A Discrete Time Markov Chain Based Comparison of the MAC Layer Performance of C-V2X Mode 4 and IEEE 802.11p

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Abstract—Vehicle to vehicle (V2V) communication plays a pivotal role in intelligent transport systems (ITS), with cellular-vehicle to everything (C-V2X) and IEEE 802.11p being the two competing enabling technologies. This paper presents multi-dimensional discrete time Markov chain (DTMC) based models to study the medium access control (MAC) layer performance of the ETSI ITS-G5 version of IEEE 802.11p and C-V2X Mode 4. The models are coupled with an appropriate DTMC based queue model, that consists of traffic generators for periodic cooperative awareness messages (CAMs) and event driven decentralized environmental notification messages (DENMs). Closed-form solutions for the steady state probabilities of the models are obtained, which are then utilized to express probabilities of the two communicating technologies. An application for a highway scenario is provided to present numerical results, and to draw insights on the performance. In particular, a performance comparison between IEEE 802.11p and C-V2X Mode 4 in terms of the average delay, the collision probability, and the channel utilization is presented. The results show that IEEE 802.11p is superior in terms of average delay, whereas C-V2X Mode 4 excels in collision resolution. The paper also includes design insights on possible future MAC layer performance enhancements of both standards.

Index Terms—C-V2X Mode 4, discrete time Markov chain, ETSI ITS-G5, IEEE 802.11p, medium access control, vehicle to vehicle communication.

I. INTRODUCTION

Vehicular networks primarily depend on vehicle-to-vehicle (V2V) communications to enable an active safety environment. V2V communication mainly consists of an exchange of small broadcast packets that have critical latency and reliability requirements. It has gained considerable research interest, with a focus of developing vehicular networks using the IEEE 802.11p / dedicated short-range communication (DSRC) as an enabling technology. As an alternative to 802.11p, the third generation partnership project (3GPP) published the first version of Release 14 [1] in 2017, that includes support for V2V communications using long-term evolution (LTE) sidelink communications, a.k.a., LTE-V, LTE-V2X, LTE-V2, or Cellular-V2X (C-V2X). This paper presents a medium access control (MAC) layer performance comparison of these two key enabling technologies by utilizing non-saturation discrete-time Markov chains (DTMCs).

The first Wi-Fi based standard specifically designed for vehicular communications was approved under the name IEEE 802.11p in 2010. IEEE 802.11p was later included in the IEEE 802.11-2012, now superseded by the IEEE 802.11-2016. The European telecommunications standards institute intelligent transport systems operating in the 5GHz frequency band (ETSI ITS-G5) [2]–[4] has been approved as the European version of the IEEE 802.11p standard, to be used in V2V communication applications. One speciality of the vehicular based technology is the capability of working without the necessity of joining a basic service set (BSS). In the IEEE 802.11p MAC layer, a multiple access technique called carrier sense multiple access with collision avoidance (CSMA/CA) is adopted. A vehicle that needs to transmit, senses the medium to check if it is idle, and a mechanism based on random backoff is performed to reduce the probability of collisions.

LTE sidelink was introduced for the public safety device-to-device (D2D) communications in Release 12 as Mode 1 and Mode 2. Release 14 introduced Mode 3 and Mode 4, specifically designed for V2V communications [1], [5]. In Mode 3, two vehicles directly communicate with each other although the selection and management of the resources are carried out by the cellular infrastructure. In Mode 4 [5], [6], vehicles autonomously select and manage their resources without any cellular infrastructure support. The distributed scheduling protocol enabling this feature is called sensing-based semi-persistent scheduling (SPS). Vehicles sense the previous transmissions of all vehicles to estimate free resources, hence avoiding packet collisions. Mode 4 is highly applicable for V2V based safety applications, which cannot depend on the cellular infrastructure for communication due to stringent latency constraints.

Both of these enabling technologies manage the periodic nature of cooperative awareness messages (CAMs) and Pois-
The model in our paper significantly differs from the one in [18]. CAMs, which are keep alive messages, are periodically broadcast by each vehicle to provide information of presence, position, temperature, and primary status. DENMs are event-triggered messages, which are broadcast to alert the road users of a hazardous event.

Several works have recently discussed the two technologies from various perspectives, mainly focusing on the physical (PHY) layer, with some providing performance comparisons as well [8]–[16]. A common conclusion of [8]–[13] is that, given a target performance, the physical (PHY) layer of C-V2X allows for reaching a longer distance. However, it has been shown that there are specific scenarios and settings where IEEE 802.11p provides similar or even better results [15], [16]. In our paper, the main focus is on the MAC layer performance, and [17] and [18] can be considered to be the most related to our work. To this end, the first analytical model for the MAC layer performance of C-V2X Mode 4 is proposed in [17]. In particular, the paper presents analytical results using fundamental probability theory for the average packet delivery ratio, and for four different types of transmission errors in C-V2X Mode 4. The results are validated for different transmission parameters and traffic densities, by using a simulator implemented over the Veins simulation platform [19]. In our paper, more comprehensive analytical modeling of C-V2X Mode 4 is presented by utilizing DTMCs. A DTMC is the most sought after method of modeling the MAC layer performance as it facilitates the modeling of each step of the MAC protocol using a state machine, and the steady-state probability of each state can be used to get insights on each particular step in the MAC protocol [18], [20]–[22]. [18] proposes such a DTMC based analytical model for the MAC layer of IEEE 802.11p. Our work improves the DTMC model in [18] by representing the MAC protocol of IEEE 802.11p more precisely, especially considering the effect of arbitration inter-frame spacing (AIFS) on the model. Our model for C-V2X Mode 4 allows us to study the protocol at the subframe (1 ms) level, which is the smallest time unit in its standard. To provide an insightful and fair comparison, we need to model the MAC protocol of IEEE 802.11p such that it represents the smallest time unit of its standard as well. To this end, the time unit is a 13 µs duration referred to as aSlotTime in the standard. This makes the model in our paper significantly different to the one in [18].

