Modelling activation of congestion control for estimating channel load in vehicular networks

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2021 Wireless Days (WD) | 978-1-6654-2559-9/21/$31.00 ©2021 IEEE | DOI: 10.1109/WD52248.2021.9508285

Abstract—**In this paper, we present a Markov chain based model that can be used for easy estimation of the Vehicle to Vehicle (V2V) message generation rates in a highway environment based on just the traffic flow rate and the average vehicle speed on the highway. This allows for a faster estimation of the overall channel load than using a simulation environment to do the same. Our model considers the effects of Decentralized Congestion Control based on Transmit Rate Control (DCC-TRC) on Cooperative Awareness Message (CAM) generations. The model is evaluated by comparing the results obtained with the message generation rates achieved for a highway traffic scenario in a simulation environment based on Artery and SUMO. Comparing the results shows that the Cumulative Distributive Function (CDF) of the message generation rates estimated by our model is fairly accurate as they fall within the 95% confidence interval of the CDF obtained from the simulation.**

Index Terms—**V2V communication, Markov chains, Cooperative Awareness Message, Decentralized Congestion Control, Channel load, Artery.**

I. INTRODUCTION

Vehicular communication also known as Vehicle to Everything (V2X) communication is a technology that allows vehicles to communicate with each other and also with roadside units. This allows vehicles to be better aware of their surroundings and hence makes road traffic safer and more efficient. This is also useful in fully autonomous vehicles where there are no drivers to sense the surrounding traffic and hence vehicular communication can be used for communication and coordination between these vehicles to facilitate the smooth flow of traffic [1]. Therefore it should come as no surprise that there is a lot of research being done in the domain of vehicular communication with new applications being supported by it and new message types being developed to support these applications. However, just like in any type of wireless communication, vehicular communication also has a constraint on the channel bandwidth. Since there is a limited spectrum available for vehicular communication, channel load will become an issue with an increasing number of vehicles switching to V2X communication and with a higher number of applications (involving more message transmissions) being supported. Hence it is important to have a method to estimate the channel load in vehicular networks.

Vehicle to Vehicle (V2V) communication is a subset of V2X communication where communication between vehicles are considered. In our earlier work [2], we have shown how a queuing network and the underlying Markov chain can be used to estimate the overall message generation rate of one such V2V message type, namely the Cooperative Awareness Message (CAM) in a highway environment based on the traffic flow and the average vehicle speed in the traffic. CAM is the most basic type of message that the vehicles transmit so that all the vehicles within the communication range are aware of the presence of each other. These messages are generated based on the change in vehicle speed, position and direction as given in ETSI EN 302 637-2 [3]. In [2], however, we had not considered the effects of the current congestion control algorithms on the overall message generation rate. Congestion control algorithms allow for controlling the channel load by varying the message transmission rate, transmission power or data rate. A popular kind of congestion control used in V2V communication is the Decentralized Congestion Control based on Transmit Rate Control (DCC-TRC) [4]. This algorithm controls the message generation rate by the vehicles based on the Channel Busy Ratio (CBR) at that point in time. Hence if the CBR is too high, the message generation rate would be reduced to decrease congestion in the channel. In this paper, we extend the model created in [2] to also consider the effects of DCC-TRC on the message generation rate. Therefore the research question that we would like to answer with this paper is: Based on the traffic flow rate and the average vehicle speed on a highway if a model can be constructed that can accurately estimate the channel load experienced by a vehicle on a highway given that a congestion control algorithm based on DCC-TRC is used to regulate the channel load?

To answer our research question we have considered a highway segment of length corresponding to the communication range of the vehicle in middle. Therefore modelling the overall message generation rate of the vehicles in this segment would allow us to estimate the channel load experienced by the vehicle in the middle of this highway segment. We have designed a Markov chain based model for the number of vehicles in different DCC states based on the traffic flow rate, the average vehicle speed on the highway and the DCC configuration parameters. This is then used to estimate the probability distribution of the overall CAM generation rate in that scenario. We evaluated our model with a simulation environment based on Artery [5] and SUMO [6]. Comparing the results of our model with that from the simulation environment showed that our model was able to estimate the overall CAM generation rate 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 monitoring and dealing with the issue of communication channel load. Section III gives the design of our model for estimating the CAM generation rate 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. 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 in vehicular networks. Most of these studies consider message generation to be periodic or require actual vehicle traces or a simulation environment to determine the overall message generations.

