Joint Optimization of Emergency and Periodic Message Transmissions in Vehicular Networks

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***Abstract*—There are two broad safety related message categories in vehicular networks: emergency and periodic messages that should share the scarce wireless resource simultaneously. Emergency messages deliver time-critical information with guaranteed reliability, e.g., road-safety information, whereas periodic ones convey normal status update information, e.g., vehicular positions, that is less time- and loss-critical. Recent studies on efficient Medium Access Controls (MACs) under these requirements propose to use the IEEE 802.11e Enhanced Distributed Channel Access (EDCA) protocol with a *strict* priority. In this paper, we first model this protocol by a *coupled* embedded markov chain, and consider an optimization problem that requires to *jointly* characterize delivery probability and delay of those two types of messages. Our characterization of delivery probability and delay using the modeled embedded Markov chain enables one to easily find the right protocol parameters that satisfy given requirements of emergent and periodic messages, providing a useful engineering value in running the MAC protocol over vehicular networks. We conduct extensive simulations to validate our analytical findings, which we believe is of broad interest to an environment consisting of emergent and periodic message transmissions such as tactical networks with drones.**

I. Introduction

Vehicular Ad-hoc Networks (VANETs) are experiencing a rapid development in recent years due to an increasing demand for the road safety and entertainment service in personal/public vehicles. In the Intelligent Transport System (ITS), a Dedicated Short-Range Communication (DSRC) is a set of protocols and standards on one-way or two-way short to medium range wireless communications specifically designed for automotive use [1], designed to support both public safety and infotainment (information and entertainment) applications. A large proportion of the messages used in such applications are delivered through broadcasting. For example, routine messages[1] need to be broadcast to its neighbors periodically for announcing the state (*e.g.,* location, speed, direction and acceleration) of a vehicle and emergency messages need to broadcasted once a vehicle has an emergency (*e.g.,* accident or hard brake) or making change in moving (*e.g.,* lane changing and overtaking).

IEEE Standard 802.11p [2] has been ratified as a standard to provide Wireless Access in Vehicular Environment (WAVE), recently. It is based on the prioritized Enhanced Distributed Channel Access (EDCA) protocols and the multi-channel architecture specified in IEEE 1609.4 [3], which uses one common Control CHannel (CCH) for signaling and safety-crucial data exchange and up to six Service CHannels (SCHs) for non-safety (e.g., comfort and infotainment) data exchanges. Periodical and synchronous switching between CCH and SCH is mandatory for a single-radio device. In WAVE, there are two types of WAVE device, On-Board Unit (OBU) and RoadSide Unit (RSU). The OBU is a communication equipment that is mounted on a mobile vehicle. The RSUs are connected to a wired infrastructure network and are located at fixed places on a road. The IEEE 802.11p and IEEE 1609.4 standards describe the Medium Access Control (MAC) and physical layer (PHY) protocols for the Vehicle-to-Vehicle (V2V) communication among OBUs and the Vehicle-to-Infrastructure (V2I) communication between an OBU and an RSU [4].

Safety-related messages are classified into periodic and emergency ones. In general, periodic messages are generated every 300 msec to broadcast a vehicular status. Emergency messages, that are generated asynchronously, have to be broadcast within 100 msec with more than 99% of its reliability. The current draft of IEEE 802.11p [2] and most of other MAC protocols cannot meet the strict requirement of reliability latency for safety-related communication applications due to the lack of strict guarantees for the safety related message transmissions using the conventional EDCA MAC protocols. Despite recent researches which use the EDCA to consider the priorities among messages in VANETs [4]–[10], to the best of our knowledge, there does not exist a rigorous, analytical study which jointly considers emergency and periodic message transmissions at CCH in one framework under the alternating channel switching. The main contributions of our work are summarized as follows:

- (i) First, to guarantee the strict reliability and latency requirements, we adopt the modified EDCA MAC protocols, *e.g.,* one in [10] to give the strict higher priority for emergency messages than others. Based on this MAC, we consider a method based on D/M/1 queueing model for the periodic broadcast and construct a *coupled* Markov chain for these two message transmissions because they are correlated by sharing a common channel in VANETs.
- (ii) Second, we formulate an optimization problem that requires to *jointly* characterize successful delivery probability and average delay of those two types of messages. Our characterization of these measures using the modeled embedded Markov chain enables one to easily find the right protocol parameters that satisfy given requirements of emergency and periodic messages, providing a useful engineering value in running the MAC protocol over vehicular networks.

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[1]In this paper, we use "periodic message" and "routine message" interchangeably.

