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MAC protocols with dynamic interval schemes for VANETs



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ABSTRACT

Under the dynamically changing topology of Vehicular Ad-hoc NETworks (VANETs), the restricted intervals in Medium Access Control (MAC) protocols cannot provide sufficient capacity to carry both safety and non-safety applications. One approach which can solve these issues is a dynamic MAC protocol that can adapt itself to the vehicle density or traffic conditions. In this survey, we, therefore, study various techniques for dynamic intervals used in MAC protocols, their advantages, and disadvantages. First, we classify these protocols into three following categories: 1) contention-based, 2) contention-free, and 3) a hybrid between contention-free and contention-based medium access methods. Second, in each medium access method, we classify the methodologies depending on their operating principles. The conclusions of our study are as follows: 1) Adaptive MAC protocols improve the channel utilization and adapt themselves to various traffic states, 2) Adaptive MAC protocols perform better than protocols using fixed intervals, 3) Currently, MAC protocols using dynamic intervals, which are suitable to VANET standards, are only applicable to optimize control channel interval; therefore, it is necessary to expand to both optimize control channel interval and service channel interval according to network and traffic condition. Finally, we discuss some open issues and whether designing MAC protocols using dynamic intervals can meet the QoS requirements for different applications in the future.

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1. Introduction

Recently, transportation has become one of the most important global issues. According to World Health Organization (WHO), traffic accidents kill 100 million people annually accounting for economic losses of \$500 billion [1]. To enhance the safety, reduce traffic accidents, and improve transportation efficiency, vehicles use wireless communication equipment, a.k.a. On Board Units (OBUs), enabling them to connect with others, and Road Side Units (RSUs) are positioned along the road. Some applications require communications between the vehicles, for example, lane change assistance, cooperative collision warning, and crash prevention. Other applications require coordination between the vehicles and RSUs, for example, vehicle infotainment applications and Internet connectivity [2,3]. Vehicular Ad-hoc NETwork (VANET) is created to connect and exchange information from a vehicle to vehicle (V2V) or from vehicle to roadside infrastructure (V2R). In general, applications over VANET can be split into three following categories:

* Corresponding authors. E-mail addresses: johnhuh@khu.ac.kr (E.-N. Huh), cshong@khu.ac.kr (C.S. Hong). safety, traffic management, and user-oriented services [4,5]. We summarize the specific requirements for different applications, as shown in Table 1. First, safety-related services (such as blind spot warning, precrash sensing) require reliable and fast broadcasting mechanisms and hence, each vehicle must periodically broadcast its information about a position, speed, acceleration, etc. [6,7]. Second, traffic management services consist of intersection management, delay warning, road congestion prevention, toll collection, and Cooperative Adaptive Cruise Control. Third, user-oriented services provide information, advertisements, and entertainment for users while traveling. User-oriented services have two basic applications: Internet connectivity and peer-to-peer applications [4]. However, safety services require not only fast access but also low delay, while user-oriented services require large bandwidth [8].

Although different services have different requirements, Medium Access Control (MAC) is responsible for satisfying them. MAC schemes are proposed to provide efficient and fair access to the wireless medium between vehicles and providers (i.e., OBUs and RSUs). In general, MAC protocols are separated into three classification: 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 the carrier



| Table | 1 | |
|-------|---------|---------------|
| DSRC | service | requirements. |

| Service type | Description | Packet size (bytes) | Maximum transmission delay (ms) | Transmission range (m) |
|--------------|-------------------------------|---------------------|---------------------------------|------------------------|
| Periodic | Cooperation collision warning | 100 | 100 | 50-300 |
| Periodic | Work zone warning | 100 | 1000 | 300 |
| Periodic | Announcements | 100 | 500 | 0-90 |
| Event | Collision warning | 100 | 100 | 300 |
| Event | Vehicle signal | 100 | 1000 | 300-1000 |
| Event | Toll connections | 100 | 50 | 15 |

Comparison of survey of MAC protocols.

| Ref. | Published | Performance | Limitation |
|----------|-----------|--|---|
| [14] | 2006 | Study the designed or adapted MAC protocols for vehicular MANETs | MAC protocols using dynamic intervals are not discussed |
| [13] | 2011 | The advantages and limitations of disparate MAC approaches | Dynamical adaptation based on vehicle density is one of the MAC research challenges, but it is not studied |
| [8] | 2015 | Identify the reasons for using the Time-Division Multiple Ac- cess (TDMA)-based MAC paradigm in VANETs | TDMA-based protocols using dynamic intervals are not clearly discussed |
| [10] | 2016 | Hybrid MAC protocols in VANET | Comparisons between hybrid MAC protocols using dynamic in- tervals and hybrid MAC protocols using fixed intervals were not considered |
| [15] | 2013 | Various dynamic interval schemes applying to VANET | Only focuses on contention-based medium access methods |
| Our work | | Survey of MAC protocols using a dynamic intervals scheme for VANETs including contention-based and time-division multiple access-based medium access methods | Study a limited number of proposed MAC protocols since 2009 |

sensing mechanism [12]. However, a data packet collision occurs at the destination vehicle when neighboring vehicles sense that the channel is free, and they simultaneously transmit their data. In addition, contention-based MAC protocols allow that each vehicle will randomly attempt to transmit on the channel when it needs to transmit by using a priority-based access scheme that employs both Enhanced Distributed Channel Access (EDCA) and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanisms [8]. In real-time applications, they increase 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 the 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 contention-free methods into a single mechanism to increase QoS and system throughput.

The most widely used MAC protocols in VANETs are surveyed in [13,14]. In [14], the authors study the designed or adapted MAC protocols for vehicular MANETs. However, the author did not study dynamic adaptation based on a varying number of vehicles, which is one of the many challenges of MAC protocols [13]. Specifically, according to the classification of MAC protocols, Mohamed Hadded et al. [8] studied the TDMA-based MAC paradigm in VANETs through analyzing the advantages and disadvantages compared with other MAC methods. In [8], the authors classified TDMA-based MAC protocols under different scenarios and studied their advantages and limitations. The authors consider varying vehicles densities because of the high vehicle mobility, which is the main contribution of hybrid MAC protocols. Nonetheless, TDMAbased protocols using dynamic intervals are not clearly discussed, including the benefits and drawbacks as compared with TDMAbased protocols using fixed intervals. Hybrid MAC protocols are also discussed in [10]. Hybrid MAC protocols ensure that all vehicles obtain fair channel access. However, comparisons between hybrid MAC protocols using dynamic intervals and hybrid MAC protocols using fixed intervals were not considered. Yoo et al. [15] studied various dynamic interval schemes applying to VANET. Nevertheless, the authors only focused on contention-based medium access methods. The comparison of surveys of MAC protocols is summarized in Table 2. In most of the above surveys, a common challenge of designing MAC protocols is having the MAC protocols adapt to different traffic conditions, such as vehicle density and traffic load. In this survey, we study about various MAC protocols using a dynamic intervals mechanism. We discuss how well these protocols can handle a highly dynamic topology as well as variations in the vehicle density and traffic load in VANETs. The major contributions of our survey are summarized as follows.

- 1. We identify the reasons for using dynamic intervals in VANETs. Compared with MAC protocols using fixed intervals, MAC protocols using dynamic intervals increase the throughput of nonsafety applications and the Packet Delivery Ratio (PDR), which can additionally guarantee QoS for real-time applications.
- 2. We present a new classification and an overview of MAC protocols using dynamic intervals. Depending on the channel access methods and methodologies used, we classify MAC protocols using dynamic intervals into different sections. The protocols using the same channel access methods and methodologies are grouped together. Hence, the methodology trend for each channel access method is focused. We also discuss the benefits and limitations of each method.
- 3. We qualitatively compare MAC protocols using the same channel access methods but different methodologies.
- 4. We discuss issues and promising future MAC protocols using dynamic intervals in each channel access method. One of these issues is designing MAC protocols to improve the implementation of MAC protocols using dynamic intervals for V2V communication under large speed variance conditions.

We believe that our work provides some helpful insights regarding MAC protocols using dynamic intervals. We summarize our major observations as follows:

Simulation results of packet delivery ratio and system throughput.

| Parameters | 50 vehicles/km | | 35 vehicles/km | | 25 packets/second | |
|-------------------|----------------|---------|----------------|--------|-------------------|--------|
| | TM-MAC [16] | 802.11p | HER-MAC [17] | 1609.4 | APDM [18] | 1609.4 |
| PDR | 0.92 | 0.28 | 0.78 | 0.31 | N/A | N/A |
| Throughput (Mbps) | 0.64 | 0.61 | 84(*) | 78(*) | 0.19 | 0.1 |

(*) Normalized throughput.



Fig. 1. The periodic synchronization intervals.