In [7], the authors design a mathematical model, that can estimate the channel load contributed by a single vehicle based on its communication model and the number of transmissions from the surrounding vehicles within a unit time frame. However, they have considered message generations to be at a fixed rate and also the effects of congestion control algorithms are not modelled in this work. In [8], the authors use macroscopic traffic parameters to model the required channel capacities to accommodate message generations. However, even here message generation is considered to be at a fixed rate and the effects of congestion control algorithms on increasing the channel capacity is not discussed. [9] also uses the macroscopic traffic parameters for modelling the channel load. Here the channel load is represented by the aggregated power. The authors have designed a Markov based model which estimates the aggregated power level at a location based on the vehicle traffic flow, vehicle density, transmission power and transmission probability. The estimation of the aggregated power can then be used by the vehicles to reconfigure their transmission power or rate to reduce the channel load. In all these works message generations is considered to be at a fixed rate. In our work, we consider the effect of the macroscopic traffic parameters and decentralized congestion control algorithms on the vehicle message generation rate.

III. MODELLING THE OVERALL CAM GENERATION IN A HIGHWAY SEGMENT

To answer the research question asked in Section I, we need to also consider the message generations by the surrounding vehicles within the communication range of the vehicle we have considered, as these other vehicles would also contend for the same channel and hence will have an effect on the channel load. Therefore, in a highway environment, we need to consider message generations by vehicles within the 2 × communication range of the vehicle we have considered (As we need to take into account the vehicles both in front and behind this vehicle). We have assumed the highway traffic to be homogeneous, so all these vehicles which are contending for the spectrum will experience the same channel load within 2 × their communication range. Hence, we have considered one segment of the highway of length 2 × communication range and constructed a Markov chain based model for estimating the overall CAM generation rate within this highway segment, assuming that all vehicles in this segment will be able to receive messages from each other. In this section, we explain the traffic scenario on this highway environment and the construction of the Markov model for this scenario.

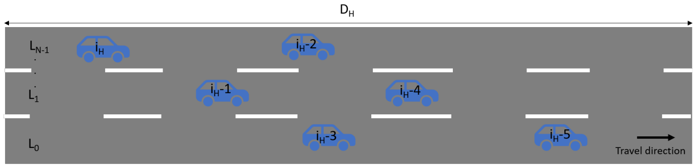

Fig. 1: Illustration of the traffic scenario being modelled

A. *Traffic scenario*

Figure 1 shows a segment of a highway of length D_H and number of lanes, L_N. 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 [10]. This means that the time between vehicle entries into the segment follows an exponential distribution with mean inter-arrival time $\frac{1}{\lambda_\mathrm{H}}$. Also as we have shown in [2], since we are considering a free flow of traffic in a highway environment, the desired vehicle speed, v_i of the i^{th} vehicle can be considered to follow a normal distribution with mean v_{Traffic} and standard deviation σ, with coefficient of variation between 0.1 and 0.18 as shown in many studies like [11], [12] and [13]. Knowing the vehicle speed, v_i of i^{th}, vehicle, allows us to formalise the CAM generation rate for that vehicle, $g_{i,\mathrm{c}}$. CAMs are triggered based on certain triggering conditions which are given in its standardization in [3]. They are mainly due to a vehicle's change in position, change in speed or due to change in direction. Since vehicle speed on a highway does not vary too much and since we are considering a straight road, the majority of CAMs in our scenario will be triggered due to a change in vehicle position. We have already formalised the CAM generation rate for vehicle i on a highway in [2] as

$$g_{i,\mathrm{c}} = \begin{cases} 10 & v_i > 40 \text{ m/s} \\ 1 & v_i < 4 \text{ m/s} \\ \frac{v_i}{4} & \quad \textit{else}. \end{cases} \tag{1}$$

Since we are considering highway traffic, we can assume that 4 m/s $< v_i \leq$ 40 m/s, which is in line with vehicle traces from real highway traffic [14]. Hence Eq. 1 can be reduced to $g_{i,\mathrm{c}} = \frac{v_i}{4}$.

If the messages were generated based on just the CAM triggering conditions without the implementation of any congestion control algorithm, finding the PDF for the overall CAM generations would be just finding the PDF of the number

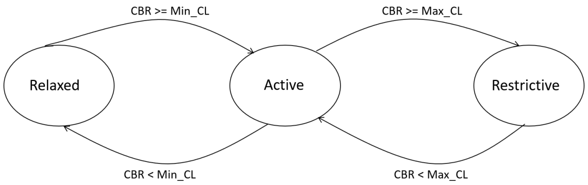

Fig. 2: DCC activation states

of vehicles present in the highway, $p_{n_{\mathrm{H}}}$ (probability of n vehicles being present on the highway) and then the PDF for the overall CAM generation rate can be given as,

$$p_{X_{\mathrm{H}}} = \begin{cases} p_{n_{\mathrm{H}}} & \frac{X_{\mathrm{H}}}{g_{\mathrm{c}}} \in \mathbb{N} \\ 0 & else. \end{cases} \tag{2}$$

This was one of the research contributions of [2]. However, when DCC-TRC is enabled then messages will not be transmitted based on just the CAM triggering conditions. This is where our new model comes into use.