(iii) Third, the performance of our MAC protocol is verified through numerical studies and simulations. These results show that our MAC outperforms compared to conventional EDCA MAC in VANETs for the emergency message. For guaranteeing the maximum successful transmission probability for the periodic message, we obtain optimal parameters on the formulated optimization problem by numerically. We believe that this will be a guideline how to choose the parameters in practice.

Related Works. There have been extensive researches on the analysis of broadcast services in DSRC. In [6], the authors suggested a performance analysis of broadcast messages in VANET safety applications. They also considered emergency and routine message transmissions but they assumed that these two messages are independent so they modeled this by two independent M/G/1-like processes, which does not clearly hold in practice, because if the channel is occupied with routine messages, the emergency messages can not be transmitted immediately. The authors in [5] proposed a model only for periodic messages, by using a D/M/1 queueing system, where they obtained a collision probability of periodic messages, a buffer empty probability and a sojourn time of periodic message, respectively. In [8], the authors proposed a design of a robust broadcast scheme for VANET safety-related services with its analysis. In particular, they proposed and justified an effective solution to the design of the control channel in DSRC with three levels of safety-related broadcast services that are critical to most possible safety applications. Furthermore, they constructed an analytic model to evaluate the reliability and the performance of one-hop and multi-hop IEEE 802.11-based broadcast for the safety-related services under harsh wireless communication environments. In that model, they used the distance-based scheme and the random accessing delay (RAD) scheme to give a high priority and to avoid collision. However, those three levels of safety-related messages are also modeled independently which is not practical. The authors in [4] considered a multi-radio setup so as to remove the need of alternatively multi-accessing the channel due to the dedicated radio for safety messages to guarantee the high success probability. However, there still remains a cost issue for equipping all vehicles with multiple radios.

II. Model and Goal

A. Network, Channel and Traffic

We consider a one-dimensional VANETs model, where consists of a collection of statistically identical vehicles randomly located on a line. This is popularly adopted for mathematical tractability, being a good approximation of VANET on highway when the distances between lanes on highways are negligible, compared with the length of those [8]. We assume that there are N vehicles each being equipped with a single radio and they interfere with each other. Note that an RSU can receive any broadcast message from vehicles since all vehicles are located within the coverage of RSUs. Hence, to improve the reliability of the broadcasted messages, we assume that only an RSU is allowed to sends an Acknowledgement (ACK) for the emergency message when they are transmitted successfully as in [4]. The single-radio environment requires that each vehicle has to alternatively access the channel between CCHI and SCHI as depicted in Fig. 1. We denote T_{cch} and T_{sch} by the lengths of CCHI and SCHI, respectively and denote $T_{si} = T_{cch} + T_{sch}$ by the length of Synchronization Interval (SI). Each vehicle generates emergency and periodic messages, where we assume that emergency messages are generated by a Poisson process with rate λ_e, and periodic messages are generated by a deterministically periodic process with rate $\lambda_p = 1/T_p$ where T_p is the period of the message. We denote a transmission time of each message $x \in \{e, p\}$ (e:emergency, p:period) by T_s^x for a successful transmission and T_c^x for a collision which are given by

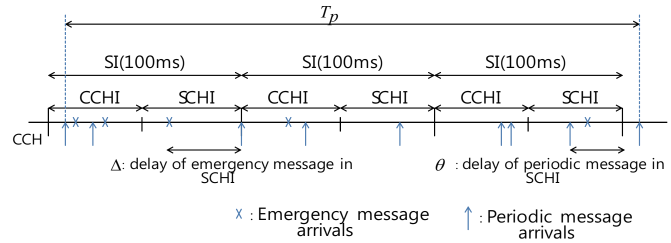


Fig. 1: Safety-related events occur on the alternating channel. (SI: Synchronization Interval, CCHI: Control Channel Interval, SCHI: Service Channel Interval.)

$$\begin{cases} T_s^x = (L_H + L_x)/R_{cch} + SIFS + ACK + DIFS + \delta, \\ T_c^x = (L_H + L_x)/R_{cch} + EIFS + \delta, \end{cases}$$

where R_{cch} is the data rate of control channel, L_H, L_p and L_e are lengths of packet header, lengths of periodic message and of emergency message, respectively. The term ACK is a transmission time of an ACK message and SIFS, DIFS are the Short and Distributed Coordination Function (DCF) Interframe Space durations, EIFS is the Extended Interframe Space time for the collision of packets, which includes the transmission time of ACK frame, SIFS and DIFS, respectively and δ is the propagation delay.

To see the impact of MAC layer issues, we assume that there are no channel shadowing/ fading and the capture effect of transmissions. In addition, for guaranteing the transmission of the safety related messages, we assume that the reservation for the infortainment message in SCHI start after finishing of broadcast of safety related messages with the ACK from the RSU for a successful reservation. Finally, we assume that if there is no ACK for the reservations of SCH, the safety-related message can be sent even in the SCHI.