- 1. MAC protocols using dynamic intervals guarantee a delay constraint of safety messages and maximize the throughput of Service CHannels (SCHs) by dynamically adjusting the intervals according to their own criteria. According to the channel access methods used, the operation of MAC protocols using dynamic intervals can be adjusted by the vehicle itself or by the channel coordinator.
- 2. Compared with IEEE 802.11p, IEEE 1609.4, and MAC protocols using fixed intervals, the simulation results show that MAC protocols using dynamic intervals have better performance in terms of the Packet Delivery Ratio (PDR) and system throughput, as shown in Table 3. For instance, with 50 vehicle/km, PDR in TM-MAC protocol is greater than that of IEEE 802.11p. The heavy packet arrival rate of 25 packets/second throughput in the APDM protocol is more efficient than IEEE 1609.4.
- 3. MAC protocols using dynamic intervals focus on how to adjust the interval lengths in Control Channel (CCH). However, Dedicated Short Range Communication (DSRC) services are split into seven channels. Hence, it is necessary to utilize all seven channels.
- 4. MAC protocols that use Markov chains to calculate the ratio of lengths in CCH depends on a specific system parameter. Nevertheless, this parameter cannot be dynamically adjusted according to changing networks condition, and hence, these protocols cannot guarantee appropriate operation [11].
- 5. In a method where a channel coordinator exists, the channel schedule will be lost when the cluster head moves out of its cluster. Hence, the information for interval lengths in CCH will not be received by any neighbors and the collisions will increase under large speed variance conditions. On the other hand, when the cluster head moves out of its cluster, there are two cluster head election methods [19]: 1) a secondary and alternative cluster head [20–22] and 2) a standby secondary cluster head [23]. In present, dynamic-interval-based MAC protocols assume that there are RSU or a cluster head, which has the lowest ID or in the center of the cluster. Future dynamic-interval-based MAC protocol should combine with VANET clustering approaches to create a stable design of the cluster.

The organization of this paper is presented as follows. In Section 2, we review VANETs standardization. The challenges of MAC design are presented in Section 3. Section 4 describes the reasons for implementing MAC protocols using dynamic intervals. Section 5 introduces a general classification. In Sections 6, 7, and 8 we provide a classification as well as the design of MAC protocols using dynamic intervals. Finally, the conclusion is provided in Section 9.

2. Standardization in VANETs

In this section, we review VANETs standardization. Over the years, VANETs have attracted significant attention in terms of standardization and development.

2.1. Dedicated Short Range Communication (DSRC)

In 1999, the United States Federal Communications Commission allocated one Control CHannel (CCH) and six Service CHannels (SCHs) for applications of VANETs in the 5.9 GHz band. The DSRC standard is covered (within Europe) by national regulations [24, 13] to specify the operational frequencies and system bandwidths. Especially, CCH is dedicated to exchange network management and high priority packets. On the other hand, SCHs are used to transmit another packets, including non-safety packets. IEEE 802.11p [25] was accepted as the MAC, and PHYsical layer (PHY) specification used for VANETs.

2.2. IEEE 802.11p

The IEEE 802.11 standard [26] was enhanced to the IEEE 802.11p standard [25] to support VANETs. The Enhanced Distributed Channel Access (EDCA) functionality is used to ameliorate the Quality of Service (QoS). Safety messages are transmitted with a higher priority than lower priority messages by using one of the four Access Categories (ACs). ACs consist of variable Contention Windows (CWs) and Arbitration Inter-Frame Spaces (AIFS). CWs and AIFS can increase the successful probability that a node transmits real-time messages [27]. As shown in Fig. 1, the periodic synchronization interval of 100 ms is uniformly split into CCH Intervals (CCHI) and SCH Intervals (SCHI). In addition, a synchronization scheme based on Coordinated Universal Time (UTC) is used to efficiently access a channel for VANET equipment at the start of each interval. This standard defines a Guard Interval (GI) of 4 µs, as shown in Fig. 1. The GI is not used for transmission and is necessary for the radio to switch between CCHI and SCHI. As defined in the coordination scheme, all vehicles tune to CCH to send/receive safety packets or private advertisements. If vehicles decide to use their services on a specified SCH channel, they tune to the specified SCHs during their SCHI on the CCH. The multichannel operation for the MAC of the IEEE 802.11p standard, IEEE 1609.4 [28], is proposed to enable the concurrent use of different applications simultaneously.

 Table 4

 IEEE standards for VANET [13 29]

| 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 mes- sages, processing, and message exchange |
| WAVE networking services | 1609.3 | Routing and networking services |
| Multichannel operation | 1609.4 | Multiple-channel operation |
| WAVE PHY and MAC | 802.11p | Enable operation in rapidly varying vehicular environments |

2.3. IEEE 1609 standard and Wireless Access in Vehicular Environment (WAVE)

The IEEE standards P1609.1 to P1609.4 are summarized in Table 4 [13,29]. WAVE allows 802.11p devices to use in the DSRC band. The IEEE 1609 standards include the resource manager, security service for applications and management messages, networking service,¹ and multichannel operation² [29].

We focus on IEEE 802.11p and 1609.4 because they are the standards concerning the design of MAC protocols. IEEE 802.11p cannot address the requirements of VANET applications and cannot guarantee QoS for safety critical messages. On the other hand, IEEE 1609.4 defines multiple channel operation dealing with prioritization, routing, and coordination. In addition, CCH is used to transmit the WAVE Service Advertisements (WSA), safety and control packets.

3. Challenges in MAC design

VANET is one type of MANET with the following special characteristics: variable vehicle density, large-scale networks, predictable mobility model. To provide wireless communications in a VANET environment, MAC layer design must overcome the following challenges to implementing a highly efficient MAC protocol for VANET networks [8,10].

3.1. Rapid topology changes

In a VANET environment, vehicles move with different speeds and thus, vehicles can join or leave a specific cluster. Consequently, the length of CCH is increased when vehicle density is large. Otherwise, when the vehicle density is low, the length of CCH is decreased. Hence, a dynamic interval in MAC protocol is necessary to adapt to rapid topology changes.

3.2. Channel interference

When two transceivers simultaneously operate (e.g., one tunes to CCH and one tunes to SCH), interference occurs due to a parallel usage of the CCH and SCH. This affects the packet delivery ratios of WSA packets and safety messages.

3.3. Time synchronization

In TDMA-based MAC protocols, each vehicle must synchronize at the start of each frame using a Global Position System (GPS) signal. GPSs can provide accurate and real-time information on the



Fig. 2. Example of the hidden terminal problem.



Fig. 3. Example of the exposed terminal problem.

position, direction, and velocity, as well as precise timing. However, GPS cannot be guaranteed to operate correctly in all scenarios.

3.4. Exposed and hidden terminal effects

The hidden terminal problem [30] takes place among three-hop neighbor set when two vehicles concurrently transmit to a third vehicle which is in an overlapping area of transmission range of the transmitting vehicles. As displayed in Fig. 2, the collision occurs when vehicles c and b start to simultaneously send data packets to vehicle a. The exposed terminal problem takes place when a vehicle avoids transmitting packets because another vehicle at its one-hop neighbor is attempting to transmit. Fig. 3 shows an example of the exposed terminal problem. If a transmission between vehicles a and c is taking place, vehicle b is prevented from transmitting to vehicle d. The reason is that the transmission of vehicle *b* will interfere with the transmission of vehicle *a* at vehicle *d*. However, vehicle *d* can receive transmissions from *b* without interference because it is outside the range of *a*. The packets loss, which occurs in exposed and hidden terminal problem, affect the PDR of application messages.

3.5. Lack of central coordination

A channel coordinator is necessary to ensure the control and management of vehicles in adaptive MAC protocol operations. When channel coordinator is not present in a place, each vehicle has to periodically exchange control messages to guarantee fair channel utilization.

3.6. Different QoS requirement

The various applications used in VANETs consist of three types: safety services, traffic management, and user-oriented applications [4,5]. The QoS requirements for these applications vary significantly, such as a strict end-to-end delay, a minimum bandwidth requirement, guaranteed access to the channel. Hence, MAC protocols need the ability to provide the QoS requirements corresponding to various VANET services.

3.7. Scalability

MAC protocols need to broadcast and utilize the wireless channel effectively depending on whether the traffic is dense or sparse.

¹ According to layer 2, 3 and 4 of OSI model.

² According to layer 2 of OSI model.