B. DCC-TRC

Before going into the design of our model, it is important to know how the Decentralized Congestion Control based on Transmit Rate Control (DCC-TRC) works. Hence this section will give a brief overview of DCC-TRC.

Decentralised Congestion Control (DCC) is used as a mechanism to control communication channel load in vehicular networks. Each vehicle periodically monitors the fraction of time, the channel is busy within a fixed interval of time and calculates the Channel Busy Ratio (CBR) [15]. Based on the value of the calculated CBR, they are designated into a specified DCC state as shown in Fig. 2 and given in [16]. There are different types of DCC mechanisms, with some having more than one active states. However, in our research, we have considered a 3 state DCC model. In DCC-TRC, based on the DCC state the vehicle is in, its message generation rate would vary. In the "Relaxed" state, DCC is disabled as the Channel Load (CL) is not significant. Hence the vehicle would generate messages at its default rate. So in the case of CAM, message generation would be based on CAM triggering conditions. When the CBR increases beyond Min_{CL} for a certain amount of time given by T_{Up}, then the vehicle changes its DCC state to "Active" and messages are generated at a constant rate lower than the rate being generated in the "Relaxed" state, thus reducing the channel load. However, if the CBR still increases to go beyond Max_{CL} then the vehicle changes its DCC state to "Restrictive" and further reduces its message generation rate. Similarly if the CBR goes below Max_{CL} or Min_{CL} for T_{Down} time units, then the DCC state for the vehicle changes to "Active" and "Relaxed" respectively. Therefore modelling the number of vehicles in each DCC state for our highway segment will enable us to estimate the total message generation rate in this highway segment.

C. Modelling

We have created a Continous Time Markov chain (CTMC) that models the number of vehicles in each DCC state. State (l, m, n) denotes that there are l vehicles in "Relaxed" state, m vehicles in "Active" state and n vehicles in "Restrictive" state. From the initial state, $(0, 0, 0)$, as there are no vehicles in any of the states, a change in DCC is not possible. Hence the only transition possible is an entry of a new vehicle. Since there are no vehicles currently present, the channel load due to V2V communication will be 0. Therefore the state transition will always be to $(1, 0, 0)$ with the rate λ_{H}, which is the vehicle arrival rate into the highway segment as explained in Section III-A. The average service time, $E[S]$ will be the time a vehicle remains in the highway segment on an average. This can be approximated as shown in [2] based on [17] to be,

$$\begin{aligned} E[S] &= \frac{D_{\mathrm{H}}}{v_{\text{Traffic}}}\left(1 + \frac{\sigma^2}{v^2_{\text{Traffic}}}\right) \\ E[S] &\approx \frac{D_{\mathrm{H}}}{v_{\text{Traffic}}}. \end{aligned} \tag{3}$$

Hence the service rate will be $\mu = \frac{1}{E[S]}$. Since we are using a Markov chain, service times are assumed to be exponentially distributed. Hence, we have approximated the vehicle speeds, which are normally distributed with mean v_{Traffic} to an exponential distribution of mean v_{Traffic}. This approximation, allows us to use the existing techniques for solving Markov chains and it does not lead to a high inaccuracy in the final estimation of message generation rate. In general, a new vehicle arrival can be to any of the DCC states. Hence from a Markov state (l, m, n) transition due to vehicle arrival can be to any one of the states, $(l+1, m, n)$, $(l, m+1, n)$ or $(l, m, n+1)$ with the rate λ_{H}, depending on the CBR calculated. However, vehicle exiting the highway segment can be from any of the DCC states. Therefore from Markov state (l, m, n) there would be transitions to state (l-1,m,n), (l,m-1,n) and (l,m,n-1) with the rates $l\mu$, $m\mu$ and $n\mu$ respectively. We have assumed the free flow of traffic and travel times of vehicles to not be affected by each other. Hence vehicles can be serviced in parallel. In a real scenario, this would mean that a faster-moving vehicle would be able to overtake a slower-moving vehicle in front to achieve its desired travel time. Other than the vehicle entry and exit to and from the highway segment, there is also possible transitions between different DCC states based on the CBR at that point in time. All the possible transitions from a state (l, m, n) are shown in Fig. 3. The solid arrows in the figure represent the transitions from state (l, m, n). The dashed arrows are shown to illustrate the structure of our Markov chain.