Our contributions can be summarized as follows. We provide detailed modeling of the MAC layer protocols of C-V2X Mode 4 and ETSI ITS-G5 version of IEEE 802.11p using DTMCs in non-saturation mode. The complete Markov model consists of a state machine each for the two competing technologies and a queue model to represent the device level packet queue. The queue model consists of hidden Markov model traffic generators for CAM and DENM. We solve the models in close form to get expressions for the steady-state probabilities. They are then used to derive expressions for performance metrics such as the average delay, the collision probability, and the channel utilization of the system. We present an application of the models for a highway scenario to provide insights and comparisons on the derived performance indicators, through simulations. Parameters are initialized and the appropriate DTMCs are run iteratively in parallel until the parameters converge. Based on the numerical results, we can observe that C-V2X Mode 4 exhibits a lower collision probability compared to IEEE 802.11, but IEEE 802.11p maintains a lower average delay compared to C-V2X Mode 4.

Design insights on how the MAC layer performance of both technologies can be improved are presented as well.

The remainder of the paper is organized as follows. The analytical models and steady-state solutions are presented in Sections II and III respectively. Section IV consists of the performance analysis. The numerical results and discussion follows in Section V and Section VI concludes the paper.

## II. Analytical Models

This section presents three analytical models based on DTMCs. The first DTMC models CAM and DENM packet generation and the device level packet queue. This DTMC serves as the common packet generator and queue model for the second and third DTMC models. To this end, the second DTMC models C-V2X Mode 4 operation while utilizing the SPS algorithm for radio resource allocation, and we refer to this model as the state machine for C-V2X Mode 4. The third DTMC models ETSI ITS-G5 version of IEEE 802.11p, which is referred to as the state machine for IEEE 802.11p. We note that all DTMCs are ergodic, i.e., they are aperiodic and positive recurrent, hence, a steady-state distribution exists.

### A. CAM and DENM packet generator and the device level packet queue

The queue model represents the packet arrival queue of a vehicle for two types of packets, CAM and DENM [7]. CAM queue is modeled using a fixed inter-arrival time model, where the inter-arrival time is set according to the standard. The DENM queue is modeled using a Poisson arrival model since DENM are event-triggered messages. Additionally once generated, the DENM generator repeats the generated message \( k \) number of times using fixed inter-arrival process. Fig. 1 illustrates the DTMC queue model, where the maximum size of the queue is considered to be \( m \). Each state of the queue model is explained by the traffic generator DTMC model shown in Fig. 2. In Fig. 2 the transition probabilities and states particularly associated with the CAM and DENM packet generation are represented by blue and red, respectively. The transition probabilities and states common to both processes are represented using black. In state notations, let \( x \in \{t, z\} \). We consider \( x = t \) with regards to the CAM generator, and it represents the inter-arrival time between CAM packets. We consider \( x = z \) with regards to the DENM generator, and it represents the repetition interval of DENM packets. Furthermore, in the DENM model, \( k \) denotes the average number of repetitions and \( \lambda \) denotes the DENM packet arrival rate (packets per second). For DENM packets, the probability of at least one packet arriving in a \( T \) second interval can be given by \( 1 - e^{-XT} \) by using the Poisson arrival assumption. Moreover, in the DENM generator, an additional idle state can be observed compared to the CAM generator. In the state notation, \( e \) and \( c \)
denote the generated message transmitted and not transmitted before new message generation, respectively. The transition probabilities of the queue model are derived from the steady-state probabilities of the generator models.

B. State machine for C-V2X Mode 4

1) Semi-persistent scheduling algorithm: The main purpose of the SPS algorithm is to enable the selection of radio resources for the vehicle without the assistance of an eNodeB. Based on the SPS algorithm, the following three steps are followed by each vehicle for resource reservation.

Step 1: Within the selection window, which is a time window that initiates with the packet generation, vehicle \( v \) identifies all possible candidate single-subframe (1 ms) resources (CSRs) that can be reserved. CSRs are groups of adjacent sub-channels within the given 1 ms sub-frame that are large enough to fit in the sidelink control information (SCI) and the transport block (TB), which will be transmitted. The length of the selection window is defined in the standard as the maximum latency \( \delta \), and a CSR should be selected within this duration.

Step 2: \( v \) creates list \( L_1 \) that consists of CSRs it can reserve, based on the information received in the previous 1000 sub-frames (sensing window). \( L_1 \) includes all the CSRs in the selection window except those that satisfy the following conditions.

1) CSRs used by vehicle \( v \) during the sensing window. This is done as a precautionary measure due to \( v \) not being able to sense these CSRs during its half-duplex transmissions.

2) CSRs that have a received signal strength indicator (RSSI) value above a threshold level \( (l_{th}) \), and are being used by other vehicles at the time \( v \) tries to utilize them.

If \( L_1 \) contains more than 20% of the total CSRs in the selection window, the system moves to Step 3. Otherwise, \( l_{th} \) is increased by 3dB and Step 2 is repeated.

Step 3: From \( L_1 \), \( v \) filters out the CSRs that experience the lowest average RSSI values. For each CSR, the averaging is done over the previous 10 sub-frames, and the CSRs with the lowest average RSSI values are added to a new list \( L_2 \) such that the size of \( L_2 \) amounts to 20% of the total CSRs in the selection window. \( v \) randomly and uniformly selects a CSR in \( L_2 \) and reserves it for the next \( RC \) transmissions, where \( RC \) denotes the value of the resource counter. \( RC \) is decremented by 1 for each transmission of a packet. Let \( RC_F \) denote the starting value of the resource counter. When \( RC = 1 \), new CSRs should be selected and reserved with probability \( (1 - P_{rk}) \), where \( P_{rk} \in [0, 0.8] \).