B. Medium Access Control: EDCA-based

1) Conventional EDCA: As a MAC protocol, we consider a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) that is, if the channel is idle, a node that has message attempts to transmit this, immediately. If the channel is busy due to transmission of other message, a node that has a message waits until the end of broadcasting and begins its backoff procedure to broadcast its message. To guarantee the high reliability transmission with fast delivery, it is required to set a higher priority for the emergency message than that of the periodic one. In a conventional EDCA MAC protocol, there are four different Access Categories (ACs) at the MAC layer [7] where each AC[i] uses a value of Arbitration Inter-Frame Space (AIFS) to access the channel for its message as

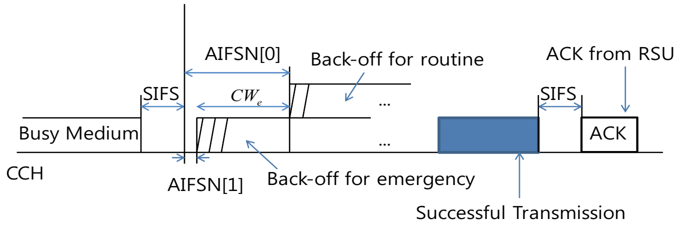


Fig. 2: Strict priority in IEEE 802.11e EDCA [10].

$AIFS[i] = SIFS + AIFSN[i] \times \sigma, \quad i = 0, 1, 2, 3$, where σ is a slot time of idle channel. The high value of i is assigned to the message with high priority.

2) Modified EDCA (S-EDCA): To guarantee a strict priority for the emergency message transmission in VANETs, we adopt a modified version of EDCA which is called by S-EDCA (Strict EDCA). This is a kind of EDCA such that before it sends a packet, it first senses the CCH continuously for DIFS period. If the CCH is idle for this duration, then it transmit the message, otherwise, the it immediately perform the backoff procedure after the CCH is detected as busy, by randomly selecting a backoff counter from the range $[0, CW-1]$ where CW is a contention window (CW) size for the message. The AC_i decrements the backoff counter whenever it senses that the CCH is idle and when it senses that the CCH is busy, it freezes the backoff counter. Lastly, the AC_i transmit the message if its backoff counter reaches zero. In the S-EDCA, we consider two kinds of ACs with strict priority as follows.

Emergency messages. For the emergency message, we set $AIFSN[1] = \sigma$ and from the assumption that the RSU sends a ACK, if it detect the collision of the message, it doubles its CW size up to a maximum value $CW_{max,e}$ with a backoff stage m as follows:

$$CW_{max,e} = 2^m CW_{min,e}, \tag{1}$$

where $CW_{min,e}$ is the minimum CW for the emergency message. We consider that the emergency message is not dropped even if there is a collision when it reaches the maximum backoff stage because it should be transmitted to neighbors. Hence, at the maximum backoff stage, it chooses the CW in $[0, CW_{max,e} - 1]$ uniformly random without doubling. We assume that a busy tone signal is transmitted with the emergency message to suspend the backoff procedure of the period message.

Periodic messages. For the periodic message, we set $AIFSN[0] = AIFSN[1] + CW_{min,e}$ to give a strict priority for the emergency message as in Fig.2. We assume that the RSU does not send an ACK for the successful broadcast for the periodic message due to the overhead. Hence, there is no doubling of contention window which is denoted by CW_p.

C. Goal: An Optimization Problem

From the S-EDCA MAC for the emergency message transmission, there can be large performance degradation of the periodic message transmission if we do not consider how to choose the control parameters such as m, $CW_{min,e}$ and CW_p. To handle this, we formulate an optimization problem which maximizes the successful delivery of the periodic message under strict constraints for the emergency message transmission. We denote P_{se}, P_{sp} as the successful delivery probabilities for the emergency message, periodic message, respectively and denote D_e as the delivery delay for the emergency message. Then, our optimization problem is formulated as follows:

$$\textbf{OPT:} \quad \max_{m, CW_{min,e}, CW_p} P_{sp}, \qquad s.t. \quad P_{se} \geq \vartheta,\ E[D_e] \leq \varepsilon. \tag{2}$$

where ϑ and ε are the thresholds for the successful delivery probability, average delivery delay $E[D_e]$ of the emergency message, respectively.

To solve this **OPT**, we first need to characterize P_{se}, P_{sp} and $E[D_e]$, respectively. However, it is not easy because these are correlated each other and there are many parameters such as message collision probabilities, channel busy probabilities, and message generation probability, etc for both message transmissions. To handle these issues, we first construct a coupled Markov chain and obtain stationary probabilities where are used to characterize the **OPT**. Using this, we finally find parameters m, $CW_{min,e}$ and CW_p that solves this **OPT**.