The equations below formulate the transition rates for our Markov model. Let $q_{(l+1,m,n)}$ be the transition rate for transition from state (l, m, n) to state $(l+1, m, n)$ and is given as,

$$q_{(l+1,m,n)} = \begin{cases} \lambda & CBR < Min_{\mathrm{CL}} \\ 0 & else. \end{cases} \tag{4}$$

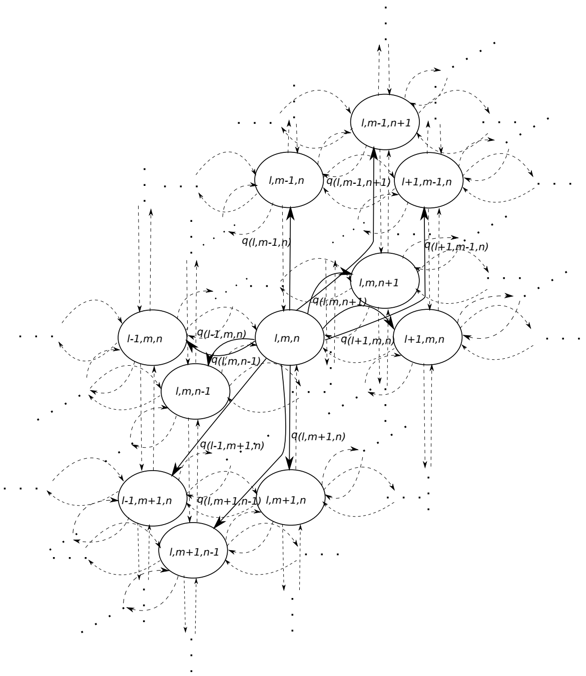

Fig. 3: State transition diagram from state (l, m, n)

Similarly, transitions to state $(l, m+1, n)$ and $(l, m, n+1)$ are given by $q_{(l,m+1,n)}$ and $q_{(l,m,n+1)}$ respectively and are given in Eq. 5 and 6.

$$q_{(l,m+1,n)} = \begin{cases} \lambda \;\; Min_{\text{CL}} \leq CBR < Max_{\text{CL}} \\ 0 \qquad\qquad else \end{cases} \tag{5}$$

$$q_{(l,m,n+1)} = \begin{cases} \lambda \;\; CBR \geq Max_{\text{CL}} \\ 0 \qquad else. \end{cases} \tag{6}$$

As mentioned in Section III-B, a DCC state change occurs when the CBR is higher than Min_{CL} or Max_{CL} for T_{Up} time units or if the CBR is lower than Min_{CL} or Max_{CL} for T_{Down} time units. T_{Up} and T_{Down} can be represented as rates $\nu_{\text{Up}} = \frac{1}{T_{\text{Up}}}$ and $\nu_{\text{Down}} = \frac{1}{T_{\text{Down}}}$ respectively. Again we approximate the channel congestion monitor interval as an exponential distribution with mean T_{Up} and T_{Down} so that we can model using a Markov chain. From our results in Section IV-B, you can see that this approximation did not have a big impact on the accuracy of the estimation of the CAM generation rates by our model. A vehicle changing to a higher DCC state can lead to transitions from state (l, m, n) to state $(l-1, m+1, n)$ or $(l, m-1, n+1)$ as shown in Eq. 7 and 8.

$$q_{(l-1,m+1,n)} = \begin{cases} l \times \nu_{\text{Up}} \;\; CBR \geq Min_{\text{CL}} \;\;\&\;\; l \neq 0 \\ \quad 0 \qquad\qquad\qquad else. \end{cases} \tag{7}$$

$$q_{(l,m-1,n+1)} = \begin{cases} m \times \nu_{\text{Up}} \;\; CBR \geq Max_{\text{CL}} \;\;\&\;\; m \neq 0 \\ \quad 0 \qquad\qquad\qquad else. \end{cases} \tag{8}$$

Similarly a vehicle changing to a lower DCC state can lead to transitions to state $(l, m+1, n-1)$ or $(l+1, m-1, n)$. The rates for these transitions are given by Eq. 9 and 10.

$$q_{(l,m+1,n-1)} = \begin{cases} n \times \nu_{\text{Down}} \;\; CBR < Max_{\text{CL}} \;\;\&\;\; n \neq 0 \\ \quad 0 \qquad\qquad\qquad else. \end{cases} \tag{9}$$

$$q_{(l+1,m-1,n)} = \begin{cases} m \times \nu_{\text{Down}} \;\; CBR < Min_{\text{CL}} \;\;\&\;\; m \neq 0 \\ \quad 0 \qquad\qquad\qquad else. \end{cases} \tag{10}$$

