

A comparison of interval division methods in adaptive IEEE 802.11p-based multi-channel medium access control protocols for vehicular ad hoc networks

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Abstract

Recently, vehicular ad hoc networks, which organize communications between vehicles and between vehicles and infrastructures, have played an important role in providing safe transportation and infotainment applications. To satisfy the various requirements of applications such as delay-bounded transmission of safety packets, a broad bandwidth of non-safety packets, known as medium access control has been developed. In addition, to cope with the frequent topology changes of vehicular ad hoc networks, adaptive IEEE 802.11p-based multi-channel medium access control protocols have been proposed, which can adapt to different traffic conditions. In this article, we focus on such protocols and classify them according to interval division methods. Here, we perform comparisons between these protocols following three main categories: the fixed safety transmission interval, safety and Wireless Access in Vehicular Environment Service Advertisement/Acknowledgment transmission interval, and safety and Wireless Access in Vehicular Environment Service Advertisement transmission interval. We performed simulations in NS-3 under the assumption of saturated throughput for Wireless Access in Vehicular Environment Service Advertisement packets and a Poisson arrival process for the safety packets. From the simulation results, it is evident that the design of a new multi-channel medium access control protocol based on IEEE 802.11p needs to balance the trade-off between transmission delay and packet delivery ratio to be efficient, reliable and adaptive. Moreover, such a medium access control protocol can provide efficient vehicle-to-vehicle and vehicle-to-infrastructure communications, which affect the stability of the vehicular cloud.

Keywords

Vehicular ad hoc networks, multi-channel medium access control, medium access control, IEEE 802.11p, vehicular cloud

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Introduction

According to the World Health Organization, the number of deaths in traffic accidents worldwide annually is 100 million, which accounts for an economic loss of 500 billion.¹ Vehicular ad hoc networks (VANETs) are a part of the Intelligent Transportation System (ITS), which aims to enhance vehicular safety, reduce traffic

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accidents, and improve transportation efficiency. VANETs consist of vehicles that use wireless communication equipment, that is, On-Board Units (OBUs), enabling them to connect with other vehicles, and Road Side Units (RSUs), which are positioned along the road. Therefore, VANETs perform two types of communications: vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I). Based on these communications, VANETs classify applications into mainly three categories:^{2,3} (1) safety-related applications (e.g. emergency brakes, collision avoidance, and automatic notification of crashes on roads); (2) transport efficiency applications (e.g. intersection management and navigation and lane merging assistance); and (3) infotainment applications (e.g. voice over IP, video, web browsing, and mobile multiplayer gaming). Non-safety applications are defined as representing transport efficiency and infotainment applications. Note that safety and non-safety applications have various requirements, such as a short delay constraint and wide bandwidth, as shown in Table 1.

Recently, modern vehicles are expected to carry relatively more communication systems, on-board computing facilities, storage, and increased sensing power.⁵ However, there is an increasing need for resources, in particular, for safety applications that require cooperation between vehicles. The vehicular cloud offers to users the opportunity to rent resources on-demand or to share them freely to run their applications or to carry out some tasks.⁶ The vehicular cloud is used to improve safety, increase efficiency, and help the economy.⁷ Moreover, the vehicular cloud can dynamically adapt according to changing application requirements and system environments. In contrast, in VANETs, safety packets require strict reliability and timeliness requirements; when a vehicle is performing certain actions, such as changing direction dramatically or driving over

the speed limit, emergency warning messages (EWMs) will be generated and sent to the cloud storage and surrounding vehicles on the road.⁵ In addition, many schemes⁸ proposed for VANETs can increase the throughput for non-safety packets and alleviate the congestion of some channels. By comparing the requirements of VANET applications and benefit of the vehicular cloud, the need for a medium access control (MAC) protocol which provides efficient transmission delay and the use of rationalized radio resources⁵ is crucial for VANETs.

MAC is designed to meet the requirements of safety and non-safety applications. It provides an efficient broadcast service and shares this with different vehicles in an efficient and fair manner. Various MAC protocols have been proposed for VANETs that improve the throughput for non-safety applications and support the reliability of safety applications. In general, MAC protocols are separated into three categories: contention-based, contention-free, and hybrid MAC protocols.⁸⁻¹¹ In contention-based MAC protocols, if vehicles have data to transmit, they will access the channel using a carrier sensing mechanism.¹² However, a data packet collision occurs at the destination vehicle when neighboring vehicles sense that the channel is free and simultaneously transmit their data. In addition, contention-based MAC protocols allow each vehicle to attempt to transmit across the channel without any collisions.⁹ In real-time applications, such protocols increase the packet loss ratio and access delay. The second category is contention-free MAC protocols, which prevent collisions by allowing only one vehicle in a neighborhood to access the channel at any given time. Hence, they allow for periodic transmission of control messages. However, all vehicles are required to store the schedule table and time synchronization. Finally, hybrid MAC protocols have tried to combine contention-based and

Table 1. DSRC service requirements.²⁻⁴

Service type	Description	Packet size (bytes)	Maximum transmission delay (ms)	Transmission range (m)
Periodic	Intersection collision warning	100	100	150
Periodic	Cooperation collision warning	100	100	50-300
Periodic	Traffic light speed advisory/violation	100	100	150
Periodic	Work zone warning	100	1000	300
Periodic	Emergency vehicle warning	100	100	150
Periodic	Announcements	100	500	0-90
Periodic	Speed limited notification	100	100	300
Event	Collision warning	100	100	300
Event	Vehicle signal	100	1000	300-1000
Event	Toll connections	100	50	15
Event	Lane change assistance	100	100	150
Event	Motorcycle approaching indication	100	100	150

DSRC: dedicated short-range communication.

Table 2. IEEE standards for VANET.^{36,37}

Protocols	IEEE std.	Functions
WAVE resource manager	1609.1	Allow for the interaction of OBUs and outside of the OBUs
WAVE security services	1609.2	Security, the format of secure messages, processing, and message exchange
WAVE networking services	1609.3	Routing and networking services
Multi-channel operation	1609.4	Multiple-channel operation
WAVE PHY and MAC	802.11p	Enable operation in rapidly varying vehicular environments

VANET: vehicular ad hoc network; WAVE: Wireless Access in Vehicular Environment; MAC: medium access control; OBU: On-Board Unit.

contention-free methods into a single mechanism to increase the quality of service (QoS) and system throughput.