2) DTMC Model: Fig. 3 illustrates the DTMC model for C-V2X Mode 4 operation. Transition probabilities and states in the model are as follows. The state space of the model is as follows. The state space of the model are {Idle, Common, CAM}. The DTMC model for C-V2X Mode 4 is shown in Fig. 3.
Table I
Selection of AIFS\textsubscript{N} for different values of $C$ and access categories (AC)

| AC          | $C$ | AIFS\textsubscript{N} |
|-------------|-----|---------------------|
| AC\_background (BK) | 15  | 9                   |
| AC\_best Effort (BE) | 15  | 6                   |
| AC\_video (VI)   | 7   | 3                   |
| AC\_voice (VO)   | 3   | 2                   |

$RC_F \in [5, 15]$, $\Gamma = 50$ ms with $RC_F \in [10, 30]$ and $\Gamma = 20$ ms with $RC_F \in [25, 75]$.

If a new packet arrives when $RC = 1$, the SPS algorithm has to allocate a radio resource for the transmission of this packet. The maximum time that can be allocated to the SPS algorithm for this purpose is $(\Gamma - 1)$ ms. Hence, the waiting time duration before the transmission of a packet is represented by $\Gamma - 1$ equiprobable states: $(w, 0)$ to $(w, \Gamma - 2)$. After the waiting time is over, $v$ selects a value randomly and uniformly from the set of $(1 + R_{ht} - R_{t}) RC$ values. At every state $(i, 0)$, where $i \in \{1, \ldots, R_{ht}\}$, there is a transmission opportunity. In fact, at that point, the device will transmit the control information related to its persistent scheduling. If the queue is not empty, data transmission will happen, $i$ will be decremented, and the vehicle will wait for the next transmission opportunity, that will arise after $\Gamma$ ms. The respective waiting time is represented by states $(i - 1, 1)$ to $(i - 1, \Gamma - 1)$. If the queue is empty, the vehicle will similarly wait $\Gamma$ ms for the next transmission opportunity, while maintaining the same RC value $i$. This process will repeat until the system reaches state $(1, 0)$. If the queue is still not empty, the vehicle has the option to use the same radio resource (with probability $P_r$), or choose a new radio resource. If the same radio resource is used, the vehicle has to wait for the maximum waiting time of $\Gamma - 1$ ms before choosing a $RC$ value. Note that selecting a new radio resource may incur less delay than keeping the old one as new resource ends up in one of the $\Gamma - 1$ waiting states, $(w, 0)$ to $(w, \Gamma - 2)$, with equal probability.

C. State machine for IEEE 802.11p

The state machine is shown in Fig. 4. $C$ denotes the minimum contention window size. Transition probabilities and states in the model are as follows. The state space of the model is denoted by $S_{11p}$. The $Idle$ state represents the state where there are no packet arrivals, thus the queue is empty. If a packet arrives, the MAC protocol listens for an $AIFS$ duration before transmitting. The $AIFS$ duration is calculated according to $AIFS = aSIFS + AIFS * aSlotTime$, where $aSlotTime$ is 13 $\mu$s, $aSIFS$ is 32 $\mu$s and $AIFS$ is selected according to Table I depending on the access category and the value of $C$.

States $(A_i)$ for $i \in \{1, \ldots, \Omega\}$, represent the $AIFS$ waiting time, and $\Omega$ denotes the maximum number of $aSlotTime$ durations the MAC needs to wait to complete the $AIFS$ duration. $\theta$ represents the probability of the channel being busy (channel busy ratio). If the channel is idle for an $AIFS$ duration, the vehicle transmits. Transmission is represented by states $(Tx, i)$, where $i \in \{1, \ldots, \theta\}$, and $\theta$ denotes the number of $aSlotTime$ durations required to transmit a packet of 134 bytes over a 6 Mbps control channel (CCH).

If the channel becomes busy during the $AIFS$ duration, the vehicle waits $\theta \times aSlotTime$, the time taken for transmission, until the channel is free again. The waiting is represented by states $(B, i)$, where $i \in \{1, \ldots, \theta\}$. The channel being busy at state $A_1$ depicts a scenario where the packet arrival of the vehicle of interest has occurred during the channel is busy, i.e., another vehicle is transmitting. Thus, the time it has to wait until the channel becomes free again will be $j \times aSlotTime$, where $j$ is a uniformly distributed random integer in $[1, \theta]$.

When the channel becomes free again, that is at state $(B, \theta)$, $v$ initiates a backoff process. The backoff counter value is selected as a random number in $[0, C]$, and the backoff stage is selected depending on the selected backoff counter value. According to the standard, backoff counter value 0 and 1 both lead to backoff stage 0. Thus the probability of backoff stage 0 is twice the probability of any other backoff stage. Then $v$ waits for another $AIFS$ duration before sensing the channel again. For backoff counter value $i \in \{0, \ldots, (C - 1)\}$, states $(i, A_j)$, where $j \in \{1, \ldots, (\Omega - 1)\}$, represent the waiting duration, and $(I, i)$ represent the sensing states. If the channel is found busy at state $(I, i)$, $v$ waits for $\theta \times aSlotTime$, which is represented by states $(\Delta, j)$, where $j \in \{1, \ldots, \theta\}$, and another $AIFS$ duration at the same backoff stage $i$. This loop continues until the channel is found idle at state $(I, 0)$. When the channel is found idle, the backoff counter will be decremented, and we will arrive at state $(I, i - 1)$. If $v$ finds the channel to be free at state $(I, 0)$, it transmits its packet.