Solving this Markov model will give us the steady-state probability for the overall CAM generation rate within the highway segment D_{H}. Please note, we have assumed that at any given time only a single vehicle can change its DCC state, which may not be the case in reality. This assumption helps us in simplifying our model without affecting the accuracy of the results too much. Since we are interested in the total message generation rate, we have represented CBR, Min_{CL} and Max_{CL} in terms of number of messages per second which are denoted by, Current Generation Rate (CGR), Min_{CLR} and Max_{CLR}. To convert channel load into message generation rate, we have calculated the Maximum Message Generation Rate (MMGR) possible which would correspond to CBR=1. and this can be given by a simple equation as,

$$MMGR = \frac{DataRate}{PacketLength} \text{ messages/s.} \tag{11}$$

Therefore $Min_{\text{CLR}} = MMGR \times Min_{\text{CL}}$ and $Max_{\text{CLR}} = MMGR \times Max_{\text{CL}}$. As mentioned in Section III-B, when in DCC "Active" or DCC "Restrictive" state, the vehicles generate messages at a fixed rate. We shall denote these fixed rates for DCC "Active" and "Restrictive" state as g_{DCCA} and g_{DCCR}. We have already calculated the message generation rate when the vehicle is in "Relaxed" state as shown in Eq. 1. Therefore CGR can be calculated as,

$$CGR = \sum_{i=1}^{l} g_{i,\text{c}} + m \times g_{\text{DCCA}} + n \times g_{\text{DCCR}}. \tag{12}$$

Here l, m and n are the number of vehicles in each of the DCC states, "Relaxed", "Active" and "Restrictive" respectively. Since the vehicles in a highway move with speed closer to their average speed v_{Traffic}, with lower coefficient of variation, we can simplify the message generation rate for each vehicle, $g_{i,\text{c}} = \frac{v_i}{4}$ to general CAM generation rate based on average vehicle speed, $g_{\text{c}} = \frac{v_{\text{Traffic}}}{4}$. Therefore Eq. 12 can be reduced to

$$CGR \approx l \times g_{\text{c}} + m \times g_{\text{DCCA}} + n \times g_{\text{DCCR}}. \tag{13}$$

This simplification again makes it easier to calculate the message generation rate due to CAM triggering based on the number of vehicles in the relaxed state without having a big impact on the results as can be seen in Section IV-B. The Channel Busy Ratio (CBR), can then be calculated using Eq. 11 and 13 to

$$CBR = \frac{CGR}{MMGR}. \tag{14}$$

Solving for the steady state probability of this Markov model will give the probability distribution for number of vehicles in the three DCC states. Knowing the steady state probability distribution for the number of vehicles, allows us to also calculate the probability distribution for the message generation rate as, $P_{\text{V}}(l,m,n) = P_{\text{X}}(g_{\text{c}}l + g_{\text{DCCA}}m + g_{\text{DCCR}}n)$ using Equation 13. P_{V} and P_{X} are the steady state probability distribution for number of vehicles in different DCC states and the CAM generation rate respectively.

IV. EVALUATION

We have implemented our model using Matlab. If we assume M to be the maximum number of vehicles possible, then the total number of states in our Markov chain will be $(M+1)^3$ which is pretty high for large values of M. However, since each state can only have a maximum of 10 transitions from it, most of the elements in the transition matrix will be zero. Therefore to reduce memory requirements and computation time, we have used a Sparse matrix [18] for constructing the transition matrix. To validate our earlier model, the one without DCC we had used actual vehicle traces of a highway environment and shown that our model was able to estimate the CAM generation rates accurately within the 95% confidence interval of the CAM generation rates obtained using the vehicle trace [2]. However, the traffic density in those vehicle traces are quite low and not enough to validate our model for activation of DCC. Hence to validate our proposed model and to assess the impact of the simplifying assumptions on our results, we validate our model using a simulation environment. We emulate a highway scenario in a simulation environment using Artery and Sumo. Artery provides a framework that can be used for simulating V2X applications based on European Telecommunications Standards Institute's (ETSI) Intelligent Transportation System-G5 (ITS-G5) protocols [5]. Cooperative awareness messaging and DCC-TRC are already implemented in Artery. SUMO is a vehicle traffic simulator that allows us to simulate the traffic behaviour in the highway [6]. In this section, we explain the configuration details for simulating our scenario and also discuss the results obtained after comparing the message generation rates estimated by our model and the actual message generation rates obtained from Artery.

A. Simulation Environment

As mentioned before, our simulation environment consists of Artery and SUMO. A 10 lane highway is designed in SUMO of length 950m. The speed limit of the highway is set to v_{H}. The vehicle's initial velocity, when it enters the simulation would be random, so that the simulator can attain the desired traffic flow rate λ_{H}. Therefore the first 250m of the highway segment, D_{Buf} is used for the vehicles to reach their cruise velocity, v_i taken from a normal distribution with mean v_{H} and standard deviation $\sigma = 0.1$. Therefore the effective length of highway on which the CAM generations would be measured will be $D_{\text{H}} = 700$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 $v_{\text{Traffic}} \leq v_{\text{H}}$. The measured v_{Traffic} is used as the average vehicle speed in our model. We have considered a high value for the total number of lanes L_{N}, to be able to evaluate our model at higher traffic loads. The CAM packet size is fixed at 323 bytes and the default data rate of 6 Mbps is used. The DCC mechanism is already implemented in Artery as per the standardisation given in [16]. The simulation is run for different configurations of traffic flow (λ_{H}), minimum channel load (Min_{CL}) and maximum channel load (Max_{CL}). The parameters that are kept the same for all the simulations are shown in Table I.