3.8. Internet of Vehicles (IoVs): MAC protocol challenges

In the 5G era [31], VANETs have evolved into the Internet of Vehicles (IoV) to support ubiquitous and smart services. For instance, Vehicular Cloud Computing (VCC) [32,33] allows vehicles to share their resources or rent them to satisfy the various resource requirements such as bandwidth, storage and computing. Furthermore, Peer-to-Peer (P2P)-based vehicular networks provide a large amount of data carrying heterogeneous media services (such as MP3 music and video news) for moving vehicles [34] in VANETs. On the other hand, IoV is defined as a specific case of the Internet of Things (IoT) to support information sharing and interactions among vehicles, infrastructures, and users. The IoV consists of five types of vehicular communications: V2V, V2R, vehicle-toinfrastructure of cellular networks, vehicle-to-personal devices, and vehicle-to-sensor [35]. Hence, IoV provides various applications such as safety applications, smart and green transportation management (e.g., intelligent traffic scheduling), location-dependent services, and Internet access [36]. A big challenge to design an efficient MAC protocol is to satisfy various QoS requirements because of unreliable links and high vehicle mobility in IoVs.

Many approaches are proposed to design MAC protocol for IoV, or more generally, for VANETs. For instance, MCC-MAC [37] protocol is proposed to improve the reliability of safety messages and supply QoS for various applications in IoVs. Recently, the Third Generation Partnership Project (3GPP) has been standardized for Long Term Evolution (LTE)-based V2X [38,39] (V2X: vehicleto-vehicle, vehicle-to-pedestrian, and vehicle-to-infrastructure/network) to enhance LTE systems to provide communication between vehicle and other objects such as vehicles, pedestrians, and infrastructure in order to receive road safety, controlling traffic flow, and various traffic notifications [40]. However, LTE-based V2X has heavy capacity, delay constrained backhaul links, and the cell overload problem [41]. To enhance the QoS of V2V communications, Device-to-Device Vehicle-to-Vehicle (D2D-V2V)-based IoV can reduce the transmission delay and improve spectrum efficiency [42] since the effective data offloading from a vehicle to infrastructure can be attained through D2D links. Due to the fast mobility features of vehicles, the D2D-V2V links are dynamic and unreliable. In [41], the authors optimized a content dissemination under various QoS requirements by combining the physical and social layer information in IoV.

Although MAC protocols have been developed for IoV, there are new technical challenges as follows.

- Dynamic topology: Since IoV is an evolution of VANETs, the high mobility and rapid change of topology cause frequent network disconnection and link failures.
- Delay constraints: Many IoV applications have restricted differential time delays. Safety requires that it should be delivered within a short delay constraint.
- Multihop communication: In IoV, a weak connection limits information forwarding or dissemination [43].
- 4. Variable network density: Because IoV usually involves a very large number of vehicles, high mobility and frequently changing topology, the MAC protocol should be adjusted according to network conditions [44].
- 5. Reliability requirements: The most important requirement for transportation and driving-related applications is reliability.

4. Why do MAC protocols use dynamic intervals schemes?

IEEE 802.11p divides the channels (CCH/SCHs) into two intervals (CCHI and SCHI) of 50 ms each in a 100 ms synchronization interval. The transmission of safety messages or WSA messages are performed by all vehicles operating on CCH. During SCHI, sender and receiver switch to a specifically chosen SCH to exchange data. IEEE 802.11p can decrease the transmission delay and enable concurrent transmission [45]. However, when the vehicle density is high, the 50 ms CCHI will not be sufficient for disseminating all of the safety messages. Furthermore, when the vehicle density is low, the restricted CCHI is underutilized [16]. Consequently, a fixed interval makes the throughput decrease under dynamic traffic conditions [16,9,46,18]. Considering the QoS requirements in VANETs, safety and non-safety applications are considered as delay- and throughput-sensitive applications, respectively [47].

During dense traffic conditions, the fixed length of CCHI cannot provide sufficient bandwidth when large safety and control messages are transmitted. When the vehicle density is sparse, transmissions on the CCH will occasionally waste channel resources, whereas sufficient bandwidth resources on the SCHs cannot be obtained for some large bandwidth consuming applications [9,48]. In addition, for single-radio devices, a safety message is dropped when its lifetime is greater than the delay constraint [49].

MAC protocols, that use dynamic interval schemes to dynamically adjust the intervals according to their own criteria, can guarantee the transmission of safety packets and improve the system throughput. Using dynamic intervals provides the MAC protocols with significant benefits, which are summarized as follows:

- Improved throughput of non-safety applications and the PDR [10].
- Improved channel utilization [61,17].
- Reduced slot collision and merging collision rate compared with TDMA MAC protocols [71,72,70,16].
- Reduced time delay of service packets [56,55].
- Guaranteed QoS for real-time applications [53,18].
- Fair channel access with centralized channel assignment methods [69,68].

Besides, MAC protocols using dynamic intervals have the common challenges in MAC design in Section 3. In addition, dynamicinterval-based MAC protocols are characterized by dynamic adjusting the length of interval. Hence, the challenges in dynamicinterval-based MAC protocols implement a highly efficient MAC protocol for VANET networks as follows.

- In a VANET, the vehicle density frequently changes with time and space. Hence, the optimized CCH, which is computed based on vehicle density, should be performed under more traffic conditions.
- A safety interval including beacon transmissions should be calculated considering characteristics of beacon transmissions, such as rate and power.
- When vehicles are moving at high speed, the requested service transmitted by vehicles can be lost because of a limited time period.
- Simulations need to take into account urban scenarios under different traffic conditions such as traffic lights, buildings, and junctions.
- Dynamic-interval-based MAC protocols using the centralized channel assignment method require stability of the cluster. If the cluster head is absent, the centralized management will fail and packet collisions will occur.

5. MAC protocols using dynamic intervals in VANETs

Considering MAC protocols in VANETs, various MAC protocols are designed with different benefits such as the TDMA-based MAC, the contention-based MAC, and hybrid MAC protocols. The TDMA-based MAC protocols, such as those in [74–81,71,72,82,70,83], can support an efficient channel utilization, a reliable communication,



Fig. 4. Classification of MAC protocols using dynamic intervals according to access channel methods.



Fig. 5. Classification of MAC protocols using dynamic intervals according to methods and metrics.

and deterministic access time even with a large traffic load, and QoS requirements. On the other hand, contention-based MAC protocols, e.g., [25,84,85,9,53], allow vehicles which have data to randomly attempt to access 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, (e.g., [61,17,62,63]) have tried to combine contention-based and contention-free mechanisms into a single mechanism to increase QoS and system throughput.

According to [8–10], MAC protocols using dynamic intervals are split into three categories, depending on the channel access method: 1) contention-based MAC protocols, 2) contention-free MAC protocols, and 3) a hybrid between contention-based and contention-free MAC protocols. All three categories are presented in Fig. 4. Each method and metric can be used to optimize different aspects, hence we classify the protocols into two categories: self-adjustment and coordinators. From another point of view, we can categorize MAC protocols by vehicle density and traffic load metrics, as shown in Fig. 5.

6. Contention-free MAC protocols using dynamic intervals

One approach of MAC protocols that allow vehicles to access the CCHI using predetermined time slots is called contention-free MAC protocol. Most of the MAC protocols divide CCH and SCH into periodic frames of 100 ms, according to the synchronization interval in IEEE 802.11p and 1609.4. Then, each frame is split into fixed time slots. One of the ideas of MAC protocols using dynamic intervals is enhanced VeMAC [79] protocol. VeMAC protocol divides each frame into three sets: *L* and *R* according to the direction of the moving vehicles, and *F* which is associated with the RSUs. VeMAC outperforms ADHOC MAC [75] using a TDMA mechanism in terms of the rate of transmission collisions and throughput. However, vehicle density in a highway scenario is not uniformly distributed. Thus, the number of time slots needs to be adjusted in proportion to vehicle density. In addition, when the vehicle density is high, merging collision problems still occur. Consequently, contention-free MAC protocols using dynamic intervals are designed to improve VeMAC, which adapts to different vehicle densities in VANETs.

6.1. Methodology

There are two main methodologies that are used: 1) directionbased and 2) coordination-based. First, the ATSA [71,72], CFR [70], and TM-MAC [16] protocols are proposed to help the VeMAC protocol adapt to dynamically exchanging vehicular traffic conditions. Second, CBMAC [73] is used to adjust the cluster size controlled by the Cluster Head (CH).

6.1.1. Direction-based method

In contention-free MAC protocols, each vehicle is required to have GPS device, which provides two main functions: providing status (the vehicle location, speed, and direction) and time synchronization. Corresponding to these services, three protocols are proposed according to vehicle speed, the order of the reserved time slots, and the channel coordinator in order to adjust the frame length or the length of the time slots, as shown in Fig. 6.

6.1.1.1 Vehicle speed The CFR [70] was proposed to solve the merging collision problem. After collecting two-hop neighbor information, including their speeds, each vehicle calculates the average speed \bar{v} and the relative speed $\Delta v = v - \bar{v}$ between its speed (v) and the average speed. According to v and Δv , each direction is divided into three-speed levels, *Low*, *Medium*, and *High*, as shown in Fig. 6. In CFR protocol, the method used to adjust the number of time slots is based on both vehicle speed level and number of vehicles that move at that speed. Using these three



Fig. 6. Vehicle density-based methodologies in the same direction.

speed levels, CFR can mitigate the effects of the merging collision problem which occurs in vehicles moving at different speeds. CFR also significantly reduces the access delay compared with VeMAC and 802.11p. However, CFR is not suitable for scenarios with large speed variance when each vehicle frequently changes its speed.

