like Collective Perception Message (CPM), which has similar generation conditions to CAM but has a larger packet size and hence has more influence on the channel load. In our earlier work in [2] we had shown how an analytical model can be used for estimating the overall message generation rates of CAM messages in a highway environment using the macroscopic traffic parameters, traffic flow rate and average vehicle speed instead of using the microscopic parameters of each individual vehicle's speed and position which determines when the CAM message is triggered. In our previous work [3], we had improved our model to also consider the effects of one of the current congestion control algorithms, namely Decentralised Congestion Control based on Transmit Rate Control (DCC-TRC) on the overall message generation rate. DCC-TRC allow for controlling the channel load by varying the vehicle's message transmission rate [4]. However, both of these works focused on the transmission side of communication and not on the reception side. Therefore, the goal of this paper is to check if we can use the macroscopic traffic parameters and the DCC configuration settings to also model for the successful packet delivery of a V2V message. Hence, in this paper we extend our model by also modelling the behaviour of the IEEE 802.11p Medium Access (MAC) layer to estimate the message reception rate by an arbitrary vehicle within the communication range based on the message generations by all the vehicles within the same communication range. We also introduce a method to estimate the PDR based on the macroscopic parameters and the DCC-TRC configuration parameters and show how these have an effect on the PDR. The key contribution of this paper is a validated simple, computationally efficient performance model for estimation of the PDR and the successful message reception rate for CAM messages over IEEE 802.11p, based on the macroscopic traffic parameters and the DCC configuration parameters which is faster in its computation of PDR than using a simulation environment by a factor of around 10^2 . Comparing the results of our model with that from a simulation environment showed

that our model was able to estimate the PDR with high accuracy. At the same time, our model only took a fraction of the execution time taken by the simulation environment.

This paper is organized as follows. In Section II, we explain briefly the current state of the art in calculating and estimating the probability of packet loss in vehicular communication. Section III gives the design of our model for estimating the PDR in a highway environment. This is followed by Section IV where our model is evaluated by comparing its results with the results obtained from a vehicular communication simulator. Here we also show a use case of our model to determine the DCC-TR configuration settings based on the PDR and the message reception rate. We finally end this paper with conclusions based on our results and some future work in the direction of this research, in Section V.

II. RELATED WORK

In this section, we discuss some of the prior works on estimating communication channel load and PDR in vehicular networks. Most of these studies consider message generation to be periodic or the number of vehicles within the communication range to be a constant.

In [5], the authors have developed a simple analytical model that can compute the probability of successful message reception in an IEEE 802.11p vehicular adhoc network for a message with fixed beaconing interval by considering the message arrivals to follow a deterministic process and the number of nodes within the communication range to be a constant. In [6], the authors model for the successful packet delivery by considering the packet arrivals to follow the Bernoulli arrival process. Here too, the number of surrounding nodes within the communication range is considered to be a constant. In another work, [7], the authors have modelled the IEEE 802.11p CSMA/CA as Markov chain for a fixed beaconing rate and for fixed number of vehicles and were able to estimate the successful reception rate with good accuracy when compared with a simulation environment. Even though all these works were on estimating the PDR, none of them used the overall traffic scenario which can be described using the macroscopic parameters to estimate the message generations and the PDR.

Our work is different from these above works in the way that, we use the macroscopic traffic parameters, which represent the vehicle traffic in an area to model the message generation rate and the number of vehicles within the communication range and also consider the effects of Decentralised Congestion Control on improving the PDR.

III. MODELLING FOR THE PACKET DELIVERY RATIO

To estimate the PDR, we need to estimate both the packet transmission rate and the packet reception rate. We have already modelled for the CAM message generations on a highway traffic in our previous work [3]. In this section we model the packet reception rate for the same traffic scenario considered in [3] and then finally use that to estimate the PDR based on the traffic and communication parameters.