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
Simulation time	1000s

The CAM generation time stamps for each of the vehicles are recorded from the simulation and the 95% confidence interval of its Cumulative Distributive Function (CDF) is plotted using the Dvoretzky Kiefer Wolfowitz inequality method [19]. The CDF of the message generation rate from our model is then validated by checking if it fits within this confidence interval.

B. Results

Figure 4 and 5 show the results for CAM generation rates for a traffic flow of 720 vehicles/hr/lane. Here Min_{CL} and Max_{CL} are set to 0.19 and 0.59 respectively and the average vehicle speed, $v_{\text{traffic}} = 32$ m/s. Figure 4 shows the distribution of message generation rates due to activation of DCC, observed in Artery. The majority of the CAMs are generated in DCC "Relaxed" state. Hence these messages are triggered based on the CAM generation conditions. Only a small proportion of messages are generated due to the DCC "Active" state. No messages were generated due to vehicles being in the DCC "Restrictive" state. Therefore, it would seem that most of the vehicles in the simulation were in the DCC "Relaxed" state. Figure 5 shows the Cumulative Distribution Function (CDF) of the message generation rate obtained from our current Markov model for this configuration. It can be seen that this CDF falls between the 95% confidence interval of the CDF of the message generation rate obtained from the simulation. One can also notice that the shape of the CDF curve changes as it reaches the end. This is because the lower message generations are due to all the vehicles being in the "Relaxed" DCC state. Since $v_{\text{Traffic}} = 32$m/s, the CAM generation rate per vehicle due to CAM triggering, g_{c} will be 8 messages per second. Hence the step increment at the lower end of the CDF occurs every 8 messages/s. As

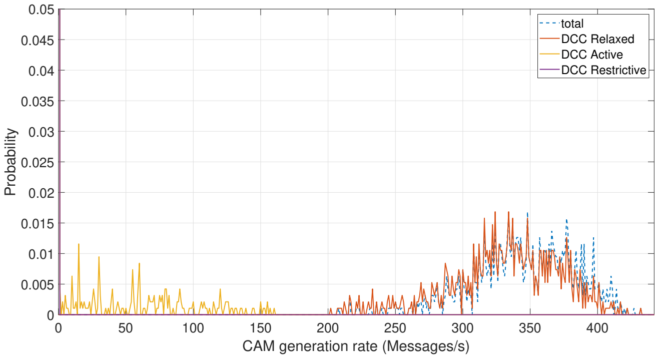

Fig. 4: Distribution of message generation rate due to activation of DCC for $\lambda_{\mathrm{H}} = 720$ vehicles/hr/lane

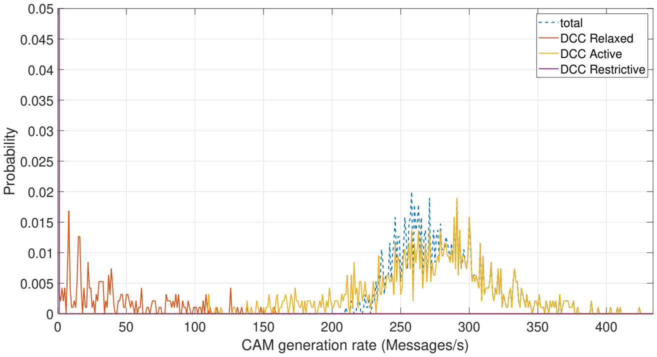

Fig. 6: Distribution of message generation rate due to activation of DCC for $\lambda_{\mathrm{H}} = 900$ vehicles/hr/lane

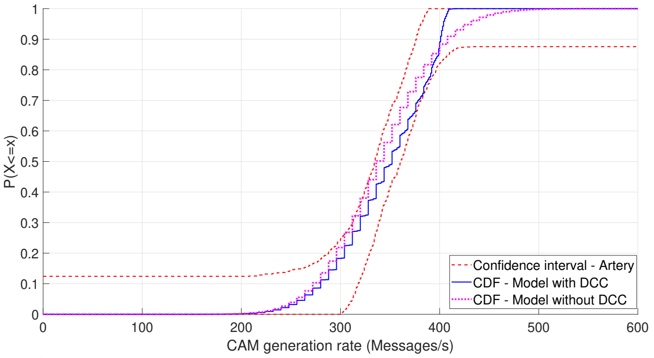

Fig. 5: Comparison of CAM generation rate between simulation in Artery and the Markov model for $\lambda_{\mathrm{H}} = 720$ vehicles/hr/lane