III. Steady-state solutions

Steady-state solutions of the DTMCs are proposed in this section. We present the steady-state solutions of the CAM and DENM device level packet queue. Then, by using these solutions, we present the steady-state solutions of the state machines developed for C-V2X Mode 4 and IEEE 802.11p.

A. Queue Model

$P_{qe}$ and $P_{que}$ are two important probability values in our analysis. These values can be obtained through the steady-state probability of state $(0)$ of the queue model. By solving the device level packet queue, we can show the steady-state probability of state $(0)$ to be

$$\pi_0 = \left[1 + c' \left(\frac{1 - \beta^{-m} c^m}{\beta - c}\right)\right]^{-1}. \tag{1}$$

However, to obtain $\beta$, $c$ and $c'$, we need the steady-state solutions of the CAM and DENM generators, which we will present next.

Let $\pi_{CAM}^i$ and $\pi_{DENM}^j$ denote the steady-state probabilities of state $(i, j)$, where $i \in \{e, c\}$ and $j \in \{0, \ldots, (x - 1)\}$, of the CAM and DENM generators, respectively. For the CAM generator, the steady-state probabilities are given by
generators, respectively. Then, we have
\[
\pi(1 - \pi) = \pi e, z c, i = 0, \pi_{0,0} = \pi_{0,1} = \pi_{1,0} = \pi_{1,1} = 0.
\]

By substituting values for \(\theta\), \(\Delta\), \(P_k\), and subsequently \(P_s\), which is the probability of successful transmission.

1) Interpreting \(P_{sch}\): We consider \(A\) CSRs in total in the selection window and that \(X\) CSRs are excluded according to the SPS algorithm, such that there are \(A - X\) CSRs in \(L_1\). Let \(N\) be the number of vehicles in the area of influence of \(v\). The value of \(X\) will depend on \(\lambda\), which denotes the number of times we encounter \(RC = 1\) in a given sensing window. Let \(\xi\) represent the ratio between the size of the sensing window and the selection window. Since \(\lambda \leq 2R_1\) according to the standard, we can hold up to 25 CSRs. Let \(\tilde{X} = \frac{\tilde{X}}{\tilde{X}}\). We will obtain an expression for \(X\) through the following lemma.

Lemma 1: \(X\) is given by
\[
X = NP_k(1 - P_{\tilde{X}}) + \sum_{i=0}^{2} (N + i)P_{\tilde{X} = i},
\]

where \(P_{\tilde{X} = i} = C_{\tilde{X} = i}/\sum_{j=0}^{2} C_{\tilde{X} = j},\ C_{\tilde{X} = j} = R_h - \xi,\ C_{\tilde{X} = 1} = (R_h - R_l + 1)(R_l - 1)(1/2)(\pi^2 + \xi - R_l(R_l + 1)),\) and \(C_{\tilde{X} = 2} = (1/2)(\pi - R_l)(R_h(\pi - R_l) - 1) - \xi R_l + \xi + R_l^2 + 1\).

Proof: See Appendix [A]

Next, we will further evaluate \(X\) with reference to the standard. According to the 3GPP C-V2X standard [B], single-carrier frequency-division multiple access (SC-FDMA) is considered for the uplink, using a 10 MHz channel. 50 resource blocks (RB) are allocated for this bandwidth per each slot (half subframe), and hence, one subframe contains 100 RBs. A CSR requires at least 4 RBs to transmit a 100-byte payload, using 64-QAM modulation. Therefore, each 1 ms subframe can hold up to 25 CSRs, and hence, the 100 ms selection window can hold up to 2500 CSRs. This means, \(L_1\) should include at least 500 CSRs to satisfy the requirement in Step 2 of the SPS algorithm, or \(X\) should be less than 2000 CSRs. If we consider \(X > 2000\), from (2) we have
\[
N > \frac{2000 - P_{\tilde{X} = 1} - 2P_{\tilde{X} = 2}}{P_{\tilde{X} = 0} + \max(P_k)(1 - P_{\tilde{X} = 0}) + P_{\tilde{X} = 1} + P_{\tilde{X} = 2}}.
\]

By substituting values for \(P_{\tilde{X} = 1}, P_{\tilde{X} = 2}\) and \(\max(P_k) = 0.8\), we get \(N > 1123\). This is a very unlikely condition in a highway scenario. Therefore, without a loss of generality, we assume \(P_{sch}\) to be 1 in our analysis.

2) Steady-state solutions: The steady-state equations of the state machine in Fig. 3 are used to derive its steady-state probabilities which are presented next. To this end, \(\pi_{Idle}\) is
\[
\pi = \pi(1 - P) + (1 - e^{-\lambda T})\pi I + \pi_{0,0}, c_{DENM} = \pi_{0,0} + (1 - e^{-\lambda T})\pi I, \beta_{DENM} = \sum_{i=1}^{t-1} \pi_{e,i} P_s, c_{CAM} = \pi_{e,0} (1 - P) + (1 - e^{-\lambda T})\pi I, \theta_{CAM} = \pi_{0,0} + (1 - e^{-\lambda T})\pi I, \beta_{CAM} = \sum_{i=1}^{t-1} \pi_{e,i} P_s, e_{CAM} = \pi_{e,0} = \pi_{0,0} + (1 - e^{-\lambda T})\pi I.
\]

B. State machine for C-V2X

Now that we have obtained \(P_{eq}\) and \(P_{qne}\), the steady-state solutions of the state machine for C-V2X can be used to obtain \(P_{sch}, P_{arr}, P_{r_k}\), and subsequently \(P_s\), which is the probability of successful transmission.

\[
\pi_{Idle} = b \pi_{eq,0},\ \text{where}\ b = \frac{(1 - P_r) \left( \frac{1}{P_r} - 1 \right)}{P_{arr} + P_{qne} (1 - P_{arr})}
\]
By substituting for $\pi_{T_x,i}$ from (7), (8), (9), (10), (11) and (12), respectively, we can show that

$$\pi_{Idle} = \frac{1+[(1-P_{arr})P_{qe}]\left[1-(1-\theta)^\Omega\right]}{2C(1-\theta)} + \frac{(C+1)\theta}{2(1-\theta)} + \frac{\theta}{2(1-\theta)}.$$

The obtained solution for $\pi_{Idle}$ can then be used to find all other steady-state probabilities, which can be used to determine $P_s = \sum_{i=1}^\Omega \pi_{T_x,i}$ and $\theta = 1 - (1 - \sum_{i=1}^\Omega \pi_{T_x,i})^{(N-1)}$.