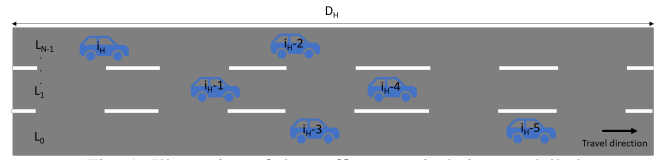


Fig. 1: Illustration of the traffic scenario being modelled

A. Traffic scenario

Fig. 1 shows a segment of a highway of length D_H and number of lanes, L_N . We have considered the traffic in the highway to be homogeneous. Therefore, vehicles within D_H are considered to be within the communication range of each other and to share the same channel bandwidth for transmitting their CAM messages. Hence all the vehicles inside this highway segment will experience the same channel load. We assume free flow of traffic and hence vehicle entry to the segment can be considered to follow a Poisson process as given in [8]. This means that the time between vehicle entries into the segment follows an exponential distribution with mean inter-arrival time $\frac{1}{\lambda_H}$. We consider the vehicle speed in a free flowing traffic to follow a normal distribution as explained in [2]. Cooperative Awareness Messages are generated based on certain conditions that are triggered based on change in microscopic vehicle parameters. However in [2], we have formalised for the general CAM generation rate of a vehicle on a highway based on the macroscopic traffic parameter, average speed (v_{Traffic}) to be $g_c = \frac{v_{\text{Traffic}}}{4}$.

B. DCC-TRC

When Decentralised Congestion Control based on Transmit Rate (DCC-TRC) is enabled then messages will not be transmitted based on just the CAM triggering conditions but also based on the DCC state that the vehicle is in. For this paper we have considered a 3 state DCC model as shown in Fig. 2. However, our model can be easily extended to also accommodate for the 5 state DCC model, where the active state is again divided into 3 sub states [9]. The ‘‘Relaxed’’ state is the equivalent of the DCC being inactive. Hence, in this state the CAMs will be generated based on its message generation conditions. Therefore, the message generation rate for the vehicles in this state can be given as g_c . When in the ‘‘Active’’ or the ‘‘Restrictive’’ state the vehicle will generate CAMs at a fixed rate lower than the rate in the previous state so as to reduce the load on the communication channel. We have denoted these rates as g_{DCCA} and g_{DCCR} . A vehicle changes state from a lower DCC state to a higher DCC state or from a higher DCC state to a lower DCC state based on how busy the channel is given by the Channel Busy Ratio (CBR). CBR is the fraction of time the channel is perceived to be busy by each vehicle within a fixed interval of time. Therefore based on the ratios of goal minimum channel load (Min_{CL}) and maximum channel load (Max_{CL}), as shown in Fig 2, the overall channel load in the region can be controlled. A detailed explanation about the DCC mechanism is given in our previous paper in [3].

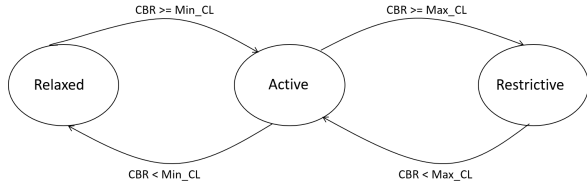


Fig. 2: DCC activation states

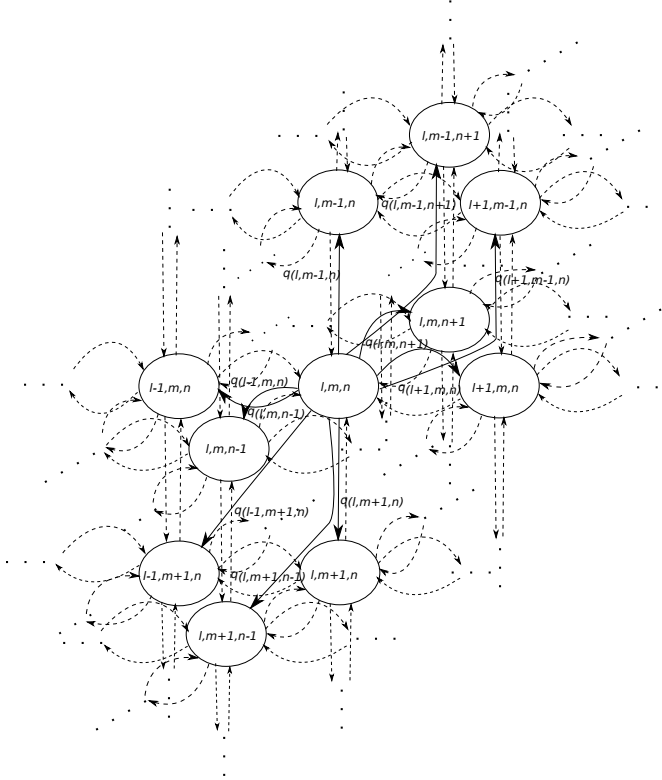


Fig. 3: State transition diagram from state (l, m, n)