III. Characterization of **OPT**

A. Modeling S-EDCA by a Coupled Markov Chain

In this section, we model a coupled Markov chain for the two different message transmissions.

Markov chain for the emergency message. Consider that there are n nodes that have an emergency message to transmit when the emergency events occur. Let $s(t)$ be the stochastic process representing the backoff stage for the tagged vehicle with state space $\{0, 1, \ldots, m\}$ at time t and let $b(t)$ be the stochastic process representing the backoff counter with state space $\{0,1,...,CW_{max,e} - 1\}$ at time t. Then $\{(s(t), b(t)) | \, t = 0, 1, 2, ..\}$ be the two dimensional embedded Markov chain with the state space is Idle $\cup \, \{(i, j) : 0 \leq i \leq m$ and $0 \leq j \leq CW_{i,e} - 1\}$ where the 'Idle' denotes the idle state in which the node does not have any packet to transmit and $CW_{i,e}$ is the CW size at backoff stage i. Hence, we have $CW_{min,e} = CW_{0,e}$ and $CW_{max,e} = CW_{m,e}$, respectively.

(1) *Transition probabilities*: The one-step transition probabilities of the Markov chain is as follows. (See [11] for the detailed diagram.) First, at the backoff stage is zero, we have

$$\begin{cases} P(0, k \mid \text{Idle}) = q/CW_{0,e}, & 0 \leq k \leq CW_{0,e} - 1, \\ P(\text{Idle} \mid \text{Idle}) = 1 - q, & \\ P(0, k \mid 0, k+1) = 1 - p_b, & 0 \leq k \leq CW_{0,e} - 2, \\ P(1, k \mid 0, k) = p_b, & 0 \leq k \leq CW_{1,e} - 1, \\ P(\text{Idle} \mid 0, 0) = (1 - p_c)(1 - q), & \\ P(0, k \mid 0, 0) = q(1 - p_c)/CW_{0,e}, & 0 \leq k \leq CW_{0,e} - 1, \\ P(1, k \mid 0, 0) = p_c/CW_{1,e}, & 0 \leq k \leq CW_{1,e} - 1, \end{cases}$$

Second, at the backoff stage $0 < i < m - 1$,

$$\begin{cases} P(i, k \mid i, k+1) = 1 - p_b^{'}, & 0 \leq k \leq CW_{i,e} - 2, \\ P(i, k \mid i, k) = p_b^{'}, & 0 \leq k \leq CW_{i,e} - 1, \\ P(i+1, k \mid i, 0) = p_c^{'}/CW_{i+1,e}, & 0 \leq k \leq CW_{i+1,e} - 1, \\ P(\text{Idle} \mid i, 0) = (1 - p_c^{'})(1 - q), & \\ P(1, k \mid i, 0) = q(1 - p_c^{'})/CW_{1,e}, & 0 \leq k \leq CW_{1,e} - 1. \end{cases}$$

$$E[D_e^1] = (1-p_b)[\gamma + (1-p_c)T_s^e + p_c E[S]] + p_b[(T^e + \gamma + (1-p_c^{'}) \cdot T_s^e + p_c^{'} \cdot E[S])], \quad (3)$$
$$E[D_e^2] = T_{sch}/2 + AIFS[1] + (CW_{min,e}-1)/2 + (1-p_c^{'}) \cdot T_s^e + p_c^{'} \cdot E[S]. \quad (4)$$

$$1/\mu = p_{sch}T_{sch}/2 + (1-\widetilde{p}_b)\eta + \widetilde{p}_b(E[\omega]+\eta). \quad (5)$$

Finally, at the backoff stage is m, the probability $P(m,k \mid m,0) = p_c^{'}/CW_{m,e}$ is only changed for the case $0 < i < m-1$.

(2) *Collision and message generation probabilities*: Next, we will explain and derive all the parameters in above transition probabilities. First, the parameter p_c is the collision probability of the tagged node that broadcasts an emergency message at backoff stage zaro. Since we assume that there are n nodes have the emergency messages and $N-n$ periodic messages, the collision probability of an emergency message at backoff stage zero is given by

$$p_c = 1 - (1-\tau_e)^{n-1}(1-\tau_p)^{N-n}, \quad (6)$$

where τ_e is the transition probability of emergency message and τ_p is the transmission probability of a periodic message. The term $p_c^{'}$ the collision probability when the backoff stage is larger than zero and is given by $p_c^{'} = 1-(1-\tau_e)^{n-1}$ due to S-EDCA. The probability p_b is channel sensed busy at backoff stage zero, $p_b^{'}$ is the channel busy probability when the backoff stage is larger than zero due to transmissions of emergency messages under the S-EDCA MAC and the parameter q is the emergency message generation probability, respectively. Due to the page limit, please see our technical report [11] for the detail derivations.