However, one of the issues among VANETs is that the high mobility and rapid changes in the topology cause frequent network disconnections and link failures. It is necessary to design MAC protocols that adapt to different traffic conditions, such as vehicle density and traffic data. Time-division multiple access (TDMA)-based MAC protocols, such as those in previous works,^{13–25} support an efficient channel utilization, reliable communication, and deterministic access times, even with a large traffic load and QoS requirements. In contrast, contention-based MAC protocols^{10,26–29} allow vehicles that wish to transfer data to randomly attempt accessing the channel. As the network load increases, the transmission collision also increases. These protocols are primarily used for safety-critical situations. In recent years, hybrid MAC protocols^{30–33} have been designed to increase the QoS and system throughput.

The IEEE 802.11p²⁶ standard, which is based on the legacy IEEE 802.11 standard, is a recently proposed MAC standard for VANETs¹⁸ and is widely implemented. To support multi-channel access for a single-radio transceiver in IEEE 802.11p, IEEE 1609.4³⁴ was developed for Wireless Access in Vehicular Environments (WAVE), as shown in Table 2. IEEE 1609.4 employs an alternate access scheme, which allows a vehicle to switch between the control channel (CCH) and service channels (SCHs) every 50 ms. In this article, we focus on multi-channel MAC protocols based on the latest drafts of the IEEE 802.11p and IEEE 1609.4 standards with a single radio transceiver. Alternatively, adaptive IEEE 802.11p-based multi-channel MAC protocols are proposed to adapt to both vehicle density and traffic data conditions. These adaptive IEEE 802.11p multi-channel MAC protocols primarily use information (the delay/ throughput performance) from Markov chains modeling. In this article, we study the main contributions of the proposed adaptive IEEE 802.11p-based multi-channel MAC protocols via their classifications using interval division methods. We perform simulations by using NS-3³⁵ and compare these protocols in terms of the packet delivery ratio of safety applications

and non-safety applications. Finally, we conclude and discuss some issues in designing adaptive IEEE 802.11p-based multi-channel MAC protocols.

In this article, we study the main contributions of the proposed adaptive IEEE 802.11p-based multi-channel MAC protocols via their classifications using interval division methods. We perform simulations by using NS-335 and compare these protocols in terms of the packet delivery ratio of safety applications and non-safety applications. Finally, we conclude and discuss some issues in designing adaptive IEEE 802.11p-based multi-channel MAC protocols.

Comparison of interval division method of adaptive IEEE 802.11p-based multi-channel MAC protocols

The main challenge of designing MAC protocols for VANETs is achieving reliable delivery of messages within a given time limit, even when the density of vehicles greatly and rapidly varies in the network,³⁸ that is, the variance of the vehicle density is large and fast. One approach is using MAC protocols to adjust the intervals according to vehicle density or traffic data. By leveraging information from Markov chains,⁸ adaptive IEEE 802.11p-based multi-channel MAC protocols can dynamically change intervals. According to Nguyen et al.,⁸ there are two different Markov chain models for safety and WAVE Service Advertisement (WSA) packets. If a vehicle has a non-safety packet, it broadcasts a WSA packet and piggybacks off the service information, eventually identifying the SCHs to be used. If a receiver agrees with the information sent by the sender, it responds to the WSA packet with an acknowledgment (ACK). In contrast, safety messages have their own special properties: bounded delay and no positive ACK. Therefore, researchers have proposed many schemes that apply Markov chain models for either safety or WSA transmission to compute the optimized intervals in MAC protocols.

According to the frameworks of control channel intervals (CCHIs), we classified adaptive IEEE 802.11p-based multi-channel MAC protocols into three main categories: the fixed safety transmission

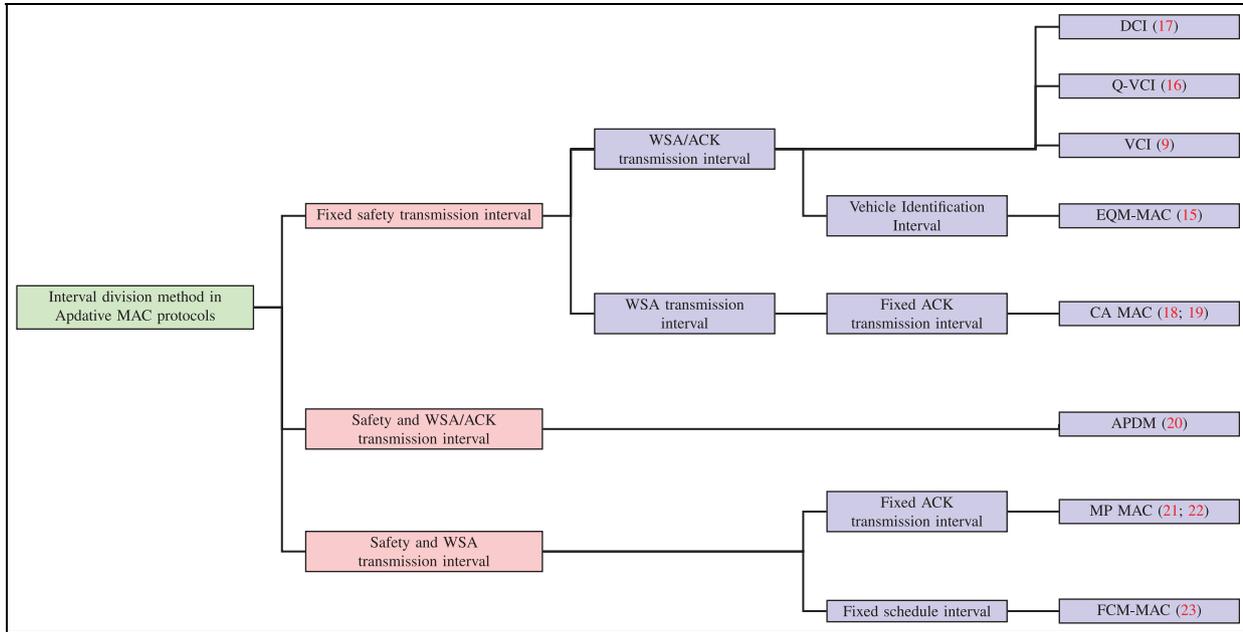


Figure 1. Classification of adaptive MAC protocols according to interval division methods.