C. Modelling

The vehicle dynamics and the DCC-TRC parameters can be used to formulate a Markov chain shown in Fig. 3. Here state (l, m, n) denotes l vehicles in DCC “Relaxed”, m vehicles in DCC “Active” and n vehicles in DCC “Restrictive” state. In the model, transitions between states are governed by vehicle arrivals and departures and by DCC activation and deactivation. Solving for the steady state probability of this Markov model will give the Probability Distribution Function (PDF) $P_v(l, m, n)$ for the number of vehicles in each of the three DCC states. The full description of this Markov model can be found in [3]. In this paper we are going to extend this Markov model to also calculate the PDR.

Calculating the Packet delivery Ratio

Since the message generation by the vehicle is determined by the message triggering conditions and the DCC state the vehicle is in, We are assuming the vehicle’s message generations to follow a Poisson distribution with mean period of $\frac{1}{g_c}$, $\frac{1}{g_{DCCA}}$ or $\frac{1}{g_{DCCR}}$ depending on the DCC state it is in. Therefore

we can also assume the overall message generation rate in a state (l, m, n) to follow a Poisson distribution with mean generation rate $\Lambda_{gl}(l, m, n) = l \times g_c + m \times g_{DCCA} + n \times g_{DCCR}$. Since in our scenario, all the vehicles are within the communication range of each other, interference from a hidden node will not play a part on packet loss. For a message to be successfully received by all the surrounding vehicles, there should not be any simultaneous transmissions by more than one vehicle. IEEE 802.11p is a broadcast mechanism which uses Carrier Sense Multiple Access based on Collision Avoidance (CSMA/CA) for its transmissions. This system can be modelled by observing if at discrete time epochs; deriving either a packet transmission, a packet collision or an unused slot. These epochs can be considered as generic time slots with three possibilities. There could be a successful transmission in the slot with a duration T_s , unsuccessful transmission (packet collision) with a duration T_c or it could be an empty slot of duration T_e . Here $T_s = T_h + L/R + DIFS + \delta$, $T_c = T_h + L/R + EIFS + \delta$ and $T_e = \sigma$, where T_h is the duration of a preamble and PLCP header, L is the packet length, R is the data rate, δ is the propagation delay and σ is the duration of an empty slot as shown in [10]. Since we have assumed the overall message generation rate to follow a Poisson distribution, its Probability Mass Function (PMF) in state (l, m, n) , $P(k|(l, m, n)) = \frac{\Lambda_{gl}(l, m, n)^k \times T \times e^{-\Lambda_{gl}(l, m, n) \times T}}{k!}$ which gives the probability of k messages being generated per time unit T , can be used to calculate the probability of a successful transmission. We abstract for CSMA/CA by assuming that the number of packets transmitted in a generic slot equals the number of packets generated in the preceding generic slot and that consecutive slots are independent. Let $p_{s|(l, m, n)}$, $p_{c|(l, m, n)}$ and $p_{e|(l, m, n)}$ be the conditional probabilities for the slot being used for a successful transmission, unsuccessful transmission and an empty slot respectively when in state (l, m, n) . If we denote the average duration of a generic slot as $T_{slot|(l, m, n)}$, then the average number of messages generated in a slot can be given as $\Lambda_{gl}(l, m, n) \times T_{slot|(l, m, n)}$. For a successful transmission only one packet should be transmitted in any given slot. Hence probability of a successful transmission $p_{s|(l, m, n)}$ can be given by

$$p_{s|(l, m, n)} = P(1|(l, m, n)) = \frac{\Lambda_{gl}(l, m, n) \times T_{slot|(l, m, n)}}{\times e^{-\Lambda_{gl}(l, m, n) T_{slot|(l, m, n)}}} \cdot (1)$$

For the slot to be an empty slot, there should not be any transmissions. Hence, $p_{e|(l, m, n)}$ can be given by

$$p_{e|(l, m, n)} = P(0|(l, m, n)) = e^{-\Lambda_{gl}(l, m, n) T_{slot|(l, m, n)}} \cdot (2)$$

Since there are only three possibilities in a slot (successful transmission, slot being empty or packet collision), the probability of an unsuccessful transmission can be given by Eq 3 and the mean slot duration $T_{slot|(l, m, n)}$ can be calculated numerically using Eq 4.