6.1.2. Order of reserved time slot The ATSA [71,72] enhances the VeMAC protocol when vehicle densities moving in each direction are different which is common in highway scenarios. Based on the two-hop neighbor's slot allocation information for each vehicle, each vehicle can use a different frame length. The binary tree algorithm is employed to decide the frame length to be doubled or shortened. Two thresholds, U_{min} and U_{max} [71], are defined to minimize or maximize the frame length. The ATSA protocol can improve channel utilization when the vehicle density is low and provide channel access fairness in case of high vehicle density. The simulation results show that ATSA reduces the number of merging collisions and has a minimal time delay compared with the ADHOC MAC [75] and VeMAC protocols. However, ATSA has some major drawbacks, such as using a single channel, the simple two-lane highway scenario, and poor choices for U_{min} and U_{max} .

6.1.1.3. Cluster head Sharath Babu et al. [16] proposed TM-MAC protocol to decrease the number of merging collisions and increase the PDR as compared to VeMAC. In TM-MAC, the free time slots can be grouped together by the leader for use in the SCH channel. TM-MAC categorizes packets transmitted in time slots into two types: 1) *Type A*, used by all vehicles, 2) and *Type B*, used only by the leader, as shown in Fig. 7. Each node selects a short identifier (SID) of size 1 byte to reduce the transmission overhead. To elect a leader, the Leader Quality Indicator (LQI) is calculated for each vehicle to ensure that the set of vehicles remains stable for a long time. The LQI is given by



(a) The Type A structure used by all vehicles.

|--|

(b) The *Type B* structure used only by the leader.

Fig. 7. Packet structure for TM-MAC protocol.

$$LQI_{i} = \frac{max\left(\sum_{j=1/slots}^{m} C_{j}, 1\right)}{\sum_{k=0}^{m} |(R_{k} - R_{i})|},$$
(1)

where C_j is a counter at the *j*th slot, and *m* is the sum of time slots. Note that C_j increases by 1 whenever that vehicle has served as a leader. R_k is the relative speed of the *k*th vehicle in a group and R_i is the velocity of vehicle *i* [16]. The node with the highest *LQI* becomes the leader and all information will be included in the *Type A* packets of each vehicle.

The leader of each group (also called the cluster head) plays a role in coordinating with members and disseminating protocol information for the schedule (*SED*) field in the *Type B* structure. The information of the number of time slots used by vehicles moving to the left (*SL*) and to the right (*SR*), and SED fields are included in the *Type B* packet transmitted by the leader, as shown in Fig. 7b.

The operation of the TM-MAC protocol can be summarized as follows.



(a) Step 0: Initialization.



(b) Step 1: Slot scheduling and leader election.



Fig. 8. Operation of TM-MAC protocol.

- 1. Step 0: Similar to VeMAC, each frame used in CCH is divided into three sets: Left, Right, and RSU. The CCHI and SCHI are 50 ms, as shown in Fig. 8a.
- 2. Step 1: Each vehicle will broadcast Type A packets in its reserved time slot. The LQIs are included in these packets. If only vehicle *x* is moving on the road, it becomes the cluster leader after it has chosen a randomly available time slot. If vehicle x has the highest LQI, it becomes the cluster leader. Otherwise, it becomes a cluster member, as shown in Fig. 8b.
- 3. Step 2: After a cluster leader has been elected, the leader will disseminate the protocol control information embedded inside its SEQ field in the Type B packets. TM-MAC allows free time slots to be grouped together and used for SCH. To do so, the leader has to reallocate vehicles (occupied slots) to the set of used time slots such that the remaining free slots are grouped behind in synchronization interval [16].

The simulation results show that TM-MAC can reduce the number of vehicles that are involved in merging collisions and that TM-MAC outperforms VeMAC and IEEE 802.11 in terms of the PDR and the throughput over SCH. However, when the CH is absent, the SED packet is lost. Hence, vehicles without management information will randomly broadcast packet with high collision probabilities.

6.1.2. Coordination-based method

Gunter et al. [73] proposed the CBMAC protocol which allows cluster head to assign bandwidth to its members. All vehicles will broadcast HELLO packets to select the Cluster Head (CH). The smaller the weight factor, the better chance a node becomes a cluster head. If a vehicle receives a HELLO packet transmitted by a CH, it will belong to that CH. In CBMAC, the medium access is organized into frames, as depicted in Fig. 9.

According to the TDMA frame structure. CH must use the first time slot to periodically broadcast the HELLO message (CH-HELLO). CH-HELLO information consists of the ID of the CH and the start



Fig. 9. The cluster-based medium access control protocol [73].

of a new frame. The next slot is also used by the CH to broadcast the slot assignment information for cluster members. Based on this packet, each member will transmit during its identified time slot. The remaining time slots are divided into two phases: the data link and the random access phase. Each vehicle will transmit data messages that include its information during the data link phase. The length of this phase can be adjusted by the CH depending on the number of cluster members. This information is included into a slot assignment message in slot #2 that is transmitted by the CH. However, the authors noticed that the phase length is fixed to 10% of the frame length in order to guarantee stability. CBMAC cannot handle merging collisions and hence, CBMAC cannot apply for the vehicles which are moving in different directions.

6.2. Summary and issues

The contention-free MAC protocols using dynamic intervals mentioned thus far are summarized in Table 5. We now discuss issues and promising future research as follows.

- Multichannel operation: Contention-free MAC protocols using dynamic intervals only consider a single channel (control channel). It is not suitable for DSRC standard in which the frequency band is partitioned into seven channels. Therefore, it is necessary to dynamically adjust all seven channels.
- Variable vehicle densities: Most contention-free MAC protocols using dynamic intervals assume that a fixed number of vehicles can access CCH at a given time. Hence, designing

Comparison of contention-free MAC protocols using dynamic intervals.

| | ATSA | CFR MAC | CBMAC | TM-MAC |
|-------------------|--|---|---|--|
| References | [71,72] | [70] | [73] | [16] |
| Published | 2013 | 2014 | 2007 | 2016 |
| Assignment | Distributed | Distributed | Centralized | Centralized |
| Coordinator | - | - | Cluster-head | Cluster-head |
| Optimal objective | Number of time slots | | | |
| Solution method | Binary tree | The relative speed | Number of cluster Member | Number of cluster Member |
| Metric | Direction | Driving statuses | Broadcast slot assignment mes- sage | Broadcast Type B packet [16] |
| Benefits | – Reduces slot collisions – Minimizes time delay – Maximizes channel utilization | Adaptive and reliable Reduces reservation delay and collision rate | – Solves hidden terminal problem – Provides a fair medium access | Reduces merging collision rate Increases reliability and throughput over SCH |
| Drawbacks | – Limited to two-lane highway scenarios – Optimal values are not determined | Require GPS positioning for current vehicle speed | Not compatible with DSRC Cannot handle merging collisions | - When the cluster leader leaves, the channel access schedule will be lost |
| Compared with | – VeMAC – ADHOC | – VeMAC – IEEE 802.11p | – IEEE 802.11p | – VeMAC – IEEE 802.11p |
| Simulator | MATLAB | N/A | [86] | OMNET++ and SUMO |

contention-free MAC protocols must handle both sparse and dense mobility to efficiently apply to the real scenario with variable vehicle densities.

- Large speed variance: When vehicles are moving at high speed, the requested service transmitted by vehicles can be lost because of a limited time period. Future MAC protocols must consider and address the fairness problem that frequently occurs when the relative velocities of vehicles have high variance.
- Mobility scenario: All contention-free MAC protocols fail to take into account urban scenarios under different traffic conditions such as traffic lights, buildings, and junctions, with the exception of [16]. Future MAC protocols must be suitable for both highway and city scenarios.

7. Contention-based MAC protocols using dynamic intervals

Unlike contention-free MAC protocols, contention-based MAC protocols allow the vehicles to randomly access the channel if they have data to transmit. In contention-based MAC protocols, each Synchronization Interval (SI) is split into two fixed intervals: the Control CHannel Interval (CCHI) and the Service CHannel Interval (SCHI). Two fixed intervals cannot give real bandwidth to transmit both safety and non-safety packets under dynamic traffic conditions. Specifically, the control channel is used only for safety applications that include exchanging control packets, such as WSA or Request For Service (RFS). Then, the length of the CCHI can be adjusted depending on the traffic conditions, such as saturation throughput, vehicle density, and end-to-end delay.