### IV. PERFORMANCE ANALYSIS

This section focuses on deriving expressions for several useful performance parameters that can be used to compare the MAC layer performance of C-V2X Mode 4 and IEEE 802.11p.

#### A. Probability of collision $P_{col}$

Even though the SPS algorithm attempts to minimize packet collisions between vehicles at transmission by considering the radio resource utilization of vehicles during the 1000 ms sensing window, there still remains a possibility for collisions. To this end, a schedule collision can occur when a vehicle selects a new radio resource for transmission. In particular, this type of collision can occur during the selection window when there is an overlap in the selection windows of neighboring vehicles, as illustrated in Fig. 5. In such a scenario, the vehicles with overlap will select a CSR independent of each other, and hence, there is a possibility of them selecting the same CSR, which results in a collision. We will start the analysis by obtaining an expression for the collision probability of C-V2X Mode 4.

**Lemma 2:** The collision probability of C-V2X Mode 4 is given by

$$P_{col}^{V2X} = 1 - \left[1 - \prod_{i=0}^{\Omega-1} \left(1 - \frac{\pi_{i,0}}{1 - \pi_{i,0}} \frac{1 - P_{rk}}{A-X}\right)\right]^{N-1}.$$  

**Proof:** See Appendix [B]**

The collision probability of IEEE 802.11p is calculated according to $P_{col}^{11p} = 1 - P_{suc}$, where $P_{suc}$ is the probability that exactly one station transmits on the channel, given that at

![Figure 5. Example of a collision in C-V2X Mode 4.](image-url)
least one station transmits \cite{22}. An expression for the collision probability is formally stated through the following lemma.

**Lemma 3:** The collision probability of IEEE 802.11p is given by

\[
P^{11p}_{\text{col}} = 1 - N \left[ (1-\theta)(\pi_{T,i}^{1} + \sum_{i=1}^{\vartheta} \pi_{T,i}) \left( 1 - \left( \pi_{I,0}^{1} + \pi_{A,i} + \sum_{i=1}^{\vartheta} \pi_{T,i} \right)^{N-1} \right) \right].
\]

**Proof:** See Appendix B

B. Average delay \(D_{\text{ave}}\)

Next, we focus on the average delay between the generation and the transmission of a packet. The delay value captures the queuing delay and the access delay, which are introduced in the queue model and the state machine, respectively. We will first focus on the average delay of C-V2X Mode 4.

**Lemma 4:** The average delay of C-V2X Mode 4 is given by

\[
d^{V2X}_{\text{ave}} = \frac{\sum_{i=1}^{m} 2\vartheta - \pi_{i}}{1 - P_{\text{qe}}}. \tag{16}
\]

**Proof:** See Appendix C

For IEEE 802.11p, the average delay is calculated by utilizing the delay of each state in the state machine, except the idle state. The normalized average delay of the system is calculated using the delay values of the individual states. Let \(D_{i,j}\) denote the delay at state \((i, j)\). \(a_{\text{SlotTime}}\) is used as the unit delay, thus \(D_{T,i} = \vartheta\) since the transmission of a packet of 134 bytes takes \(\vartheta \times a_{\text{SlotTimes}}\). We assume \(D_j = 0\). To this end, the delay at each state of the system is calculated according to the following equations.

**States \((1, i)\):**

\[
D_{i,1} = \begin{cases} 
1 + \vartheta + \theta (\Omega) & \text{for } i = 0 \\
(1-\theta) \left\{ 1 + \vartheta [1 + \theta (i-1)] + i\theta (\Omega - 1) \right\} & \text{for } i \in [2, C - 1]
\end{cases}
\]

**States \((i, A_i)\):** for \(i \in \{0, 2, ..., C - 1\}, j \in [1, (\Omega - 1)]

\[
D_{i,A_i} = (\Omega - j) + D_{i,1}.
\]

**States \((\Delta_i, j)\):** for \(i \in \{0, 2, ..., C - 1\}, j \in [1, \vartheta]

\[
D_{\Delta_i,j} = (\vartheta - j + 1) + (\Omega - 1) + D_{i,1}.
\]

**States \((B, i)\):**

\[
D_{B,i} = \begin{cases} 
1 + \frac{2}{\vartheta} (\Omega-1) + D_{i,1} + \frac{C-1}{\vartheta} (\Omega-1) + D_{i,1} & \text{for } i = \vartheta \\\n1 + D_{B,(i+1)} & \text{for } i \in [1, (\vartheta - 1)]
\end{cases}
\]

**States \((T, x, i)\):** for \(i \in [1, \vartheta]\)

\[
D_{T,x,i} = \vartheta - (i - 1).
\]

C. Average channel utilization

The average channel utilization depicts the average number of users accessing the channel simultaneously. Thus the average channel utilization of C-V2X Mode 4 and IEEE 802.11p is given by

\[
CU^{V2X}_{\text{ave}} = \frac{P_{s}N(1 - P^{V2X}_{\text{col}})}{\text{CSRs per subframe}} \quad \text{(18)}
\]

and

\[
CU^{11p}_{\text{ave}} = \frac{P_{s}N(1 - P^{11p}_{\text{col}})}{\text{CSRs per subframe}} \quad \text{(19)}
\]

respectively. Note that, since we are interested in finding the average channel utilization within a single subframe in C-V2X Mode 4, we normalize the channel utilization value by the total number of CSRs within a single subframe.