$$p_{c|(l, m, n)} = 1 - p_{e|(l, m, n)} - p_{s|(l, m, n)} \quad (3)$$

$$T_{\text{slot}|(l,m,n)} = p_{s|(l,m,n)}T_s + p_{c|(l,m,n)}T_c + p_{e|(l,m,n)}T_e \quad (4)$$

Finally the successful packet reception rate in state (l, m, n) can be give as

$$\wedge_r|(l,m,n) = \frac{p_{s|(l,m,n)}}{T_{\text{slot}}}. \quad (5)$$

The overall message generation rate (\wedge_g) and the overall message reception rate (\wedge_r) for the traffic scenario can be calculated using the the PDF for the number of vehicles in each of the three DCC states ($P_v(l, m, n)$) as shown in Equations 6 and 7 respectively.

$$\wedge_g = \sum_{l=0}^{l_{\max}} \sum_{m=0}^{m_{\max}} \sum_{n=0}^{n_{\max}} \wedge_{g|(l,m,n)} \times P_v(l, m, n) \quad (6)$$

$$\wedge_r = \sum_{l=0}^{l_{\max}} \sum_{m=0}^{m_{\max}} \sum_{n=0}^{n_{\max}} \wedge_{r|(l,m,n)} \times P_v(l, m, n) \quad (7)$$

Finally the PDR for the given traffic scenario based on the DCC and other communication parameters can be given as

$$\text{PDR} = \frac{\wedge_r}{\wedge_g}. \quad (8)$$

IV. VALIDATION AND EVALUATION

The simulation environment used for validating our model is based on Artery, SUMO and Veins [11]. Artery emulates the application layer responsible for CAM message generations and also the DCC mechanism. Veins is used for emulating the IEEE 802.11p protocol for vehicular communication. SUMO is a traffic simulator that is used for emulating the highway traffic scenario. A library called TraCI acts as an interface between SUMO and Artery and Veins.

A. Simulation Environment

A 10 lane highway is designed in SUMO of length 950m. The speed limit of the highway is set to v_H . Vehicles enter the simulation with a random velocity and use the first 250m denoted by D_{Buf} to reach their cruise velocity, v_i which is taken from a normal distribution with mean v_H and standard deviation $\sigma = 0.1$. Messages are only generated by the vehicle after D_{Buf} and we also only consider the messages received by the vehicle after D_{Buf} . Therefore, the effective length of highway on which the CAM generations and receptions would be measured will be $D_H = 700\text{m}$. Since the cruise vehicle velocity is taken from a normal distribution, it is possible that at higher traffic flows vehicles are not able to achieve their desired vehicle speed due to dependency with the vehicle ahead [2]. Hence, the measured avg vehicle speed $v_{\text{Traffic}} \leq v_H$. The measured v_{Traffic} is used as the average vehicle speed in our model. The DCC mechanism is already implemented in Artery as per the standardisation given in [12]. The simulation is run for different configurations of traffic flow (λ_H) and DCC configurations, with 30 runs being done for each configuration

TABLE I: Simulation parameters

D_{Buf}	250 m
D_H	700 m
Max vehicle acceleration rate	4 m/s ²
Max vehicle speed	40 m/s
v_H	32 m/s
DataRate	6 Mbps
CAM Packet length	323 Bytes
g_{DCCA}	5 messages/s
g_{DCCR}	2 messages/s

settings so as to get a fairly accurate estimation of the PDR in a real environment. Since the time for completing the simulation increases with increase in traffic flow rate, the simulation time limit was kept as $\frac{1000}{\lambda_H}$. This allows us to keep the total number of packet arrivals the same for different traffic flow rate. The parameters that are kept the same for all the simulations are shown in Table I.