7.1. Methodology

Based on the WSA and safety packet transmissions, many methodologies have been conducted such as DID-MMAC [45], MP MAC [51,52], VCI MAC [9], Q-VCI MAC [53], DSI [57], and APDM [18]. Markov chain methods are widely used in this area. Hence, we summarize a group of Markov chains methods and draw the comparison with other methods.

7.1.1. Markov chains method

According to IEEE 1609.4 and 802.11p standards, the safety packet is defined to have higher priority than other packets. In addition, the probability of successful transmission occurring on the channel and the average time for successful reservations can be calculated via the relevant Markov chains and backoff window sizes [27]. To compute the optimized interval, most (not all) contention-based MAC protocols using Markov Chains (CMMC) are based on the condition which is defined as the number of reservations made on the CCHI equivalent to the number of service packets transmitted on all SCHs. Generally, CCHI in CMMC can be split into two main intervals: the control and the Markov chain interval, as shown in Fig. 10. We classify the Markov chain methods into two main methods: Markov chains for WSA transmission and multi-priority Markov chains.

7.1.1.1. WSA transmission Under saturation throughput, the VCI [9] allows the length of the CCH to be adjusted according to the traffic load. The optimal CCH is calculated by the RSUs. Each RSU needs to know the current vehicular environment and needs to broad-cast VCI packets, as shown in Fig. 10. VCI MAC can enhance the saturation system throughput and decrease the transmission delay. Furthermore, VCI MAC also guarantees the transmission of safety and control packets. However, the VCI MAC cannot support different applications which have various QoS requirements.

The Q-VCI [53] was proposed to improve the VCI MAC under different applications. In Q-VCI, each node calculates the minimum CWs for different service classes and then uses this CW to attempt to access the CCH. Hence, the Q-VCI MAC scheme can operate in multi-rate multichannel environment. The authors presented the Markov chain and stochastic processes to obtain the minimum CWs for different applications as well as the optimal CCHI and SCHI. Q-VCI MAC can provide different throughput and delays depending on different applications. It also outperforms VCI MAC in terms of the channel utilization and saturation throughput. Note that the length of the safety interval in VCI is constant, but can be adjusted in Q-VCI based on the throughput obtained for SCH.

On the other hand, the DCI MAC [54] was proposed to adjust the intervals of CCHI and SCHI based on the reservation time for WSA packets. In DCI MAC, the length of CCHI is calculated to maximize the number of data packets that can be transmitted on SCHI.



Fig. 10. Various methodologies using the Markov chains method.

The DCI MAC improves the throughput under different network traffic conditions compared to VCI and WAVE MAC.

One known problem in the Markov chains for WSA transmission in CMMC is the delay of safety messages is not guaranteed with the restrictions for the safety applications in [6]. The reason is that if a node has a safety message that arrives in the safety interval, it must wait for the next frame to transmit it.

7.1.1.2. Multi-priority transmission To solve the problem of Markov chains for WSA transmission in CMMC, multi-priority Markov chains methods have been proposed. The CCH in CMMC using multi-priority Markov chains is split into two intervals: the control and the multi-priority Markov chains intervals. Alternatively, one can also use three intervals: the control interval, the multi-priority Markov chains interval, and the ACKnowledgment (ACK) interval according to different protocols.

To improve the VCI under the highway scenario, the CA MAC [46,50] have been proposed. The optimized interval is calculated by the RSUs or the platoon, and this information is broadcast at the beginning of the CCHI. Here, the platoon is a group of vehicles consisting of a leader vehicle and its follower vehicles [87]. In CA MAC, CCHI is partitioned into three intervals: the safety interval (SAFI), the WSA interval (WSAI), and the ACK interval (ACKI), as shown in Fig. 10. In CA MAC, the length of SAFI is designed to guarantee that the all vehicles transmit their safety packets. In addition, the length of ACKI is also designed to ensure the senders are aware of successful transmissions of their safety packets. Finally, the length of WSAI can be optimized via the RSUs or platoons. In CA MAC [46], the WSA packets are classified into two types: WSA packets broadcast by platoons (WSAP) and WSA packet broadcast by the ordinary vehicles (WSAO). Note that the WSAPs have higher priority. Multi-priority Markov models



Fig. 11. DID-MMAC protocol [45].

for WSAP and WSAO are proposed to obtain the optimal length of WSAI according to dynamic networks. The CA MAC improves the throughput for service channel by dynamically adjusting the duration of CCHI and SCHI. The authors have studied the connectivity probabilities for V2V and V2I communications under consideration of platoon-based VANETs scenarios. However, the platoons strategically require an area to place antennas with large transmission ranges, thus this system is expensive.

To guarantee that the safety packets can be transmitted when they arrive at the nodes, some approaches allow the WSA packets and safety packets to broadcast in the same interval. During CCH, most of these protocols sort packets into two priority categories using different AC. The higher priority AC_1 is dedicated to broadcast event-triggered safety applications, and a lower priority AC_2 is used to exchange other control packets (such as periodic packets and WSA packets).

In the first case, WSA/ACK, RFS/ACK and safety packets are transmitted during the same multi-priority Markov chains interval, as shown in Fig. 10. The APDM [18] was proposed as an adaptive multichannel MAC for traffic conditions. The channel coordinator is elected as RSU or Optimizing Node (OpN) that has the minimal MAC address. At the start of each CCHI, the OpN will broadcast the Optimal Ratio Packet (ORP) including the optimal duration for CCHI. For the OpN, the optimized length of CCHI is processed as follows.

- Detect the channel condition and calculate the number of neighbors by counting the received packets.
- 2. Count the number of the low and high priority packets.
- 3. Compute the busy or idle probability of the channel.
- 4. Derive the optimal CCHI based on the Markov chain and the M/M/1 queue model.

The APDM MAC protocol ensures timely and reliable delivery of the safety packets and improves the throughput for service channels. However, the channel access schedule is lost when the OpN is absent due to the fast mobility features of vehicles.

In the second case, the ACK is cut-off into the independent interval. WSA and safety packets will be transmitted during the same intervals, as shown in Fig. 10. The MP MAC [51,52] was proposed to ensure prioritized transmission of the safety packets. At the begin of the frame, the RSU must broadcast an MP packet. Then, all vehicles in its coverage receive MP packet and know the optimal CCHI and ACKI. During the random access interval (RAI), vehicles transmit either safety packets or WSA packets. When the ACKI starts, the vehicles send ACK packets during the time slots which are allocated by the RSU. The authors used a multi-priority Markov chain with different priorities to calculate the optimal CCHI. MP MAC can support higher saturation throughput of the CCH as compared to WAVE MAC. In addition, MP MAC protocol can adapt to various traffic loads. However, the authors did not study multi-hop communications.

7.1.2. Other methods

7.1.2.1. Traffic data Based on studies conducted in the Berkeley Highway Lab (BHL) [88], the DID-MMAC [45] improved the broadcast reliability and the average delay of safety packets. DID-MMAC is classified into three phases: the Service Announcement Phase (SAP), the Beacon Phase (BP) and the Peer-to-peer Reservation Phase (PRP), as shown in Fig. 11. SAP uses a constant Contention Window (CW) to transmit a WSA packet. BP allows each vehicle to broadcast its safety/vehicle status. PRP is used to exchange the lowest priority packets, compared to WSA and Beacon packets. DID-MMAC can reduce transmission delay of safety packets and improve the system throughput. However, timing signals for switching synchronization between SAP, BP and PRP interval are not studied.

7.1.2.2. End-to-end delay Yassine Maalej et al. [56] proposed the AAA Protocol. AAA not only computes the optimal length of CCHI but also maintains a default Synchronization Interval (SI). If a new vehicle moves into the RSU's coverage, it has to send both Vehicle Cloud (VC)³ packet and beacon message (BSM). A BSM is used to calculate the average end-to-end delay. In addition, RSU based on received BMs knows the number of vehicles in its coverage. Based on VCs and BMs, the RSU will broadcast information of the average number of sent BSMs and the average end-to-end delay of the received BSM to vehicles. In AAA, RSU plays an important role in computing the average effective CCH utilization during the current CCHI [56]. Compared with IEEE 1609.4, the AAA significantly increases the throughput of the VC and reduces both the average number of dropped virtual machines and the average end-to-end delay for non-safety applications.

7.1.2.3. Vehicle density and context Considering vehicle density and safety information, Sharath Babu et al. [55] proposed the CAVI-MAC protocol. The authors classify the safety packets into two different types: 1) event driven packets and 2) periodic packets. In CAVI-MAC, although both of these types use the same category (AC_4), event driven packets get associated with the highest priority. The location information including a vehicle's speed, position, and direction of movement is stored in periodic packets. Along with this information, the authors added four more fields: 1) Event Occurred (EO), 2) Successfully Received (SR), 3) Resent (RS), and 4) Length Index (LI), as shown in Fig. 12. The four fields are only included in periodic messages, and not in event-driven messages. Based on the periodic messages, the CAVI-MAC adjust

³ Vehicle cloud is implemented by consolidating the OBUs of geographically colocated parked vehicles [89].