(3) *Stationary distribution*: Consider a stationary distribution of the Markov chain which is denoted by $b_{i,k} = \lim_{t\to\infty} P[s(t)=i, b(t)=k]$ for each states $(s(t), b(t))$. Then it exists from the ergodicity of the model. Based on the normalization of probability, we have $\left(\sum_{i=0}^{m}\sum_{k=0}^{CW_{i,e}-1} b_{0,k}\right) + b_{Idle} = 1$.

Markov chain for the periodic message. For the periodic message case, we model a similar Markov chain in [5] but different parameters by jointly consideration with the emergency message transmissions. Please refer [11] for the details of the Markov chain. Since we assume that there are $N-n$ nodes have periodic message to transmit, the channel is busy for the tagged node when the emergency messages are transmitting or other periodic messages are transmitting in the system. Hence, the channel busy probability $\widetilde{p}_b$ is given by

$$\widetilde{p}_b = 1 - (1-\tau_e)^n(1-\tau_p)^{N-n-1}, \quad (7)$$

which coincides the collision probability for the periodic message $\tilde{p_c}$ of the tagged node. Let $b_k = \lim_{t\to\infty} Pr[b_p(t) = k]$, $(0 \le k \le CW_p - 1)$ be the stationary distribution of the Markov chain then from the normalization of probability and basic calculations, we obtain all b_k.

Coupled transmission probabilities. Since a transmission is occurred at the backoff counter is zero, the transmission probability of emergency message τ_e is given by

$$\tau_e = \sum_{i=0}^{m} b_{i,0}, \quad (8)$$

and the transmission probability of periodic message is given by

$$\tau_p = b_o = \frac{2(1-\widetilde{p}_b)(1-p_e)}{(CW_p+1)(1-p_e) + 2p_e(1-\widetilde{p}_b)}, \quad (9)$$

where p_e is the probability that buffer is empty. Given a set of system parameters, the right term of (8) and (9) are a function of two unknowns τ_e and τ_p. As an example, the parameters p_c and $\widetilde{p}_b$ in transition probabilities of each Markov chain involve the unknown τ_e and τ_p as in (6) and (7). Hence, we solve these nonlinear equations jointly and then finally we obtain these probabilities, respectively.

B. Delivery Probability and Delay

From the definition of D_e, we have the successful delivery probability by $P_{se} = P[D_e < \epsilon]$ for a target allowed latency $\epsilon > 0$. From the Poisson arrival process of the message, the probability that an emergency message is generated during CCHI is $p_{cch} = T_{cch}/T_{si}$ and SCHI is $p_{sch} = T_{sch}/T_{si}$, respectively. Based on this, we obtain the following result.

Theorem 1 (Emergency message): For any $\epsilon > 0$,

$$P_{se} = P[D_e < \epsilon] \ge 1 - e^{-\frac{\epsilon^2}{3ME[D_e]}},$$

where $M = CW_{max,e} = 2^m CW_{min,e}$. The average delay $E[D_e]$ is given by

$$E[D_e] = p_{cch}E[D_e^1] + p_{sch}E[D_e^2], \quad (10)$$

where $E[D_e^1]$ and $E[D_e^2]$ are average delays when the emergency message is generated during CCHI and SCHI which are given in (3) and (4), respectively. The term $E[S] = \frac{1}{1-p_c^{'}}\left(E[T_g^e](\sum_{i=0}^{m} CW_{i,e})/m + T_c^e\right)$ is an average delay after a collision of the emergency message at backoff stage zero and $\gamma = AIFS[1] + ((CW_{min,e}-1)/2)E[T_g^e]$. [2]

This result indicates that first, if ϵ is large value then the successful delivery probability increases as we expected. Second, if the backoff stage m or $CW_{min,e}$ increases, the probability of collision for this message decreases but, the average of delays for both messages increase and vise versa. Hence, we see a tradeoff issue for choosing them.

Next, we will obtain a result for periodic message transmissions. We denote T be the delivery delay for this message then, we have the following result.

Theorem 2 (Periodic message): The successful delivery probability and average delay for the periodic message are given by

$$P_{sp} = (1-\widetilde{p}_c)p_e, \quad E[T] = 1/\mu(1-z),$$

where $\widetilde{p}_c$ is a collision probability of periodic message which is given in (7) and $p_e = 1 - z$ is the probability that the

[2]The term $E[T_g^e]$ is a generic slot time of the Markov chain for the emergency message. See [11] for details.

message is transmitted within its period, respectively. Further, z is the solution of $z = e^{-\mu(1-z)/\lambda_p}$ where μ is given in (5).