interval, safety and WSA/ACK transmission interval, and safety and WSA transmission interval, as shown in Figure 1. For the fixed safety transmission interval methods, we classify them using Markov chain models: (a) the WSA/ACK transmission interval^{10,29,39} and (b) the WSA transmission interval with a fixed ACK transmission interval.⁴⁰ The APDM⁴¹ uses both the safety and WSA/ACK transmission intervals method. By separating ACK into independent intervals, APDM⁴¹ divides the WSA/ACK transmissions into two intervals: a WSA transmission interval and an ACK interval. FCM-MAC⁴² is split into WSA transmissions and RSU broadcast Reservation (RES) messages, which contain the SCH assignment and scheduling order for each link of service data transmission.

Bianchi et al.⁴³ presented a Markov chain model to compute the saturation throughput performance of the 802.11 Distributed Coordination Function (DCF). (All nodes providing service always have available WSA packets.) Based on this model, VCI¹⁰ is enhanced by considering the frozen backoff timer and holding the maximal backoff stage. In VCI, CCHI is split into two intervals: a safety interval and a WSA/ACK interval. However, VCI cannot avoid interference from hidden nodes. EQM-MAC⁴⁰ is extended from VCI, which considers the number of vehicles in the RSU's coverage. EQM-MAC divides the CCHI into three intervals: a safety interval, a vehicle identification interval, and a WSA/ACK interval (Song et al.⁴⁰ define this interval as a contention-free interval). To improve the throughput for non-safety applications, CA MAC^{44,45} divides the WSA/ACK interval in VCI¹⁰ into two independent

intervals: the WSA and ACK intervals. However, fixed safety interval methods^{10,40,44,45} have a disadvantage in that the safety packet that arrives in the WSA interval has to wait for the next safety interval to broadcast the safety packets.

To improve the reliability of safety transmission, the safety and WSA/ACK transmissions are transmitted together in the same interval in APDM.⁴¹ APDM divides the CCHI into two intervals: the multi-priority (MP) broadcast interval, which is used to broadcast the optimal ratio packet (ORP), and the random contention interval. MP MAC^{46,47} divides the WSA/ACK interval in VCI¹⁰ into two independent intervals: the WSA interval and the ACK interval. One fixed interval is used to broadcast an MP-supported p -persistent (MP) packet (which is a fixed interval), and the other interval is used to dynamically adjust the broadcast safety and WSA packet. Alternatively, based on RSU, FCM-MAC⁴² proposes a fixed interval for broadcasting an RES packet in exchange for a fixed ACK interval in MP MAC.^{46,47} All operations of the existing adaptive IEEE 802.11p-based multi-channel MAC protocols are shown in Figure 2.

In Table 3, we discuss the advantages and disadvantages of adaptive IEEE 802.11p-based multi-channel MAC protocols. Although these protocols use different interval division methods, their advantages are summarized as follows:

1. Improve the saturated throughput;
2. Adapt to the amount of traffic data;
3. Ensure safety packet transmission;

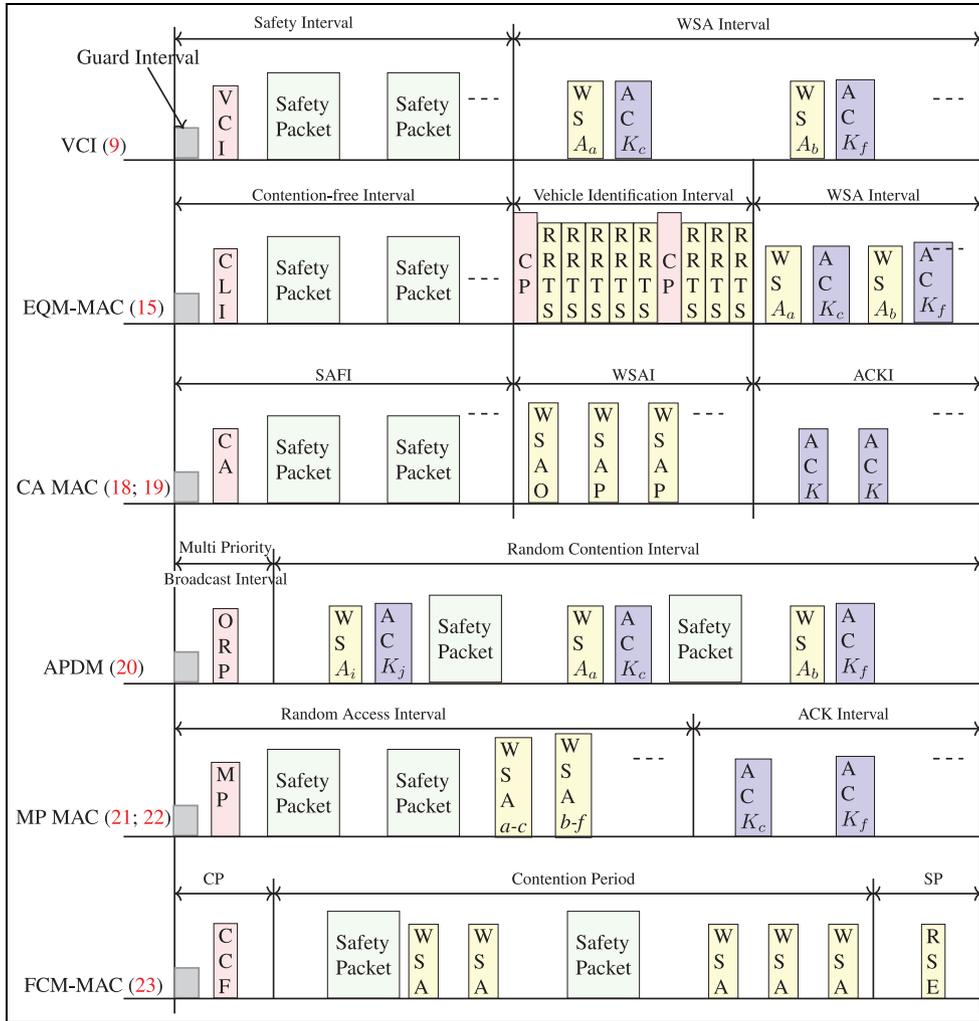


Figure 2. Operation of existing adaptive IEEE 802.11p-based multi-channel MAC protocols.