V. NUMERICAL RESULTS AND DISCUSSION

In this section, we present an application of the models for a highway scenario to provide insights and comparisons on key performance indicators, through simulations.

A. Instantiation of CAM, DENM and the DTMC models in a highway

We consider a highway with four parallel lanes in each direction. We assume that the vehicles move at a constant speed of 100 km/h on the highway, and the average inter-vehicle gap is 50 m. We also assume that only CAM and DENM are utilized for V2V communication \cite{7, 23}, while their reference packet formats are specified according to the European telecommunications standards institute (ETSI) \cite{2}. Both CAM and DENM are transmitted to vehicles in the geographical region of influence by the target vehicle.

A maximum size of 10 packets \((m = 10)\) is considered in the queue model. We consider the CAM packet inter-arrival time to be between 100 ms and 1 s, according to the specifications \cite{2}. The inter-arrival time of the event triggered DENM is modeled by a Poisson process, while the
average repetition interval of DENM packets is considered to be \( z = 100, 200 \), and 300 ms, and the average number of repetitions of packets is considered to be between \( k = 1 \) and 9. The packet arrival rate \( \lambda \) is considered to be 1, 0.2, and 0.011 packets/s. Steady-state solutions of the state machine and the queue models are calculated in parallel. \( P_s \) and \( P_{qe} \) are recomputed iteratively based on the steady-state probabilities, until the probability values stop varying significantly.

Similarly in IEEE 802.11p the steady-state solutions of the state machine and the queue model can be calculated in parallel. \( \theta \) and \( P_{qe} \) are recomputed iteratively based on the steady-state probabilities, until their values converge. The time between the transmission of two consecutive packets is regulated under the transmit rate control (TRC) technique of the ETSI ITS-G5 decentralized congestion control (DCC) algorithm of IEEE 802.11p. During high utilization periods, the TRC increases the time between two packets and vice-versa [24]. This is termed as adaptive CAM rate in the simulations.

**B. Performance Comparison of C-V2X Mode 4 and IEEE 802.11p**

1) **Average delay:** Average delay is calculated according to (16) and (17) for C-V2X Mode 4 and IEEE 802.11p, respectively. Fig. 6 illustrates the variation of average delay with the number of vehicles. We can observe the average delay increasing with \( \Gamma \) in C-V2X Mode 4. For a given \( \Gamma \) value, a higher average delay can be obviously observed when the CAM inter-arrival time decreases from 200 to 100 ms. However, it is interesting to note that the average delay is not very sensitive to the number of vehicles in C-V2X Mode 4. On the other hand, the average delay increases with \( N \) in IEEE 802.11p. This is due to the the channel busy ratio \( \theta \) increasing with the number of vehicles as shown in Fig. 7. The channel busy ratio is used to capture the channel busyness of IEEE 802.11p. We consider that the channel is busy if a vehicle other than the target vehicle is transmitting. It can also be seen from Fig. 7 that the adaptive packet arrival rate leads to a lower channel busy ratio compared to a constant packet arrival rate, and hence, a lower average delay can be observed in Fig. 6 when the packet arrival rate is adaptive.

The results show that IEEE 802.11p has less average delay compared to C-V2X Mode 4. In C-V2X Mode 4, the lowest average delay is reached when the selection window size is equal to 20 ms, however, still, it is higher than the maximum delay of IEEE 802.11p. The reason for this is the maximum AIFS duration (AC_BK) of IEEE 802.11p being 149 \( \mu \)s. This is approximately equal to 12 aSlotTimes, and to transmit a 134 byte packet, it takes 14 aSlotTimes over the CCH. Thus even after adding the average backoff delay to the above calculated delay, it is unlikely that the total average delay is greater than few milliseconds. This is much smaller compared to the smallest selection window size of 20 ms in C-V2X Mode 4.

2) **Collision probability:** As shown in Fig. 8 it is not surprising to observe the collision probability increasing with \( N \) in both C-V2X Mode 4 and IEEE 802.11p. However, a vehicle that utilizes C-V2X Mode 4 has a lower collision probability compared to a vehicle that utilizes IEEE 802.11p. Thus, it seems that the SPS algorithm performs better in terms of collision resolution compared to the contention based method in IEEE 802.11p. We can observe the collision probability in C-V2X Mode 4 increasing with \( \Gamma \). Higher values of \( \Gamma \) leads to longer selection windows, which increases the chance of two or more selection windows overlapping, as explained with regards to Fig. 5. Thus, the collision probability increases with the value of \( \Gamma \). It can be observed that the the adaptive CAM rate alleviates the collision probability of IEEE 802.11p marginally, but the collision rate is at unacceptable levels for higher than \( N = 50 \) vehicles.

3) **Channel utilization:** As illustrated in Fig. 9 the channel utilization of C-V2X Mode 4 increases almost linearly with \( N \). The rate at which the channel utilization increases, decreases with the value of \( \Gamma \). The system also exhibits lower channel utilization for longer selection window sizes. In IEEE 802.11p, the channel utilization increases with \( N \) up to about 200, and then saturates since there are \( N^2 \) term and \( N - 1 \) and \( N \) power terms in the expression for \( CU_{ave}^{11p} \). The channel utilization
Figure 8. The behavior of the collision probability of C-V2X Mode 4 and IEEE 802.11p.