In (5), $\eta = (AIFS[0] + ((CW_p - 1)/2)E[T_g^p] + T_s^p)$ is the time until transmission of the periodic message where $E[T_g^p]$ is the generic time for this message and $E[\omega]$ is the average suspending duration due to the emergency message broadcasting before the transmission of periodic one which are given in [11]. This indicates that the service rate of periodic message can be reduced due to the emergency message transmission with strict priority in S-EDCA MAC. Due to the implicit form of the objective function in the **OPT**, we solve the problem by numerically in Section V.

IV. Proof Sketch of Theorems

A. Proof of Theorem 1

From the constructed Markov chain of the emergency message, we consider two cases for obtaining the delay D_e as follows. First one is a delay during the backoff counter reduction and the second one is a delay for increasing the backoff stage. To analyze these, we set X_i be the random variable which takes one if the message does not transmitted at backoff stage i successfully, otherwise zero. Next, we set Y_k^i be the random variable which takes one if the sensed channel is busy at state $(s(t) = i, b(t) = k)$, otherwise zero. Then, we see that all X_i and Y_k^i are independent and the delay is upper bounded by $X + Y$ where $X = T^e \sum_{i=0}^{S} X_i$ and $Y = T^e \left(\sum_{i=0}^{S} \sum_{k=1}^{CW_{max,e}} Y_k^i \right)$ where T^e is the transmission time of the message and S is a stopping time of the backoff stage. Hence, by using the Chernoff bound, we have

$$\begin{aligned} P[D_e < \epsilon] &= P\left[X + Y < (1+\delta)E[D_e]\right] \\ &= 1 - P\left[X + Y \geq (1+\delta)E[D_e]\right] \\ &\geq 1 - e^{-\frac{\delta^2 E[D_e]}{3MT^e}} \geq 1 - e^{-\frac{\epsilon^2}{3ME[D_e]}}, \end{aligned} \quad (11)$$

where $E[D_e]$ is the average delivery delay, $\delta = \epsilon/E[D_e] - 1$ and $M = CW_{max,e} = 2^m CW_{min,e}$, respectively. The last inequality can be obtained by simple algebra. Then, it remains to obtain $E[D_e]$ for finishing the proof. To do this, consider that the total transmission latency D_e consists of the head-of-line delay[3] and transmission time. From the alternating channel model, we need to consider following two cases. First, the emergency event is occurred in the CCHI and second, it is occurred in the SCHI when it is occupied by transmissions of infortainment service messages. For the first case, it starts the backoff procedure immediately to broadcast. However, in the second case, the node have to wait up to the end of the SCHI (See Fig.1) and starts the contention in the beginning of the CCHI. By considering these facts, we first obtain the average transmission time for the first case $E[D_e^1]$ that consists of head-of-line delay and transmission time which is given by (3). The term $\gamma = AIFS[1] + ((CW_{min,e} - 1)/2)E[T_g^e]$ is the time to transmission of the message when it is successfully broadcast where $E[T_g^e]$ is a generic time slot at backoff stage one of the emergency message, T_s^e is the successful transmission time and $E[T^{p,e}]$ is the average transmission time of two types of messages that are given in [11]. The term $E[S]$ is an average

[3]We assume the queueing delay is zero due to the highest priority.

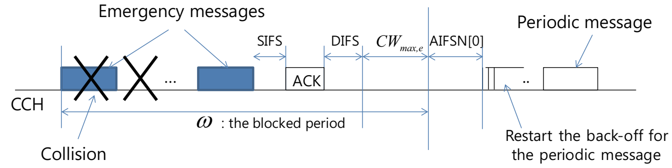


Fig. 3: The waiting time of periodic broadcast.

delay until the successful transmission when there is a collision of emergency message of tagged node at backoff stage zero which is given by

$$\begin{aligned} E[S] &= \sum_{k=0}^{\infty} (p_c^{'})^k \left(E[T_g^e] \frac{CW_k - 1}{2} + T_c^e \right) \\ &= \frac{1}{1 - p_c^{'}} \left(E[T_g^e] E[CW_e] + T_c^e \right), \end{aligned}$$

where $E[CW_e] = (\sum_{i=0}^{m} CW_{i,e})/m$. Next, we obtain the average delay for the second case $E[D_e^2]$ that the message is occurred in SCHI given in (4) where $E[\triangle] = T_{sch}/2$ is the average delay in SCH interval (See Fig. 1) with the length of SCH interval T_{sch}. Finally, we obtain the average transmission latency for the emergency message by (10) and this completes the proof of Theorem 1.