Fig. 12. Packet structure of the CAVI-MAC protocol.



Fig. 13. Structure of the CAVI-MAC protocol [55].

the length of CCH (*CCH*_{len}) depending on the neighborhood density and the context, as shown in Fig. 13. Compared with DSI, VCI, and IEEE 802.11p, CAVI-MAC provides advantages in terms of the packet delivery ratio by providing a virtual interference-free environment for the propagation of event-driven messages.

7.1.2.4. Transmission range Relating to the hidden terminal problem, Yoo et al. proposed the DSI [57]. DSI allows CCHI to dynamically adjust its length by considering the presence of hidden vehicles. The CCHI is computed based on the number of vehicles including the hidden vehicles. In DSI, the hidden vehicles are considered to be located within interference range r_i of the destination and outside of carrier sensing range r_c of the sender. A collision, thus, happens when a receiver is receiving a packet and a hidden vehicle wants to concurrently transmit. Specifically, vehicles will share the safety interval if the distance between them and vehicle *i* is smaller than the spatial reuse distance d_{sr} . This safety interval is called the Extended Contention Domain (ECD). DSI divides the street into cells. To organize the cell, each vehicle *i* must measure the number of vehicles which are located within i's transmission range. Hence, DSI based on the number of vehicles in the ECD can calculate the optimal safety interval by considering the average contention delay and the link latency. Although the DSI can provide a better PDR for periodic messages (such as the beacon messages), DSI requires the exact GPS position and uses a digital map to calculate the cells. All of this makes the DSI system very expensive.

7.1.2.5. Optimal message generation rate method On the other hand, Wang et al. [58] proposed the use of a variable interval mechanism (a.k.a DAN) to improve the system throughput based on message generation rate of the safety applications. For the simulation, the authors randomly generated k 100-byte packets within each CCHI, and the simulation results show that in order to maintain 90–95% reliability for safety messages, k should be changed according to the synchronization interval. In DAN, although adaptive schemes can achieve the maximal message generation rate of DSRC, the authors did not discuss how the interval is dynamically varied.

7.1.2.6. Trigged CCHI multichannel MAC protocol TCM-MAC [59] is proposed to intelligently utilize time by switching to CCHI when required. It can dynamically adjust the length of CCHI after each transmission of safety message, depending upon whether a safety message is in the queue or not [59]. Control packet such as Cluster Member Request (CMR) and Cluster Head Request (CHR) are used to solve the hidden terminal problem. TCM-MAC is designed based on cluster-based method, which consists of two communication intra-cluster and inter-cluster communications. Hence, different clusters will have different CCHI and SCHI depending upon the situation.

Since TCM-MAC [59] can switch to CCHI from SCHI whenever required, the performance of this scheme in terms of packet deliv-

ery ratio, throughput and safety message delay in comparison to CAVI-MAC [55] and IEEE 802.11p. However, the authors did not study the switching time when the cluster head and members switch to CCHI from SCHI.

7.1.2.7. Dynamic token-based MAC protocol One such safety-related application is the use of beacon packets, which include the vehicle's position, speed, and acceleration [6,7] and are broadcast periodically by each vehicle. The token-based MAC protocols,⁴ which is able to transmit beacons with time constraints, are proposed in [91] and [92]. The token-based method does not require synchronization and extra overhead for scheduling or control data [92]. The token-based MAC protocol used a token for exclusive access to the channel and keeps requesting re-transmissions from nodes [92]. Dynamic token-based MAC protocol [91] can automatically adapt itself to changes in the network such as platoon size or beacon generation frequency. The dynamic token-based MAC protocol operation can be summarized as follows.

- 1. Vehicles temporarily reside in each other's vicinity from different groups (rings), which try to keep the token circulating between ring members as much as possible to clarify who has the privilege to access the channel [91].
- 2. The node holding the token transmits its beacon and selects another ring member as the token holder by accounting for its transmission urgency, measured as time proximity to the beacon delivery deadline for that node [91].
- 3. During that process, other ring members remain merely listening to beacon transmissions to find out when their turns to transmit beacons takes place. This is detected based on the received token data, which is piggybacked on the beacon itself [91].

Moreover, dynamic token-based MAC protocol outperforms IEEE 802.11p in terms of beacon delivery ratio, and that the improvement ratio is increased as the vehicle density and beacon generation increase. However, in this survey, we focus on the dynamicinterval-based MAC protocols and the schemes are out of the scope of this paper.

7.2. Summary and issues

All contention-based MAC protocols using dynamic intervals are summarized in Table 6. We now discuss issues and promising future research as follows.

- Dynamic VANET environment: Contention-free MAC protocols based on Markov model to calculate the CCHI. However, parameters used in their algorithms cannot be dynamically adjusted according to the changing network conditions. Hence, under changing VANET scenarios, the optimal CCHI is computed based on fixed parameters which cannot be guaranteed for all vehicles to transmit their packets. In the future, a dynamic interval ratio independent of such parameters should be considered.
- Traffic condition: In a VANET, the vehicle density frequently changes with time and space. Hence, the optimized CCH, which is computed based on vehicle density, should be performed under more traffic conditions.
- Dynamic beacon transmissions: The characteristics of beacon transmissions, such as rate and power, can affect the total load of the beacon traffic [93,15]. Hence, a safety interval including

⁴ A "token" refers to the privilege given to an individual vehicle [91].

Comparison of contention-based MAC protocols using dynamic intervals.

| | Q-VCI | DCI | CA MAC | APDM | MP MAC |
|-----------------------------|--|--|--|---|---|
| Refer- ences | [53] | [54] | [46,50] | [18] | [51,52] |
| Pub- lished | 2011 | 2013 | 2015 | 2016 | 2012, 2013 |
| Coordi- nator | RSU | | RSU or platoon | RSU | |
| Optimal objective | Contention window and CCHI | Maximum number of service packets and CCHI | ССНІ | ССНІ | ССНІ |
| Solution method | Markov and different service | Markov chain | Markov chain for WSAO and WSAP transmissions and connectivity probability | Markov chains with ACK transmissions and M/M/1 queue | Markov chains without ACK transmissions |
| Metric | Service classes | Heavy traffic load | WSA classes | Safety traffic broadcasting and WSA transmission | AC_1 and AC_2 |
| Benefits | – Ensure the different QoS requirements – Provide high saturated throughput | - Improve the system throughput based on various traffic conditions | – Improve the system throughput | – Decrease the safety transmission delay – Improve the throughput for SCHs | – Provide High channel utilization – Low safety transmission delay |
| Draw- backs | – Resources are not fully utilized | – The safety transmission delay is not studied | – The leaders require an antenna with a large transmission range | - When the OpN is absent, the channel access schedule is lost | Under saturation conditions, the inter arrival time is not taken into account |
| Com- pared with | VCI | VCI and WAVE MAC | VCI and WAVE MAC | IEEE 1609.4, VCI | 802.11 EDCA and WAVE MAC |
| Simula- tor | NS-2 [90] | N/A | MATLAB | NS-3 [90] | NS-2 |
| | DID-MMAC | AAA | CAVI | DSI | DAN |
| Refer- ences | [45] | [56] | [55] | [57] | [58] |
| Pub- lished | 2009 | 2016 | 2015 | 2012 | 2008 |
| | Distributed | Centralized | Distributed | | |
| Channel coordina- tor | - | Road side unit | - | - | - |
| Optimal objective | Peer-to-peer reservation phase | ССНІ | | | |
| Solution method | Equation [45] | Algorithm [56] | Equation [55] | Equation [57] | Equation [58] |
| Metric | Network traffic load | End-to-end delay and average packets | Vehicle density and context | Average contention delay and the link latency | Generator randomly generates packets |
| Benefits | – Reduce safety message delay – Flexible throughput | Increase system throughput Reduce dropped virtual machines Reduce delay of uploaded packets | – High packet delivery rat: – Address interference from hidden terminals | io – Increase beacon delivery m ratio | – Optimize safety message generation |
| Draw- backs | – The SCHs utilization is not fully explored | – Vehicles moving with large speed variance cannot operate AAA | The effect of beacon transmission is not considered | – This system used GPS and Digital Map is required | – The procedure for dynamic adaptation of CCHI was not mentioned |
| Com- pared with | WAVE MAC | IEEE 1609.4 | IEEE 802.11p, VCI, DSI | Safety Interval without Hidden nodes (SIH) | IEEE 1609.4, 802.11 |
| Simula- | N/A | NS-3 | NS-2, MATLAB and SUMO | NS-2 | N/A |

beacon transmissions should be calculated considering these values.