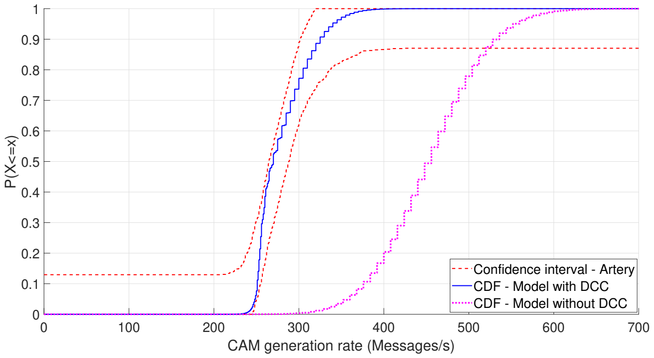

Fig. 7: Comparison of CAM generation rate between simulation in Artery and the Markov model for $\lambda_{\mathrm{H}} = 900$ vehicles/hr/lane

the vehicle density increases, few vehicles change to DCC "Active" state to balance the channel load. Therefore at higher vehicle densities, Overall CAMs generated are contributed due to vehicles being in "Relaxed" and in "Active" state. Hence we see the difference in the CDF curve.

When the vehicle flow rate is increased to $\lambda_{\mathrm{H}} = 900$ vehicles/hr/lane and the Min_{CL} is set to 0.12, such that the congestion control is activated quicker, we can see the results for CAM generation as shown in Figures 6 and 7. Here most CAMs are generated due to DCC being in the "Active" state and only a minority of CAMs are generated due to DCC "Relaxed" state as shown in Figure 6. In this case, it would mean that more vehicles in the simulation were in DCC "Active" state than in DCC "Relaxed" state. Again no messages were generated due to vehicles being in DCC "Restrictive" state. Figure 7 shows the CDF for the overall CAM generation rate estimated by our models. Again it can be seen that the CAM generation rate estimated by our current model is within the confidence interval calculated using the simulation environment. In Figure 7, we can once again notice a change in the shape of the CDF curve, this time at a lower message generation rate. Here DCC starts getting activated early on, at lower vehicle density. This is also the reason why the majority of CAMs are seen to be generated due to DCC being in the "Active" state. Hence at lower vehicle densities messages are generated due to vehicles being in DCC "Relaxed" and "Active" state and at higher vehicle densities messages are generated due to only DCC "Active" state at the rate $g_{\mathrm{DCCA}} = 5$ messages/s. Hence at the higher end of our CDF curve, the step increment occurs after every 5 messages/s.

In Figure 8 and 9, the vehicle traffic flow, λ_{H} has been increased to 1800 vehicles/hr/lane to increase the channel load. As expected, from Figure 8 it seems that DCC is always in the "Active" state during the simulation as no messages were generated due to DCC "Relaxed" or "Restrictive" state. Figure 9 shows that our current model can estimate the change in DCC state, as the message generation rate estimated by our model for this traffic configuration is again within the 95% confidence interval of the message generation rate obtained from the simulation environment. Since here all vehicles are only generating messages due to DCC being in the "Active" state, we do not see any change in the shape of the CDF curve similar to the ones noted in Figures 5 and 7. This is because now at steady state, messages are generated at a constant rate at all times. Hence the step increment occurs every 5 messages/s ($g_{\mathrm{DCCA}} = 5$ messages/s).

To show the effects of DCC on the overall message generation rate, in Figure 5, 7 and 9, we have also plotted the CDF of the CAM generation rates obtained from our previous analytical model which did not consider the effects of DCC on CAM generations. In Figure 5 as the majority of CAMs are generated while the vehicle is in DCC "Relaxed" state, which means that the CAMs are mostly generated based

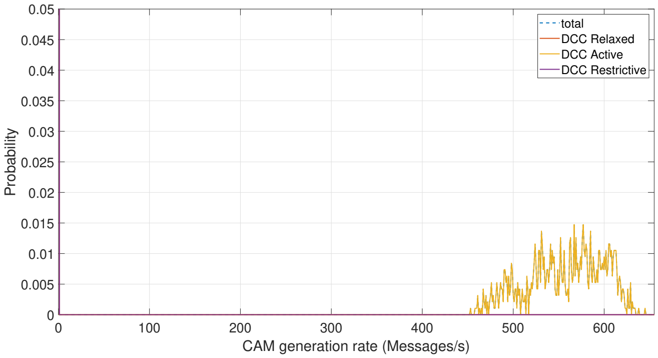

Fig. 8: Distribution of message generation rate due to activation of DCC for $\lambda_{\mathrm{H}} = 1800$ vehicles/hr/lane