Figure 9. The behavior of the channel utilization of C-V2X Mode 4 and IEEE 802.11p.

can be improved with adaptive packet arrival. In general, the channel utilization of IEEE 802.11p is higher compared to C-V2X Mode 4.

C. Further Delay Analysis of C-V2X Mode 4

In this subsection, we further study the variation of the average delay of C-V2X Mode 4 with the inter-arrival time of CAM packets, $P_{rk}$ and different values of $\Gamma$.

1) The behavior of $d_{ave}^{V2X}$ with the inter-arrival time of CAM: The behavior of $d_{ave}^{V2X}$ with the inter-arrival time of CAMs is illustrated in Fig. 10 for different parameter combinations of the DENM model. The main observation is that the delay reduces with $t$ at the start. We can observe the highest average delay when $z = 100$ ms and the lowest when $z = 300$ ms, and the average delay decreasing when the repetition interval of DENM packets is increased. When $z = 100$ ms, we can observe the average delay increasing when $k$ increases from 1 to 9. On the other hand, when $z = 200$ ms and $z = 300$ ms, we can observe the average delay decreasing when $k$ increases from 1 to 9. This phenomenon can be justified as follows. When $z = 100$ ms, the service rate is nearly equal to the packet repetition frequency. This results in more CAM and DENM packets in the queue, leading to higher queuing delays. However, when $z = 200$ ms and $z = 300$ ms, the service rate is higher than the repetition interval of DENM packets. In such a scenario, increasing the average number of repetitions results in the system encountering the random waiting time, which has an average delay of 50 ms, more frequently compared to waiting through the whole resource reservation interval (RRI), which is of 100 ms. Thus, we can observe the average delay decreasing. We can also observe the average delay increasing when the DENM packet arrival rate is increased from 0.011 to 1 packets/s.

The average delays of a vehicle operating in C-V2X Mode 4 is critical in nature, and need to be minimized for efficient V2X communication. An interesting observation in the behavior of the average delay is the existence of a local optimal point. For an example, when $z = 100$ ms, $k = 9$ and $\lambda = 0.2$ packets/s, the lowest average delay can be observed at $t = 300$ ms implying the average delay can be reduced further by dynamically changing the CAM packet generation rate based on the packet arrival rate of DENM packets. The DENM packet arrival rate is based on the occurrence of an event, and the severity of the event. Based on $\lambda$, if a vehicle can change the CAM packet generation rate to reach the local optimal point of the delay curve shown in Fig. 10, then the vehicle can reduce the overall average delay further in C-V2X Mode 4 communication.

2) The behavior of $d_{ave}^{V2X}$ with $P_{rk}$: We can also observe the average delay increasing with $P_{rk}$ in Fig. 10. High values of $P_{rk}$ curtails the vehicle from choosing new radio resources for the transmission. When $P_{rk}$ is low, a vehicle receives more opportunities to encounter the waiting interval (average duration of 50 ms), compared to the longer RRI intervals (duration of 100 ms). Thus, high $P_{rk}$ values lead to higher average delays.

3) Effect of different selection window sizes on $d_{ave}^{V2X}$: The average delay variation with $t$ for different selection window sizes is illustrated in Fig. 11. It is not hard to see that the lower
selection window size values lead to lower average delay. However, there is a tradeoff of reducing $\Gamma$. Lower values of $\Gamma$ results in lower number of CSR values, and hence, the number of vehicles that can be supported simultaneously by C-V2X Mode 4 will reduce.

VI. CONCLUSIONS

This paper has presented multi-dimensional DTMC models to compare the MAC-layer performance of the ETSI ITS-G5 version of IEEE 802.11p and C-V2X Mode 4, considering CAM and DENM packets proposed for ITS. A DTMC based queue model that consists of traffic generators has been used to feed the packets to the aforementioned DTMCs for transmission. Closed-form solutions for the steady-state probabilities of the models have been obtained, and they have been then utilized to derive expressions for key MAC layer specific performance indicators; average delay, collision probability, and average channel utilization. An application for a highway scenario has been used for numerical results. The results have shown how the performance metrics of each communication technology vary for different parameter selections. When comparing the two technologies, the average delay of C-V2X Mode 4 is comparatively higher than IEEE 802.11p. On the other hand, the collision probability of a vehicle communicating using C-V2X Mode 4 has been shown to be lower than its counterpart. The results have also shown that the average delay of C-V2X has a locally optimal combination of CAM and DENM packet arrival rates, that can be utilized to further reduce delays in C-V2X. Moreover, the TRC technique of the DCC algorithm can be used to regulate the collision probability and the channel utilization of a vehicle communicating using IEEE 802.11p.

APPENDIX A

PROOF OF LEMMA 1

Let $RC_F \in [R_h, 1]$ be the first RC value of the sensing window, and $C_{X=i}$ denotes the total possible number of instances (count) of encountering $X = i$, for $i \in \{0, 1, 2\}$. The set of possible $RC_F$ values can be represented as $\{S_1, S_2, S_3\}$, using three subsets, where $S_1 = \{R_h, R_h - 1, ..., \xi + 1\}$, $S_2 = \{\xi, \xi - 1, ..., \xi - R_t + 1\}$, and $S_3 = \{\xi - R_t, \xi - R_t - 1, ..., 1\}$. When $RC_F \in S_1$, it is not hard to see that $X = 0$, and we have $C_X = 0 = R_h - \xi$. If $RC_F \in S_2$, we encounter $X = 1$, and we can show the count given $RC_F \in S_2$ be $C_X = 1 = (R_h - R_t + 1)\{R_h - 1\} + 1$. Finally, if $RC_F \in S_3$, $X$ can either be 1 or 2, and their counts can be shown to be $C_X = 2 = (1/2)(\xi + \xi - R_t) = R_t + 1)$. We have $C_X = 3 = C_X = 1 + C_X = 1, S_3$, and $P_{\hat{x}_i} = C_X = 1 + \sum_{j=0}^{N-1} C_X = j$ for $i \in \{0, 1, 2\}$.