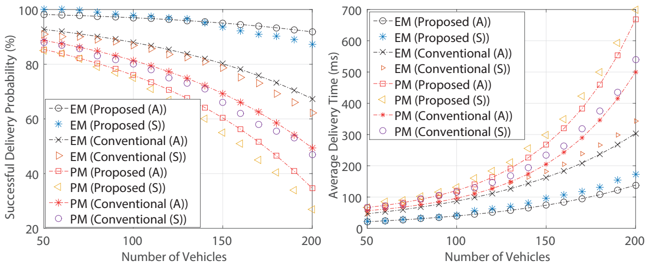
B. Proof of Theorem 2

The successful delivery is occurred when there is no collision with other transmission with the message is broadcasted within T_p. The probability $\widetilde{p}_c$ can be obtained from (7) hence it remains to obtain the probability p_e. To obtain this, let T_w and T_s be the waiting time of a periodic message in the queue and the service time for this message, respectively and we assume that the service time T_s has an exponential distribution with the probability density function $f_s(t) = \mu e^{-\mu t}$, where μ is the average service rate. Since the emergency message has higher priority than the periodic message, we need to consider the waiting time for the periodic message transmission due to the emergency messages transmissions due to the strict priority and it is denoted by ω (we call ω by *blocked period* as in Fig.3). If there are no emergency message transmissions during an interval $CW_{max,e}$, the vehicles that have a periodic message resume the backoff procedure after $AIFS[0]$. Using these facts, we obtain the average service rate of periodic message as (5) where θ is the delay due to SCHI with the expectation $E[\theta] = T_{sch}/2$, the time until transmission of the periodic message $\eta = (AIFS[0] + ((CW_p - 1)/2)E[T_g^p] + E[T_s^p])$ where $E[T_g^p]$ is the generic time for this message and $E[\omega]$ is the average suspending duration for the periodic broadcasting due to the emergency message broadcasting which are given in [11]. From the D/M/1 queueing system [12], the probability density function of waiting time in the queue is

$$f_w(t) = (1-z)\delta(t) + \mu z(1-z)e^{-\mu(1-z)t}, \quad (12)$$

and z is determined by the following relation $z = A^*[\mu(1-z)] = e^{-(\mu-\mu z)/\lambda_p} = e^{-(1-z)/\rho}$, where $\rho = \lambda_p/\mu$ and note that z has the only solution in (0,1) when $\rho < 1$. From similar approach in [5], we obtain the probability that the buffer is empty by

$$p_e = Pr[T < T_p] = \int_0^{T_p} \mu(1-z)e^{-\mu(1-z)t} dt = 1 - z,$$



(a) Successful delivery probabilities. (b) Average delivery delays.

Fig. 4: Simulation results for two performance metrics. (EM: Emergency Message, PM: Periodic Message, A: Analysis, S: Simulation.)

where $T = T_w + T_s$ is the total transmission delay of the periodic message. Using this and (7), we finally obtain the successful delivery probability P_{sp} in the theorem. The derivation for the $E[T]$ will be given in [11] due to the space limit and this completes the proof of Theorem 2.

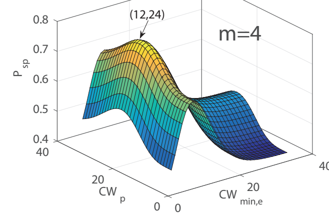
V. Numerical and Simulation Results

We use MATLAB to obtain the numerical and simulation results. In order to investigate the impact of node density, we vary the number of vehicles from 50 to 200. We assume that wireless channel is ideal without fading and shadowing. Hence, a packet will be lost due to only MAC layer issues. We ran 300 simulations with different random seeds for each case, and averaged the results. For our study, we compare S-EDCA to the conventional EDCA MAC that are defined in the IEEE 802.11p [7] with two highest access categories for emergency message and the periodic message, respectively.

Set-up. We set $T_p = 300ms$, $\lambda_e = 5$ (message/sec) and $R_{cch} = 6$ Mbps for our numerical study. Note that if the number of vehicles is 200 then we set $N = 200$ and the number of emergency message is given by $\lambda_e N$, respectively. Other parameters are given in [11].

Successful delivery probabilities and average delays. First, to obtain the performance measures for each message transmission, we set $CW_{min,e} = 8$, $m = 5$ and $CW_p = 24$, respectively. In Fig. 4(a), we see that the successful delivery probability for the emergency message of S-EDCA is higher than that of conventional EDCA MAC. Furthermore, even thought the probability decrease when the number of vehicles increase up to 200 vehicles, our S-EDCA guarantees more than 90 % of successful transmission for the emergency message whereas the conventional one has the fragile for the large number of nodes due to many contentions. As shown in Fig. 4(b), we see that the average delay for the emergency message of S-EDCA is less than that of conventional EDCA MAC because the S-EDCA suspend other transmissions when there is an emergency event and only they perform the competition whereas conventional one does not.