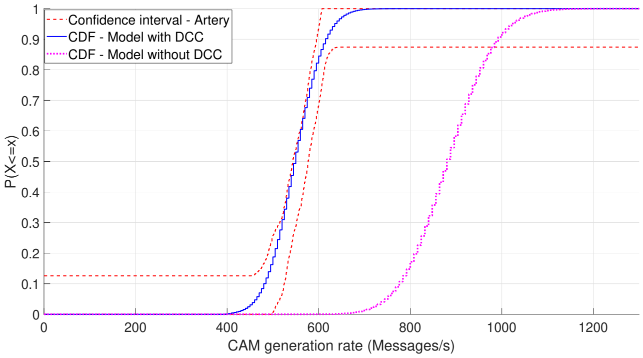

Fig. 9: Comparison of CAM generation rate between simulation in Artery and the Markov model for $\lambda_{\mathrm{H}} = 1800$ vehicles/hr/lane

on just the CAM generation conditions [20] the CDF curve from our current model and the previous model are closer to each other. However in Figure 7 and 9 as CAMs are mainly generated when in DCC “Active” state, our previous model overestimates the CAM generation rate. This effect can be seen better in Figure 10. Here we have plotted the average message generation rates and the probability of message generation rate exceeding 45% of channel capacity for different vehicle arrivals rates into the system. We achieve 100% channel capacity if $CBR = 1$, which happens when the message generation rate is $MMGR$ as given in Eq. 11. Hence based on the parameters given in Table I, more than 45% channel capacity will correspond to message generation rate being above 845 messages/s. For the model with DCC, Min_{CL} and Max_{CL} are set to 0.19 and 0.59 respectively similar to the previous evaluations. From the figure. it can be seen that the average message generation rate increases with an increase in the vehicle arrival rate. However in the model without DCC this is a linear increase whereas, in the current model, the average message generation rate increases linearly similar to the previous model until vehicle arrival rate is 2.2 vehicles/s, but then until vehicle arrival rate is 4 vehicles/s the average message generation rate does not increase to much. This is because during these periods there are vehicles in both DCC “Relaxed” and “Active” states and that helps in reducing the overall message generation rate. From the arrival rate of 4 vehicles/s, the average message generation rate again starts to increase with the vehicle arrival rate. This is because now all the message generations are due to vehicles being in DCC “Active” state and hence all vehicles generate messages at the rate g_{DCCA}. Therefore increase in vehicle arrival rates will linearly increase the overall message generation rate. However, for all these vehicle arrival rates the DCC mechanism is able to keep the channel capacity to below 45%. This though is not the case with our earlier model where the probability of message generations exceeding 45% of channel capacity starts to increase from vehicle arrival rate of 3.6 vehicles/s and reaches close to 1 at 6 vehicles/s arrival rate.

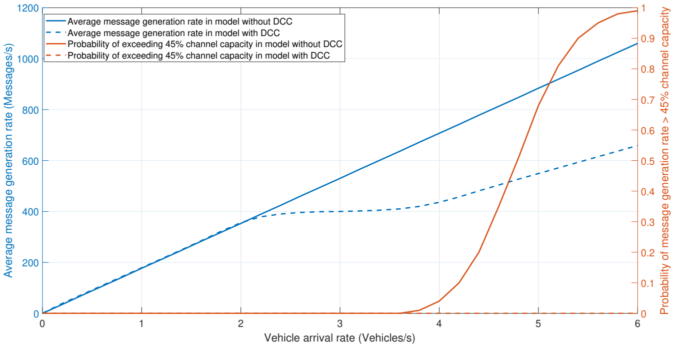

Fig. 10: Comparison between the model with DCC and without DCC with respect to the average message generation rate and the probability of exceeding 45% of channel capacity

V. CONCLUSIONS AND FUTURE WORK

In this paper, we have shown that a Markov chain based model can be used to estimate the message generation rate in Vehicle to Vehicle communication for a highway environment based on the traffic flow rate and average vehicle speed by also considering the effects of different DCC states on the overall message generation rate. We validated our model by comparing its results with the results obtained from a simulation environment and showed that our model can estimate the message generation rate with high accuracy. Our model can be used for assessing the effects of the various DCC-TRC configurations for different highway traffic scenarios by quick estimation of the overall message generation rate due to these settings as discussed in Section IV-B. It can also be used for the creation of artificial CAM generation traces.

For future work, we would like to study the effects of other congestion control algorithms like DCC based on transmit power control and LIMERIC on the overall message generation rates and check if those can also be modelled using a similar method. Further, we would like to model other types of V2V messages which have a higher payload size than CAM. One such message type is Collective Perception Message (CPM) in which, the vehicle not only transmits its vehicle parameters but also the information of other objects and surroundings perceived by it, Hence these types of messages would have a huge impact on the channel load even at a low traffic flow rate. It would also be interesting to look into other types of communication technology like C-V2X and how the congestion control algorithms present there can be modelled.

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