4. High channel utilization.

Their disadvantages are summarized as follows:

1. Not suitable for multi-hop communication because each control vehicle (RSUs or Cluster Heads (CHs)) computes the optimized interval among its one-hop neighbor.
2. The channel access schedule is lost and collision between messages will occur when CHs move out of their clusters.

In order to compare adaptive IEEE 802.11p-based multi-channel MAC protocols, we will discuss the simulation results in the next section.

Performance evaluation

In this section, we discuss the simulation results of three main categories: the fixed safety transmission interval,

safety and WSA/ACK transmission interval, and safety and WSA transmission interval division methods. Let VCI¹⁰ and CA MAC^{44,45} represent two fixed safety transmission interval division methods, APDM⁴¹ represent safety and WSA/ACK transmission interval division methods, and MP MAC^{46,47} represent safety and WSA transmission interval division methods with fixed ACK intervals.

The MAC protocols performance is based on the density of vehicles.^{8,48} Therefore, we simulate and compare the operations of different existing MAC protocols under different vehicle densities. We assume that the simulated highway segment consists of one RSU and vehicles that are placed on a straight line according to a Poisson point process with network density β (in nodes per meter). At the start of a CCHI, an RSU will broadcast a control packet with information on either (1) the ratio between the CCHI and SCHI or (2) the scheduling order for each node broadcast ACK packet or safety packet. (A control packet represents VCI, CLI, CA,

Table 3. Different adaptive IEEE 802.11p-based multi-channel MAC protocols.

Reference	Protocol name	Interval divisions	Optimized object	Advantages	Disadvantages	Published
Wang et al. ¹⁰	VCI	Safety interval WSA/ACK interval	WSA/ACK interval	Improves the saturated throughput on the SCHI. Ensures safety packet transmission and private service advertisements. Supports the various QoS requirements.	Cannot satisfy various QoS requirements.	2012
Wang et al. ²⁹	Q-VCI	Safety interval WSA/ACK interval	WSA/ACK interval	Supports the various QoS requirements.	Resources are not fully utilized.	2011
Zhu and Zhu ³⁹	DCI	Safety interval WSA/ACK interval	WSA/ACK interval	Improves the throughput. Adapts the maximum number of data packets sent.	The safety transmission delay is not studied.	2013
Omar et al. ^{18,19}	CA MAC	Safety interval WSA _j interval {j = a platoon or vehicle} ACK interval	WSA _j interval	Improves the system throughput.	The antenna that is placed in platoons requires a large transmission range.	2013
Yang et al. ^{21,22}	MP MAC	Safety and WSA interval ACK interval	Safety and WSA interval	Improves the saturated throughput on the CCH. Low transmission delay. High channel utilization.	Not suitable for multi-hop communications.	2013, 2014
Yao et al. ⁴²	FCM-MAC	Coordination Control Frame interval WSA and safety message RES interval	WSA and safety message	Supports the reliability for safety application. Allows safety and non-safety messages transmitted in a flexible way.	Considers WSA and safety messages with the same packet arrival rate.	2017
Song et al. ⁴¹	APDM	ORP interval Safety and WSA/ACK interval	Safety and WSA/ACK interval	Reduces the safety packet delay. Improves the system throughput in VANETs.	Once optimal node leaves the neighborhood, the channel access schedule is lost and collision between messages will occur.	2017
Song et al. ⁴⁰	EQMMAC	Safety interval Vehicle identification interval Safety and WSA/ACK interval	WSA/ACK interval	Provide the high saturation throughput. Improves transmission delay for non-safety applications.	Vehicles require two transceivers.	2017

MAC: medium access control; VANET: vehicular ad hoc network; WSA/ACK: Wireless Access in Vehicular Environment Service Advertisement/Acknowledgment; SCHI: service channel interval; QoS: quality of service; CCH: control channel; RES: Reservation; ORP: optimal ratio packet.

Table 4. System parameters for simulations.

Parameter	Value	Parameter	Value
No. of SCHs	4	Propagation model	Nakagami
No. of CCH	1	ACK	14 bytes
Data rate of each channel	6 Mbps	Transmission range	500 m
WSA	160 bytes	Vehicle density (β)	0.01, 0.04, 0.08
Safety application	200 bytes	W_s	16
Slot time, σ	13 μ s	W_e	8
Propagation time, δ	1 μ s	DIFS	64 μ s
Number of SerSlots, M	5	SIFS	32 μ s
Highway length	1000 m	Simulation time	2 min

SCHs: service channel; CCH: control channel; ACK: acknowledgment; WSA: Wireless Access in Vehicular Environment Service Advertisement; DIFS: distributed coordination function (DCF) inter-frame space; SIFS: short inter-frame space.

MP, and CCF packers in adaptive IEEE 802.11p-based multi-channel MAC protocols.) Therefore, the simulated highway segment is a fair scenario for comparing the operations of different existing MAC protocols.

The performance of different MAC protocols is carried out by NS-3. The parameter configurations are summarized in Table 4. The sending frequency of safety packets f_e is varied from two to eight packets per second, that is, $f_e \in \{2, 4, 6, 8\}$.

In VCI and CA MAC, CCHI consists of a fixed safety interval, while MP MAC has a fixed ACK interval. Now, we present formulas to compute these intervals.