8. Hybrid MAC protocols using dynamic intervals

The contention-free MAC protocol can provide fair channel and reliable and efficient packet transmission without collision. On the other hand, the contention-based MAC protocol supports variable packet size. The hybrid MAC protocol tries to combine contentionfree and contention-based mechanisms into a single mechanism to improve QoS and decrease the collision rate. All hybrid protocols divide the CCHI into two periods: the random access period and the contention-free access period. According to channel access schedule created in the random access period by all vehicles, they will transmit HELLO packet during their time slots in the contention-free access period According to the channel assignment methods, we divide the hybrid MAC protocols into two categories: distributed and centralized channel assignment methods.



Fig. 14. Methodologies of the hybrid MAC protocols using TDMA and CSMA.

8.1. Distributed channel assignment methods

V2V is one type of communication in a VANET. The vehicle usually collects information on its one-hop and two-hop neighbors, including the locations, speeds, and movement directions. Based on this information, vehicles in the one-hop neighborhood can adjust the length of the contention-free interval and hence, they can increase the throughput of SCH and decrease the delay in safety packet transmission.

8.1.1. Methodology

After each vehicle has collected information on its one-hop and two-hop neighbors, if there are available time slots, the vehicle will move its time slot to reduce the length of the contention-free interval. On the other hand, each vehicle can predict the number of one-hop neighbors based on its transmission range or channel access delay. We can classify these MACs into three main categories: the available time slot (as shown in Fig. 14), the transmission range, and the MAC-to-MAC channel access delay.

8.1.1.1. The available time slot method

8.1.1.1.1. Self-switching method Lu et al. [61] proposed the DM-MAC protocol. In DMMAC protocol, the safety packets under var-

ious traffic condition guarantee transmission delay and provide collision-free transmission. In DDMAC, CCHI is divided into two periods: the Adaptive Broadcasting Frame (ABF) and the Contentionbased Reservation period (CRP), as shown in Fig. 14. The DMMAC protocol allows for a dynamic Adaptive Broadcasting Frame Length (ABFL) depending on its neighbors. Each vehicle easily adjusts its ABFL in the CCHI, taking values [ABFLmin; ABFLmax], based on the Adaptive Broadcasting Implementation Protocol (ABIP) [61]. If a vehicle wants to change to a new time slot to reduce the ABFL, it announces its ID and switches to a BUSY status in the corresponding time slot. If all vehicles confirm its ID and BUSY status in that time slot, it successfully changes to the new time slot. In Fig. 14, vehicle f wants to change to time slot #2 and so vehicle f adds f and BUSY status for time slot #2 to its Frame Information (FI) and transmits in its current time slot. After one frame duration, all one-hop neighbors broadcast the FIs, including f, and if there is a BUSY status in time slot #2, vehicle f successfully changes to time slot #2 during the next sync interval. However, simulations of DMMAC are carried out on straight road scenarios with a smaller number of time slots than the number of vehicles. In addition, the presence of access and merging terminal problem, the performance of DMMAC degrades under various traffic conditions.

VanDung et al. [62] proposed the HTC-MAC protocol to enhance the throughput for the control channel in HER-MAC. In HER-MAC [17], during CCHI, there are three types of packets: WSA, HELLO, and SWITCH packets which are described in the next section. HTC-MAC eliminates HELLO and SWITCH packets in CP, as shown in Fig. 14. Like HER-MAC and DMMAC, HTC-MAC considers moving the occupied time slot of the last vehicle to reduce the length of RP. HTC-MAC is different from HER-MAC and similar to DMMAC in that a vehicle *x* transmitting at the end of the time slot will include a new time slot in an announcement packet (ANC) to broadcast during its transmitting time slot. When all one-hop neighbors include x and its new time slot into their ANCs, vehicle x moves successfully to the new time slot. Simulations show that during heavy traffic conditions, HTC-MAC outperforms HER-MAC. However, the authors only simulated HTC-MAC compared with HER-MAC. HTC-MAC also requires large overhead due to the periodic broadcasting of ANC messages.

8.1.1.1.2. Switch packet transmission method Similar to the DM-MAC protocol, HER-MAC [17] was proposed to develop and evaluate the MAC for VANET. Different from DMMAC, both CCHI and SCHI are divided into a Reservation Period (RP) and a Contentionfree Period (CP). RP constitutes time slots, which is used to transmit HELLO packets, as shown in Fig. 14. If a new vehicle attempts to occupy an available time slot in RP, it will attempt to transmit HELLO packets in CP, including its reserving time slot. If there are no collisions, it will successfully occupy that time slot. Otherwise, it will try to attempt to transmit the HELLO packet again in CP. A sender sends a Request For Service (RFS) or WSA packet for the required service and a reply is received through ACK and RES, which are sent by the receiver and sender, respectively. The finite number of time slots in RP is changed into the adaptable number of time slots, which are occupied by vehicles. HER-MAC considers the vehicle that is transmitting at the last time slot to reduce the length of the RP. The authors assume vehicle x is transmitting at the end of the time slot. Vehicle x, based on Frame Information Map (FIM), knows the available time slots that it can move to. When vehicle x wants to move, it will attempt to broadcast the SWITCH packet including its old time slot and new time slot in the CP. If all one-hop neighbors confirm that the time slot is BUSY, vehicle x successfully moves to the new time slot. All one-hop neighbors will update their FIMs. The vehicle that is transmitting at the end of time slot will continuously do so until it cannot move to a new time slot. There is a higher probability of collisions due to the number of packets (HELLO packets, SWITCH packets, and WSA/RES/ACK packets) being transmitted than DMMAC protocol. In addition, each node must periodically broadcast HELLO packets containing information on its one-hop neighbors. Hence the throughput on the CCH decreases due to the control overhead and the operation needs a high level of coordination.

8.1.1.1.3. Suggestion method Unlike DMMAC, HER-MAC and HTC-MAC, VanDung et al. [63] proposed the EFAB protocol. EFAB considers information regarding the two-hop neighbor's information of the switching node to reduce the length of RP. In contrast, DMMAC, HER-MAC, and HTC-MAC consider only one-hop neighbor information for the switching node. In EFAB, both SCH and CCH are split into two periods: the reservation period and the contention-free period. Each vehicle periodically broadcasts its Frame Information (FI), including one-hop and two-hop neighbors information, as shown in Fig. 14. The first transmitting vehicle among its one-hop neighbors will suggest that the vehicles move to new time slots. Note that the suggested vehicle is the vehicle that is transmitting the end time slot in RP. Hence, in one frame, more than one vehicle can be suggested to move to new time slots. If all one-hop neighbors confirm that each corresponding time slot is

BUSY, the suggested vehicles successfully move to the new time slots.

As shown in Fig. 14, vehicle a suggests that vehicles d and e move to time slots #2 and #4, respectively, because vehicle *a* is the first transmitting vehicle among its one-hop neighbors. Similarly, vehicle c suggests that vehicle f moves to time slot #2. If there are no collisions, both vehicles d and f will have moved to time slot #2. Since vehicle *d* is the first vehicle that was suggested by vehicle a move to time slot #2, all one-hop neighbors will release other vehicles that were suggested to move to time slot #2. Hence, vehicle d will move to time slot #2 in the next frame. After sync interval #1, three vehicles (d, f and e)moved to the new time slot. Consequently, the length of RP is reduced more rapidly than HER-MAC, HTC-MAC, and DMMAC. When a new vehicle g wants to occupy an available time slot, it must wait and listen for one frame duration to collect its one-hop neighbor information. After that, if vehicle g chooses an available time slot, for example #1, it will broadcast its FI in time slot #1. After this one-frame duration, all one-hop neighbors confirm that the time slot is BUSY, therefore vehicle g successfully occupies time slot #1. Simulations are carried out using NS-2. Simulation results show that EFAB adjusts the length of the BF more rapidly than the DMMAC and HER-MAC protocols. In addition, the EFAB protocol has a higher PDR of WSA packets than the DMMAC and HER-MAC protocols. Under large speed variance conditions, a vehicle that is making suggestions to other vehicles can move outside of the transmission range. Hence, merging collisions occur when the suggested vehicle moves to the new time slot.

8.1.2. Other methods

8.1.2.1. Transmission range method To improve the resource utilization efficiency, the CS-TDMA [64] protocol was proposed. To represent the synchronization pulse generated by the GPS or other distributed synchronization methods, the authors define the concept of "Chip" for the CCH. The "Chip" consists of two periods: the Transmission period (TS) and the Reservation period (RS). The TS uses the TDMA access scheme. TS consists of a number of time slots, denoted T_s , that is used for broadcasting safety and control messages. On the other hand, the RS period uses the CSMA access scheme. It is used for time slot reservations or the transmission of high priority safety packets. The TS and RS structures are shown in Fig. 15. The Chip Information (CI) contains: a number of T_s (N_{TS}), the identifiers of the occupier of the T_s (Node ID), the status of each T_s as either BUSY or IDLE (STATUE), the Delete flag of each T_s (D), the MR flag, and the number of T_s on the RS period (S_{ep}) [64]. In CS-TDMA MAC, the authors define a cluster according to the vehicles moving in the same regional unit. The size of a cluster is modified and optimized according to the traffic density. Although CS-TDMA can improve the broadcast performance in a VANET, performance evaluation of the CS-TDMA only took place a medium vehicle density (80 vehicles/km). In addition, access collisions and merging collisions are not discussed in [64].