Optimal parameters. Due to the performance degradation of periodic message to guarantee the emergency message transmission, we obtain optimal parameters m, $CW_{min,e}$ and CW_p that maximize the successful delivery probability of periodic message with the constraints for the emergency message transmission ($\vartheta = 0.99$ and $\varepsilon = 100ms$.) in Fig 5. We see that the probability P_{sp} is unimodular with respect to $CW_{min,e}$ and CWp for a given m by numerically in



(a) P_{sp} vs. $(CW_{min,e}, CW_p)$.

P_{sp}	m	$CW_{0,e}$	CW_p
0.71	1	24	16
0.76	2	16	12
0.72	3	16	16
0.73	4	12	24
0.84	**5**	**8**	**24**
0.72	6	4	20
0.65	7	4	16
0.62	8	4	20

(b) Optimal parameters.

Fig. 5: Optimal parameters in **OPT** with $\vartheta = 0.99$ and $\varepsilon = 100ms$ under $N = 100$, respectively.

Fig 5(a). Further, we obtain the combinations which achieve the maximum P_{sp} for each $1 \leq m \leq 8$ in Fig 5(b). These results give a guideline how to choose the parameters properly when these two kinds of messages are correlated each other. For example, in our basic numerical setting, the tuple of parameters $(m, CW_{0,e}, CW_p) = (5, 8, 24)$ is optimal to maximize P_{sp}.

VI. Conclusion

In this paper, we consider a performance analysis and an optimization problem of safety related message transmissions in VANETs. Due to the strict requirements of emergency message for the reliable transmission with lower delay, we use a strict EDCA MAC protocol and analyze it by using a coupled Markov chain. We obtain successful delivery probabilities and average delays for the two kinds of message transmissions and validate this by simulations. Further, due to the degradation of performance of period message transmission in our MAC, we formulate an optimization problem for choosing proper parameters.

References

[1] "IEEE Standard for Wireless Access in Vehicular Environments (WAVE)-Networking Serviced," *IEEE Std 1609.4-2006*, pp. 1–74, 2006.

[2] "IEEE Standard for Information technology-Telecommunications and exchange between systems-Local and metropolitan area networks-Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments," *IEEE Std 802.11p 2010*, pp. 1–55, 2010.

[3] "IEEE Standard for wireless Access im Vehicular Environments (WAVE)-Multi-Channel Operation," *IEEE Std 1609.4-2010 (Revision of IEEE Std 1609.4-2006)*, pp. 1–89, 2011.

[4] Y. Kim, Y. Bae, D. Eom, and B. Choi, "Performance Analysis of a MAC Protocol Consisting of EDCA on the CCH and a Reservation on the SCHs for the IEEE 802.11p/1609.4 WAVE," *IEEE Transactions on Vehicular Technology, to appear*.

[5] Q. Yang, J. Zheng, and L. Shen, "Modeling and Performance Analysis of Perodic Broadcast in Vehicular Ad Hoc Network," in *Proc. IEEE Globecom*, 2011.

[6] K. Hafeez, L. Zhao, B. Ma, and H. Mark, "Performance analysis and enhancement of the DSRC for VANET's safety applications," *IEEE Transactions on Vehicular Technology*, vol. 62, no. 7, pp. 3069–3083, 2013.

[7] J. Zheng and Q. Wu, "Performance Modeling and Analysis of the IEEE 802.11p EDCA Mechanism for VANETs," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 4, pp. 2673–2687, 2016.

[8] X. Ma, J. Zhang, and T.Wu, "Reliability Anaysis of One-Hop Safety-Critical Broadcast Services in VANETs," *IEEE Transactions on Vehicular Technoligy*, vol. 60, no. 8, October 2011.

[9] X. Ma, J. Zhang, X. Yin, and K. S, "Design and Analysis of a Robust Broadcast Scheme for VANET Safety-Related Services," *IEEE Transactions on Vehicular Technoligy*, vol. 61, no. 1, January 2012.

[10] M. Barradi, A. Hafid, and J. gallardo, "Estabishing strict priorities in IEEE 802.11p WAVE Vehicular Networks," in *Proc. IEEE Globecom*, 2010.

[11] [Technical Report] J. Choi and Y. Yi "Joint Optimization of Emergency and Periodic Message Transmissions in Vehicular Networks" http://lanada.kaist.ac.kr/Publication/Techreport/VANETs.pdf.

[12] R. Cooper, *Introduction to Queueing Theory*. North Holland, 1981.