A fixed safety interval. The length of a safety interval, defined as L_e , is computed as follows

$$L_e = \frac{\alpha f_e N}{R_{CCH}} \cdot 10^3 \quad (1)$$

where N presents the total number of nodes sending safety packets, R_{CCH} is the data rate of CCH, α is a pre-defined factor according to the current vehicular environment, and f_e is the sending frequency of the safety messages.¹⁰

A fixed ACK interval. The length of an ACK interval, defined as L_{ACK} , is computed as follows

$$L_{ACK} = N_{ACK} \cdot T_{ACK} \quad (2)$$

where N_{ACK} is the number of nodes that reply to the ACK packets. T_{ACK} is the transmission time of an ACK packet, which is given as follows

$$T_{ACK} = \frac{ACK}{R_{CCH}} + \delta + SIFS \quad (3)$$

Compared with VCI,¹⁰ CA MAC,^{44,45} and APDM,⁴¹ MP MAC^{46,47} can support the reliable transmission of safety packets via ACK schemes. In MP MAC, the operation of the reliability of safety packets is as follows:

1. If a node hears a safety packet, it will reply to the ACK packet during the ACK interval.
2. If a node hears an ACK packet responding to the same safety packet, it will not repeat the response.

Safety packets require a short delay constraint and efficient broadcast. Hence, we compare two parameters: (1) transmission delay (D) and (2) packet delivery ratio (PDR_e). The two parameters are defined as follows

$$D = T_s - T_i \quad (4)$$

where T_s is the time that a vehicle successfully broadcasts a safety packet, and T_i is the time in which a safety packet has arrived at the MAC layer

$$PDR_e = \frac{\text{Number of successfully broadcasting safety packets}}{\text{Number of safety packets}} \quad (5)$$

In Figure 3, we discuss the transmission delays of packets #1 and #2 in the case of using VCI, CA MAC, and MP MAC. We assume packet #1 has experienced a collision; hence, this packet must wait until the next safety interval of the Synchronization Interval (SI). Since packet #2 arrives at the same time as the service channel interval (SCH), both VCI and CA MAC skip this packet and head toward the next safety interval of the next SI to broadcast SI. In contrast, the MP MAC and CA MAC allow packet #2 to be broadcast when a corresponding vehicle attempts to successfully access the channel, as shown in Figure 3. To fairly compare VCI, CA MAC, and MP MAC, we consider the role of an RSU and define the following rules:

Rule 1. If an RSU successfully receives safety packets, it will broadcast the corresponding vehicle sender's ID by including it in the control packets.

Rule 2. If the vehicle senders overhear their IDs in the control packet broadcast by the RSU, the

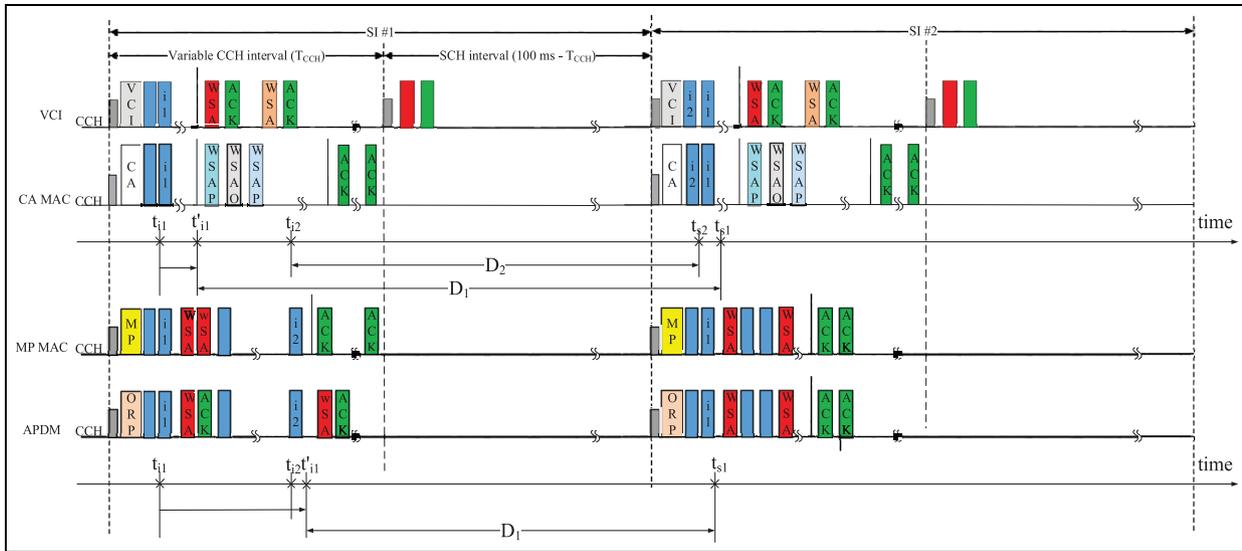


Figure 3. An example of transmission delay of safety packets.

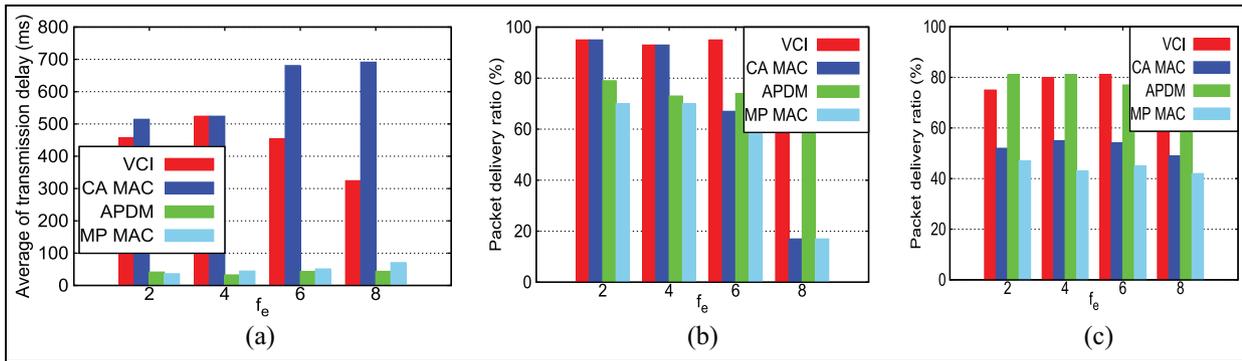


Figure 4. Low-density scenario $\beta = 0.01$. (a) Transmission delay of safety packets, (b) PDR of safety packets at an RSU, and (c) PDR of WSA packets.

vehicle senders successfully broadcast safety packets. Otherwise, the vehicle senders will attempt to access a channel and broadcast their packets again until they are successfully broadcast.