B. Results

As mentioned in Section IV-A, we validated our model by comparing it with the PDR obtained from a simulation environment. The results obtained are plotted in Fig. 4. To show that our model works well for all the three DCC activations, we evaluated our model for 3 different DCC configurations. We have compared it with a scenario where the goal channel loads are set to very high values, $\text{Min}_{\text{CL}} = 0.9$ and $\text{Max}_{\text{CL}} = 0.95$, such that the message generations are never high enough to activate DCC. Hence we can see a smooth curve for the PDR that gradually decreases with increase in the vehicle arrival rate, since with increase in the vehicle arrival rate, the number of transmissions will increase, which will lead to an increase in the chance of packets being transmitted by more than one vehicle at the same time. The next configuration that we validated our model for was for when the DCC ‘‘Active’’ state is alone triggered. For this we set $\text{Min}_{\text{CL}} = 0.19$ and $\text{Max}_{\text{CL}} = 0.95$. For lower vehicle arrival rates, since DCC will be in the relaxed state due to lower channel load, it can be seen that the curve for the PDR follows that of no DCC activation. However when the vehicle arrival rate goes above 2 vehicles/s, then the channel load exceeds that of $\text{Min}_{\text{CL}} > 0.19$ and hence DCC starts getting activated. This means that vehicles start to change from DCC ‘‘Relaxed’’ state to DCC ‘‘Active’’ state and hence reduce their message transmission rate so as to compensate for the increase in channel load. Therefore, the overall channel load ratio is maintained to be close to 0.19. This means that the overall message generation rate at this stage is quite similar hence we do not see a decrease in the PDR. Once the vehicle arrival rate increases above 4 vehicles/s, then the change in DCC state to ‘‘Active’’ is no longer enough to keep the CBR to less than 0.19 and therefore from this point the PDR again starts to decrease with increase in the vehicle arrival rate. We have also evaluated our model for $\text{Min}_{\text{CL}} = 0.19$ and $\text{Max}_{\text{CL}} = 0.23$ such that both DCC ‘‘Active’’ and ‘‘Restrictive’’ states are triggered. The deviation in estimation plot in the figure shows that our model is able to estimate the PDR within an error of 1% from what is found from the simulation.

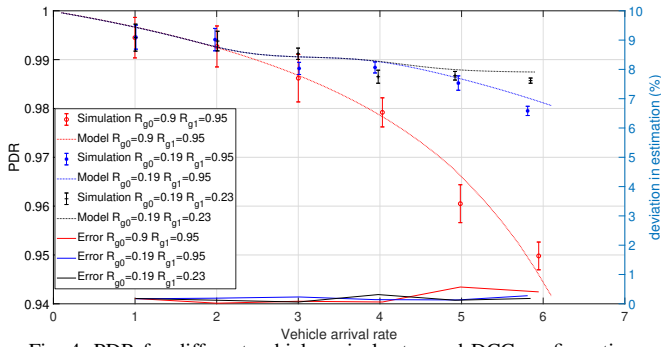


Fig. 4: PDR for different vehicle arrival rates and DCC configurations

One of the main use case of our model is that it can be used to easily and accurately find the correct DCC parameters based on the traffic parameters (macroscopic parameters). Fig. 5 shows the change in PDR and the message reception rate based on the minimum channel load ratio set (Min_{CL}). Since we would like to represent in a 2D plot for better readability, we have considered the maximum channel load ratio (Max_{CL}) to be very high (0.95), such that the “Restrictive” DCC state is not triggered. It can be seen that all the plots for PDR and message reception rate for different vehicle arrival rates λ (vehicles/second) follow the same trend. At lower minimum channel load ratios all the vehicles will be in DCC “Active” state and hence the message generation rate will be at a constant rate of g_{DCCA} messages per vehicle which is lower than the message generation rate due to CAM triggering. Hence the PDR will be very high and since the message transmission rate is going to be lower the message reception rate is also lower. As the minimum channel load ratio increases, vehicles start tending to be more in the “Relaxed” DCC state and less in the “Active” DCC state. Therefore, we see an increase in the message reception rate and a decrease in the PDR. Finally after a certain minimum channel load ratio, the PDR and the message reception rate curves start to flatten as the minimum channel load ratio is high enough such that all the vehicles can be in the relaxed state and can generate messages based on the CAM triggering conditions. From our model’s results we can clearly see that with increase in the vehicle’s arrival rate, the influence of the DCC “Active” state increases and that minimum channel load ratio required for all the vehicles to be able to be able to transmit their message based on the CAM triggering condition also increases to 0.16 for $\lambda = 1$, 0.28 for $\lambda = 2$, 0.34 for $\lambda = 3$, 0.43 for $\lambda = 4$, 0.6 for $\lambda = 5$ and $\lambda = 6$.