Let $P_{sr} = P_{\hat{x}_0} + P_{sr}(1 - P_{\hat{x}_0})$, which gives us the probability of maintaining the same CSR throughout the sensing window. Then, the number of CSRs used by the vehicle of interest $v$ is given by $(P_{sr} + 2P_{\hat{x}_1} + 3P_{\hat{x}_2})$ and the number of CSRs used by any other neighboring vehicle is given by $P_{sr} + P_{\hat{x}_1} + P_{\hat{x}_2}$. Thus, $X = (N - 1)(P_{sr} + P_{\hat{x}_1} + P_{\hat{x}_2}) + (P_{sr} + 2P_{\hat{x}_1} + 3P_{\hat{x}_2})$, which can be further simplified using $\sum_{j=0}^{N-1} P_{\hat{x}_j} = 1$ to complete the proof.

APPENDIX B

COLLISION PROBABILITY DERIVATIONS

A. Proof of Lemma 2

The selection window will initiate at reaching state $(1, 0)$, and this is the scenario where a collision can occur. The cycle time of state $(1, 0)$ is $1/\pi_{1,0}$. Consider that $v$ initiated its selection window. The probability of a neighboring vehicle reaching state $(1, 0)$ during $v$’s selection window is given by $1 - \prod_{i=0}^{\Gamma-1} \left(1 - \frac{1}{\Gamma^i \pi_{1,0}}\right) = \bar{p}$. Similarly, the probability of a neighboring vehicle reaching state $(1, 0)$ during $v$’s selection window and selecting the same CSR as $v$ is given by $\bar{p}(1 - P_{sr})/(A - X)$. Thus, the probability of all $N - 1$ neighboring vehicles not selecting the same CSR as $v$ is given by $[1 - \bar{p}(1 - P_{sr})/(A - X)]^{N-1}$, and $1 - [1 - \bar{p}(1 - P_{sr})/(A - X)]^{N-1}$, gives us the collision probability.

B. Proof of Lemma 3

Let $P_{suc} = Pr\{\text{exactly one vehicle transmits } | \text{ at least one vehicle transmits}\}$, which can be simplified as $P_{suc} = Pr\{\text{exactly one vehicle transmits}\} / Pr\{\text{at least one vehicle transmits}\}$. Successful transmission of a packet by $v$ can be obtained from the steady-state probabilities of the state machine for IEEE 802.11p as $\left(1 - \theta\right)(\pi_{I,0} + \pi_{A_0}) + \sum_{i=1}^{\theta} \pi_{T,i}$. Similarly, the probability of the $N - 1$ neighbors not transmitting is given by $\left[1 - \left(\pi_{I,0} + \pi_{A_0} + \sum_{i=1}^{\theta} \pi_{T,i}\right)\right]^{(N-1)}$. Thus, the probability of exactly one vehicle transmitting is given by $N\left(\left(1 - \theta\right)(\pi_{I,0} + \pi_{A_0}) + \sum_{i=1}^{\theta} \pi_{T,i}\right) - \left[1 - \left(\pi_{I,0} + \pi_{A_0} + \sum_{i=1}^{\theta} \pi_{T,i}\right)\right]^{(N-1)}$. 

Figure 11. The behavior of the average delay with the inter-arrival time of CAM for different selection window sizes ($N = 50$).
The probability of at least one vehicle transmitting is given by

\[ 1 - \left( \frac{\sum_{i=1}^{\theta} \pi_{T,i}^{\theta}}{1 - P_{qe}} \right)^{N} \]

The ratio of these probabilities gives us \( P_{suc} \), and \( P_{col}^{\text{2V}} = 1 - P_{suc} \) completes the proof.

**APPENDIX C**

**Average Delay Derivations**

**A. Proof of Lemma 4**

From the steady-state probabilities of the queue model, \( 1/P_{x2o} \) is the duration in milliseconds (cycle time) to serve one packet. For the first packet, we may not spend the total cycle time to serve the packet, as it will depend on the state \( s \) in \( I \). Thus, we consider the service time to be \( \frac{1}{P_{x2o}} \) (half the cycle time) for the first packet. From the second packet onwards, we add \( \frac{1}{P_{x2o}} \) to the service time of the previous packet to obtain the delay. For the example, the service times of the second and the third packets are calculated as \( 2\frac{1}{P_{x2o}} \) and \( 3\frac{1}{P_{x2o}} \), respectively. We consider a queue of length \( m \), and the averaging is done by utilizing the steady-state probability of each state, conditioned on the fact that the queue is not empty. Thus, the average delay is given by

\[ d_{ave}^{2Vx} = \sum_{i=1}^{m} \frac{i-1}{P_{x2o}} = \frac{\sum_{i=1}^{m} 2i-1}{2P_{x2o}} \]

which completes the proof.

**B. Proof of Lemma 5**

Since unit time is considered to be aSlotTime, the delay associated with the transmit states is \( \theta \). The delay associated with states \( A_{i} \) where \( i \in \{1, \ldots, \Omega\} \) is \( 1 + \sum_{j=1}^{\Omega} (1 - \theta)^{j} \). The delay associated with the remaining states, i.e., state \( i \in S_{11p} \) can be calculated by utilizing the product of the corresponding delay of each state \( (D_{i}) \), with the steady-state probability of each state conditioned on the fact that \( i \in S_{11p} \) and \( 1 \leq i \leq \Omega \). Sum of the three delay values completes the proof.

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