Rule 3 (Saturated throughput condition). In VCI, CA MAC, and MP MAC, an optimized interval is calculated based on the saturated throughput. Therefore, we assume that all vehicles always have a non-safety packet to exchange. In addition, we assume that the generated safety packets that arrive at the MAC queues follow Poisson distributions.

First, we compare these methods under a low-density scenario with $\beta = 0.01$ (10 vehicles/km). Since VCI and CA MAC have safety intervals that only broadcast safety packets and L_e in equation (1) is computed based on f_e , when a safety packet has collided with another packet, the number of safety packets, which are broadcast in the next safety interval, will increase. Hence, the

collision probability between new safety packets and collided safety packets is high. Consequently, the transmission delays of re-sent safety packets using VCI and CA MAC are greater than those using APDM and MP MAC. In addition, these delays are greater than the short delay constraint (100 ms), while the transmission delays of APDM and MP MAC meet the short delay constraint, as shown in Figure 4(a). When f_e is 2 or 4, the RSUs can receive more safety packets using VCI and CA MAC rather than APDM and MP MAC. The reason is that in VCI and CA MAC, safety packets can collide with other safety packets, while in APDM and MP MAC, safety packets can collide with other safety packets or with WSA packets. When f_e is 2 or 4, the ACK interval affects the transmission of safety packets. If a receiver did not receive a WSA packet sent by a sender, it broadcasts an ACK packet without information. To operate the ACK scheme, an RSU has to assign the scheduling order of broadcasting ACK packets for each

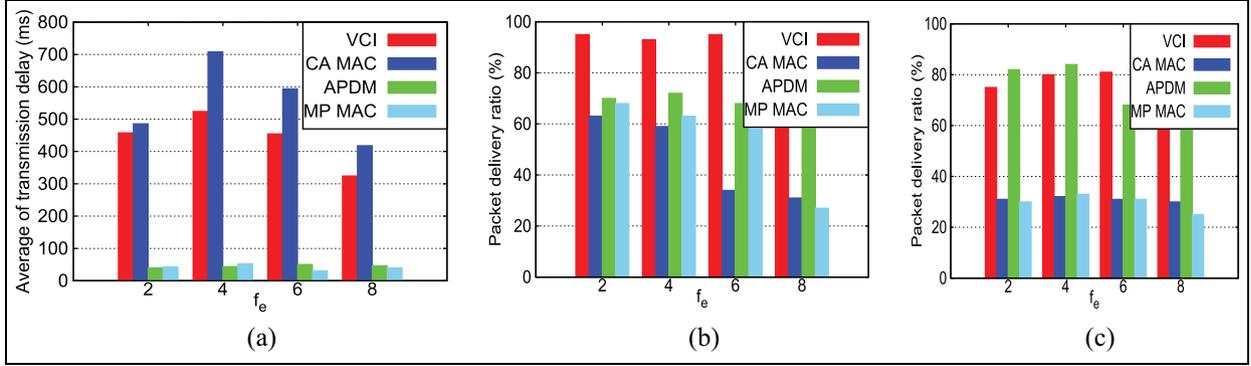


Figure 5. Average density scenario $\beta = 0.04$. (a) Transmission delay of safety packets, (b) PDR of safety packets at an RSU, and (c) PDR of WSA packets.

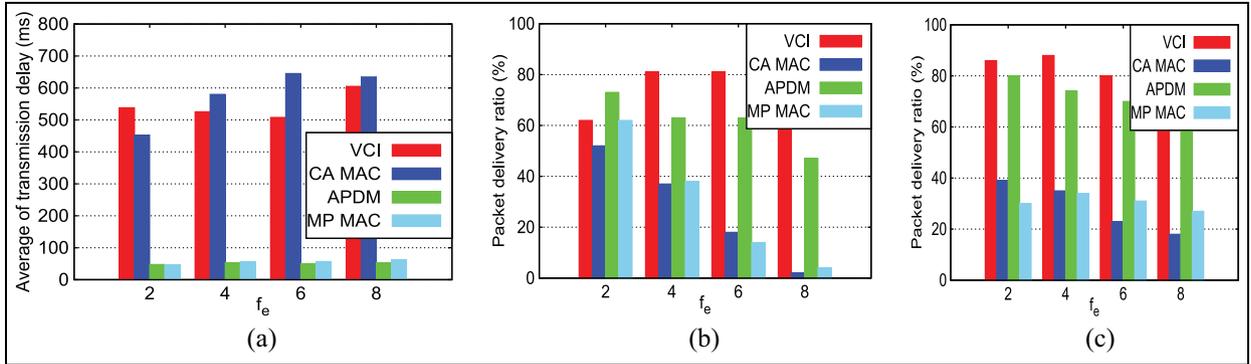


Figure 6. High-density scenario $\beta = 0.08$. (a) Transmission delay of safety packets, (b) PDR of safety packets at an RSU, and (c) PDR of WSA packets.

vehicle. Therefore, compared to fixed safety interval methods, the PDR of the safety packets at an RSU of VCI is greater than for CA MAC with an ACK interval. In non-fixed safety interval methods, the PDR of the safety packets at an RSU in APDM is greater than that of MP MAC with ACK intervals, as shown in Figure 4(b). According to the collision of safety packets, the PDRs of the WSA packets of VCI and APDM are greater than those of CA MAC and MP MAC, as seen in Figure 4(c).

Second, we consider an average density scenario with $\beta = 0.04$ (40 vehicles/km). The transmission delays using VCI and CA MAC are greater than using APDM and MP MAC, as seen in Figure 5(a). The PDR of the WSA packets in Figure 5(c) shows that the VCI protocol can support more efficient WSA packet transmission than CA MAC, APDM, and MP MAC. Figure 5(b) shows that VCI has the highest PDR of safety packets at an RSU compared with CA MAC, APDM, and MP MAC.