V. CONCLUSIONS AND FUTURE WORK

In this paper we have shown a simple method to analytically model the Packet Delivery Ratio (PDR) and the message reception rate for vehicles in a highway traffic based on the macroscopic traffic parameters and the DCC configurations. We have shown that our model is able to accurately estimate the PDR within 1% error of that calculated from the simulation environment. We have also shown a use case of our model for identifying the Minimum channel load ratio

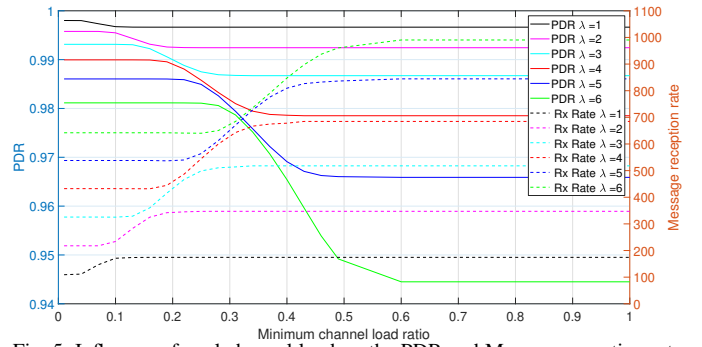


Fig. 5: Influence of goal channel load on the PDR and Message reception rate

based on the required PDR or the message reception rate. Our model can also be used for identifying the parameters within the Macroscopic traffic parameters or the DCC configuration parameters, or the communication parameters like, data rate or packet length based on the required Packet delivery ratio. Since our Markov model is mainly based on the traffic scenario and the DCC activations, it can be easily modified to also estimate the PDR for other kinds of cooperative messages like Collective Perception Message (CPM) or for vehicular communication using a different communication protocol like 5G - based V2x.

REFERENCES

- [1] T. ETSI, “Intelligent Transport Systems (ITS); vehicular communications; basic set of applications; part 2: Specification of cooperative awareness basic service,” *Draft ETSI TS*, vol. 20, pp. 448–451, 2011.
- [2] A. Chandramohan and G. Heijenk, “Modelling v2v message generation rates in a highway environment,” in *Wireless and Mobile Computing, Networking and Communications (WiMob)*, 2020, pp. 1–6.
- [3] A. Chandramohan and G. Heijenk, “Modelling activation of congestion control for estimating channel load in vehicular networks,” in *Wireless Days (WD)*. IEEE, 2021, pp. 1–8.
- [4] A. Autolitano, C. Campolo, A. Molinaro, R. M. Scopigno, and A. Vesco, “An insight into Decentralized Congestion Control techniques for VANETs from ETSI TS 102 687 V1. 1.1,” in *IFIP Wireless Days (WD)*. IEEE, 2013, pp. 1–6.
- [5] A. Vinel, V. Vishnevsky, and Y. Koucheryavy, “A simple analytical model for the periodic broadcasting in vehicular ad-hoc networks,” in *2008 IEEE Globecom Workshops*. IEEE, 2008, pp. 1–5.
- [6] A. Vinel, Y. Koucheryavy, S. Andreev, and D. Staehle, “Estimation of a successful beacon reception probability in vehicular ad-hoc networks,” in *International Wireless Communications and Mobile Computing Conference (IWCMC)*, 2009, pp. 416–420.
- [7] M. Eenennaam, A. Remke, and G. Heijenk, “An analytical model for beaconing in vanets,” in *Vehicular Networking Conference, VNC*. IEEE, 11 2012, pp. 9–16.
- [8] F. Mannering, W. Kilareski, and S. Washburn, *Principles of highway engineering and traffic analysis*. John Wiley & Sons, 2007, ch. Models of Traffic Flow, pp. 146–151.
- [9] T. ETSI, “103 175 v1. 1.1,” *Intelligent Transport Systems (ITS)*.
- [10] A. Vinel, V. Vishnevsky, and Y. Koucheryavy, “A simple analytical model for the periodic broadcasting in vehicular ad-hoc networks,” in *Globecom Workshops*. IEEE, 2008, pp. 1–5.
- [11] R. Riebl, H.-J. Günther, C. Facchi, and L. Wolf, “Artery: Extending veins for vanet applications,” in *International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS)*. IEEE, 2015, pp. 450–456.
- [12] T. ETSI, “102 687 v1. 1.1-intelligent transport systems (its)-decentralized congestion control mechanisms for intelligent transport systems operating in the 5 ghz range-access layer part,” *ETSI, Sophia-Antipolis, France*, 2011.