Finally, we consider a high vehicular density scenario with $\beta = 0.08$ (80 vehicles/km). Like Figures 4(a)

and 5(a), the transmission delays using VCI and CA MAC in Figure 6(a) are higher than using APDM and MP MAC. However, in a scenario with high vehicle density and low f_e , APDM is better than VCI, as seen in Figure 6(b). For high f_e , the PDR of the safety packets using VCI is higher than using APDM. The CA MAC and MP MAC affected by ACK intervals with a high vehicle density have a lower PDR of safety packets than VCI and APDM. Correspondingly, the PDRs of WSA packets using VCI and APDM are greater than using both CA MAC and MP MAC, as seen in Figure 6(c).

Conclusion and future works

In this article, we discuss interval division methods in adaptive IEEE 802.11p-based multi-channel MAC protocols. First, we classify the existing adaptive IEEE 802.11p-based multi-channel MAC protocols into three main categories: fixed safety transmission intervals, safety and WSA/ACK transmission intervals, and safety and WSA transmission intervals. Second, we

evaluate and compare these protocols under the same conditions. The simulation results are carried out using NS-3 under the assumptions of saturated throughput for WSA packets and safety packets following Poisson point processes. Under saturated throughput, the simulation results demonstrate the following: (1) VCI and CA MAC cannot support reliability for safety packets that have collided; (2) protocols using a separated ACK interval (CA MAC and MP MAC) have a lower packet delivery ratio of safety packets and WSA packets compare to not using a separated ACK interval (VCI and APDM); (3) VCI supports efficient broadcast of safety packets and the PDR of the WSA packets; and (4) APDM and MP MAC satisfy a short delay constraint for safety packets. Future adaptive IEEE 802.11p-based multi-channel MAC protocols should consider the trade-off between transmission delay and PDR to improve their efficiency, reliability, and adaptability.

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References

- Martinez FJ, Toh CK, Cano JC, et al. Emergency services in future intelligent transportation systems based on vehicular communication networks. *IEEE Intell Transp Syst Mag* 2010; 2(2): 6–20.
- Hartenstein H and Laberteaux LP. A tutorial survey on vehicular ad hoc networks. *IEEE Commun Mag* 2008; 46(6): 164–171.
- Toor Y, Muhlethaler P, Laouiti A, et al. Vehicle ad hoc networks: applications and related technical issues. *IEEE Commun Surv Tut* 2008; 10(3): 74–88.
- Ansari S, Sanchez M, Boutaled T, et al. SAI: safety application identifier algorithm at MAC layer for vehicular safety message dissemination over LTE VANET networks. *Wirel Commun Mobile Comput* 2018; 2018(317): 74–88.
- Whaiduzzaman M, Sookhak M, Gani A, et al. A survey on vehicular cloud computing. *J Netw Comput Appl* 2014; 40: 325–344.
- Mekki T, Jabri I, Rachedi A, et al. Vehicular cloud networks: challenges, architectures, and future directions. *Veh Commun* 2017; 9: 268–280.
- Abuelela M and Olariu S. Taking VANET to the clouds. In: *Proceedings of the 8th international conference on advances in mobile computing and multimedia*, Paris, 8–10 November 2010, pp.6–13. New York: ACM.
- Nguyen V, Kim OTT, Pham C, et al. A survey on adaptive multi-channel MAC protocols in VANETs using Markov models. *IEEE Access* 2018; 6: 16493–16514.
- Hadded M, Muhlethaler P, Laouiti A, et al. TDMA-based MAC protocols for vehicular ad hoc networks: a survey, qualitative analysis, and open research issues. *IEEE Commun Surv Tut* 2015; 17(4): 2461–2492.
- Wang Q, Leng S, Fu H, et al. An IEEE 802.11p-based multichannel MAC scheme with channel coordination for vehicular ad hoc networks. *IEEE T Intell Transp Syst* 2012; 13(2): 449–458.
- Jayaraj V, Hemanth C and Sangeetha RG. A survey on hybrid MAC protocols for vehicular ad-hoc networks. *Veh Commun* 2016; 6: 29–36.
- Ye F, Yim R, Zhang J, et al. Congestion control to achieve optimal broadcast efficiency in VANETs. In: *Proceedings of the international conference on communications*, Cape Town, South Africa, 23–27 May 2010, pp.1–5. New York: IEEE.
- Bharati S and Zhuang W. CAH-MAC: cooperative ADHOC MAC for vehicular networks. *IEEE J Select Area Commun* 2013; 31(3): 470–479.
- Borgonovo F, Capone A, Cesana M, et al. ADHOC MAC: new MAC architecture for ad hoc networks providing efficient and reliable point-to-point and broadcast service. *Wirel Netw* 2004; 10: 359–366.
- Borgonovo F, Campelli L, Cesana M, et al. Impact of user mobility on the broadcast service efficiency of the ADHOC MAC protocol. In: *Proceedings of the 61st vehicular technology conference*, Stockholm, 30 May–1 June 2005, vol. 4, pp.2310–2314. New York: IEEE.
- Bharati S and Zhuang W. Performance analysis of cooperative ADHOC MAC for vehicular networks. In: *Proceedings of the global communications conference*, Anaheim, CA, 3–7 December 2012, pp.5482–5487. New York: IEEE.
- Bharati S, Thanayankizil L, Bai F, et al. Effects of time slot reservation in cooperative ADHOC MAC for vehicular networks. In: *Proceedings of the international conference on communications*, Budapest, 9–13 June 2013, pp.6371–6375. New York: IEEE.
- Omar H, Zhuang W and Li L. VeMAC: a TDMA-based MAC protocol for reliable broadcast in VANETs. *IEEE T Mobile Comput* 2013; 12(9): 1724–1736.
- Omar H, Zhuang W, Abdrabou A, et al. Performance evaluation of VeMAC supporting safety applications in vehicular networks. *IEEE T Emerg Topic Comput* 2013; 1(1): 69–83.

20. Nguyen V, Dang DNM, Jang S, et al. e-VeMAC: an enhanced vehicular MAC protocol to mitigate the exposed terminal problem. In: *Proceedings of the 16th Asia-Pacific network operations and management symposium*, Hsinchu, Taiwan, 17–19 September 2014. New York: IEEE.
21. Yang W, Li P, Liu Y, et al. Adaptive TDMA slot assignment protocol for vehicular ad-hoc networks. *J Chin Univ Post Telecommun* 2013; 20(1): 11–25.
22. Yang W, Liu W, Li P, et al. TDMA-based control channel access for IEEE 802.11p in VANETs. *Int J Distrib Sens Netw* 2014; 10(8): 579791.
23. Ke W, Weidong Y, Pan L, et al. A decentralized adaptive TDMA scheduling strategy for VANET. In: *Proceedings of the wireless communications and networking conference workshops*, Shanghai, China, 7–10 April 2013, pp.216–221. New York: IEEE.
24. Zou R, Liu Z, Zhang L, et al. A near collision free reservation based MAC protocol for VANETs. In: *Proceedings of the wireless communications and networking conference*, Istanbul, Turkey, 6–9 April 2014, pp.1538–1543. New York: IEEE.
25. Nguyen V, Kazmi SMA and Hong CS. ECCT: an efficient-cooperative ADHOC MAC for cluster-based TDMA system in VANETs. *Int J Distrib Sens Netw* 2015; 11(8): 746438.
26. IEEE 802.11:2012. IEEE standard for information technology—telecommunications and information exchange between systems local and metropolitan area networks—specific requirements—part 11: wireless LAN medium access control (MAC) and physical layer (PHY) specifications.
27. Xiao Y. A simple and effective priority scheme for IEEE 802.11. *IEEE Commun Lett* 2003; 7(2): 70–72.
28. Zang Y, Stibor L, Walke B, et al. Towards broadband vehicular ad-hoc networks—the vehicular mesh network (VMESH) MAC protocol. In: *Proceedings of the wireless communications and networking conference*, Kowloon, China, 11–15 March 2007, pp.417–422. New York: IEEE.
29. Wang Q, Leng S, Zhang Y, et al. A QoS supported multi-channel MAC for vehicular ad hoc networks. In: *Proceedings of the 73rd vehicular technology conference*, Yokohama, Japan, 15–18 May 2011, pp.1–5. New York: IEEE.
30. Lu N, Ji Y, Liu F, et al. A dedicated multi-channel MAC protocol design for VANET with adaptive broadcasting. In: *Proceedings of the wireless communication and networking conference*, Sydney, NSW, Australia, 18–21 April 2010, pp.1–6. New York: IEEE.
31. Dang DNM, Dang HN, Nguyen V, et al. HER-MAC: a hybrid efficient and reliable MAC for vehicular ad hoc networks. In: *Proceedings of the 28th international conference on advanced information networking and applications*, Victoria, BC, Canada, 13–16 May 2014, pp.186–193. New York: IEEE.
32. Nguyen V, Oo TZ, Chuan P, et al. An efficient time slot acquisition on the hybrid TDMA/CSMA multichannel MAC in VANETs. *IEEE Commun Lett* 2016; 20(5): 970–973.
33. Nguyen V, Oo TZ, Hong CS, et al. An efficient and fast broadcast frame adjustment algorithm in VANET. *IEEE Commun Lett* 2017; 21(7): 1589–1592.
34. IEEE 1609.4:2010. IEEE standard for wireless access in vehicular environments (WAVE) — multi-channel operation.
35. Ns-2, Ns-3, <https://www.nsnam.org/releases/>
36. Booyens MJ, Zeadally S and van Rooyen GJ. Survey of media access control protocols for vehicular ad hoc networks. *IET Commun* 2011; 5(11): 1619–1631.
37. Uzcategui RA, Sucre AJD and Acosta-Marum G. Wave: a tutorial. *IEEE Commun Mag* 2009; 47(5): 126–133.
38. Mammu ASK, Hernandez-Jayo U and Sainz N. Cluster-based MAC in VANETs for safety applications. In: *Proceedings of the international conference on advances in computing, communications and informatics*, Mysore, India, 22–25 August 2013, pp.1424–1429. New York: IEEE.
39. Zhu DB and Zhu DD. Performance analysis of a multi-channel MAC with dynamic CCH interval in WAVE system. *Adv Mater Res* 2013; 767: 2621–2624.
40. Song C, Tan G and Yu C. An efficient and QoS supported multichannel MAC protocol for vehicular ad hoc networks. *Sensors* 2017; 17(10): 2293.
41. Song C, Tan G, Yu C, et al. APDM: an adaptive multi-priority distributed multichannel MAC protocol for vehicular ad hoc networks in unsaturated conditions. *Comput Commun* 2017; 104: 119–133.
42. Yao Y, Zhang K and Zhou X. A flexible multi-channel coordination MAC protocol for vehicular ad hoc networks. *IEEE Commun Lett* 2017; 21(6): 1305–1308.
43. Bianchi G. Performance analysis of the IEEE 802.11 distributed coordination function. *IEEE J Select Area Commun* 2000; 18(3): 535–547.
44. Shao C, Leng S, Zhang Y, et al. Performance analysis of connectivity probability and connectivity-aware MAC protocol design for platoon-based VANETs. *IEEE T Veh Technol* 2015; 64(12): 5596–5609.
45. Shao C, Leng S, Fan B, et al. Connectivity-aware medium access control in platoon-based vehicular ad hoc networks. In: *Proceedings of the international conference on communications*, London, 8–12 June 2015, pp.3305–3310. New York: IEEE.
46. Shao C, Leng S, Zhang Y, et al. A multi-priority supported p-persistent MAC protocol for vehicular ad hoc networks. In: *Proceedings of the wireless communications and networking conference*, Shanghai, China, 1–4 April 2012, pp.2532–2537. New York: IEEE.
47. Shao C, Leng S, Zhang Y, et al. A multi-priority supported medium access control in vehicular ad hoc networks. *Comput Commun* 2014; 39: 11–21.
48. Nguyen V, Pham C, Oo TZ, et al. MAC protocols with dynamic interval schemes for VANETs. *Veh Commun* 2019; 15: 40–62.