Fig. 15. Structure of the CS-TDMA MAC protocol.



Fig. 16. A CSMA/TDMA dynamic splitting scheme.

Comparison of hybrid MAC protocols using dynamic intervals with distributed channel assignment methods.

| | DMMAC | HER-MAC | HTC-MAC | EFAB | Dynamic split | CS-TDMA |
|-----------------------|---|--|--|--|---|---|
| Refer- ences | [61] | [17] | [62] | [63] | [60] | [64] |
| Pub- lished | 2010 | 2014 | 2016 | 2016 | 2013 | 2014 |
| Optimal objective | TDMA-based frame | | | | | |
| Solution method | The vehicle is transmittin | ng in last time slot | | | Formula [60] | Self-adapting |
| Metric | Lower available time slot | Lower available time slot | Lower available time slot | Lower available time slot | Delay and packet drop probability | Vehicle density |
| Benefits | Adapts itself to various traffic conditions Improves throughput of safety messages | Improves non-safety packet delivery ratio and throughput | Faster time slot acquisition on CCH Increases throughput on CCH | – Improves broadcast – Higher safety packet delivery ratio on CCH | - Increases reliability for time critical messages | Improves safety message broadcast Improves channel utilization |
| Draw- backs | – Does not perform contiguous slot allocation | – High collision in the contention-free frame | – Large control overhead | Does not consider the scenario where the control vehicle leaves | – Does not consider optimal values for end-to-end delay | – Does not study access collision and merging collision problems |
| Com- pared with | - WAVE MAC | – IEEE 1609.4 | – HER MAC | – DMMAC and HER MAC | – Pure CSMA/CA and STDMA | – VeMAC, SOFT MAC and IEEE 802.11p |
| Simula- tor | NS-2 | MATLAB | MATLAB | NS-2 | N/A | MATLAB |

8.1.2.2. MAC-to-MAC channel access delay method According to the traffic load, a protocol which dynamically adjusts the frame between CSMA/CA and STDMA [94] was proposed in [60]. Each frame is divided into two dynamic intervals: the CSMA-based period and the STDMA-based period, as shown in Fig. 16. The splitting of the CSMA/CA-based and TDMA-based periods can be calculated based on the MAC-to-MAC channel access delay (low and predictable) and the packet drop probability. The simulation results show that this protocol can support a more acceptable reliability level for the real-time applications in VANETs. Under the variable traffic load, the packet drop probability increases because the length of CSMA/CA fraction is greater than that of TDMA fraction.

8.1.3. Summary and issues

All hybrid MAC protocols using dynamic intervals are summarized in Table 7. We now discuss issues and promising future research as follows.

- Dynamic random access period: The length of the contentionbased interval affects to the performance of hybrid MAC protocols. If the length is too short and the vehicle density is high, the system throughput decreases. Otherwise, if the length is too large and the vehicle density is low, the length of CCHI is wasted. Hence, the length of the contention-based interval should suit the number of active vehicles.
- Access and merging collision: The hybrid MAC protocols using dynamic intervals with distributed channel assignment do not solve these collisions since there is not a centralized device and vehicles are moving at various speeds. In the future, these

MAC protocols should address these problems to improve both the throughput and the delay in channel access.

• Dynamic VANET environment: When merging collisions occur, vehicles must re-occupy time slots to avoid collisions due to two vehicles in the two-hop neighborhoods not being able to use the same time slots [79].

8.2. Centralized channel assignment methods

By collecting one-hop information, the cluster-head (CH) knows the number of cluster members in its cluster. Hence, CH can adjust the duration of the contention-free interval according to its cluster size. On the other hand, if there is an RSU, the RSU will know the vehicles in its coverage area. Thus, the RSU will allocate time slots for the existing vehicles. Both CH and RSU disseminate control information, which provides an efficient and fair channel utilization.

8.2.1. Methodology

Centralized channel assignment method is divided into two main methods according to the coordinator: coordinate with RSU and coordinate with CH.

8.2.1.1. Coordinate with RSU

8.2.1.1.1. Intra-RSU The ACFM [69] protocol using a centralized coordinator can dynamically adjust time slots in the transmission range of the RSUs. ACFM ensures that the number of active vehicles will occupy an exact number of time slots. In ACFM, RSU coverage is divided into three areas: the Left Overlapping Area (LOA), the Right Overlapping Area (ROA), and the Free Area (FA),



Fig. 18. Risk-aware dynamic MAC protocol.

as shown in Fig. 17. Each RSU maintains a cycle schedule that is formed of N, where $N \in [1, 5]$. The duration of each frame is 20 ms and is divided into a fixed number of time slots: one RSU time slot and 36 Data Slots (DSs). RSU uses the RSU time slot to transmit control packet to its members within its coverage, whereas each member uses one of 36 data slots to transmit beacon data, as shown in Fig. 17. The RSU always receives the beacon from vehicles in its coverage. After the RSU successfully received the GPS message and the received signal strength indicator (RSSI) from the vehicle, the RSU can know the vehicle's position and allocate DSs based on global insight. A new vehicle uses the distance between itself and the corresponding RSUs to choose an idle DS and RSU to join. Within two-hop distance, since there exists interference at overlapping areas, ACFM requires that two neighboring RSUs do not use the same frequency. In FA, a new vehicle only scans one frequency to find the ID of the corresponding RSU. Based on the packet transmitted by the RSU, a new vehicle will randomly select an available DS to send its message to neighbors. In another case, a vehicle that is moving in an overlapping area can observe two different frequencies from two RSUs. Hence, it needs to allocate two different DSs in order to avoid the collision.

When the number of vehicles moving in the same region is small, the corresponding RSU coordinator will shorten the number of DSs to eliminate free time slots. Otherwise, when the number of vehicles is large, the RSU increases its cycle frame to one frame. Note that, the maximum number of DSs is 36. ACFM outperforms the IEEE 802.11 and pure 3G transfer protocols in terms of the average access delay and the PDR. However, ACFM uses only a single channel and also does not meet QoS requirements for different applications. 8.2.1.1.2. Inter-RSU Guo et al. proposed the RMAC protocol [68] to extend the ACFM protocol. A complete frame consists of an RSU segment and a vehicle segment. The vehicle segment is further split into two segments: a CSMA segment and a contention-free segment, as shown in Fig. 18. Each vehicle inserts safety-related information and the corresponding RSU into a beacon and sends its beacon during a chosen time slot. Alternatively, the warning (emergency) message is transmitted in the CSMA segment. Each vehicle will be allocated via the Slot Allocation Algorithm for CSMA and TDMA (SACT) [68]. After all vehicles successfully occupied the time slots, the corresponding RSU transmits the slot allocation map to all vehicles.

In Fig. 18, there are 200 time slots in a frame. Let α be the number of time slots used for RSUs, β be the number of time slots reserved for CSMA, and γ be the number of time slots reserved for TDMA [68], then the following relation holds.

$$\alpha + \beta + \gamma = 200, \quad \alpha = 20. \tag{2}$$

The number of time slots reserved for CSMA is determined by the average number of vehicles having warning packets. R-MAC can not only support the reliable and real-time delivery of warning messages but also make fair medium access for different kinds of messages. The simulation results demonstrate R-MAC outperforms IEEE 802.11p in terms of the PDR and the average delay of medium access. However, R-MAC operation applies only to a single channel and the simulation was carried out on a simple highway (one lane and one direction).

Yunmin at el. [67] proposed the C-MAC protocol for VANETs to reduce the collision probability as well as the maximum transmission delay of safety message. The C-MAC protocol operates by combining TDMA scheme which is designed by RSU and CSMA



Fig. 19. Coordinated multichannel MAC protocol.



Fig. 20. Frame of the CBMMAC protocol.

schemes for broadcasting control packets. Each CCHI is divided into three intervals: the Length Information Broadcast Phase (LIBP), the Safety Message Phase (SMP), and Channel Reservation Phase (CRP), as shown in Fig. 19.

Each SCHI in CCH is divided into frames. The RSU will broadcast a packet during a Control Slot (CS) to assign the number of subsequent time slots in each frame. Each vehicle receives RSU's packet and then, each vehicle will randomly choose a time slot for the access channel. If RSU receives packets transmitted by vehicles, it will assign time slots in SMP for them and broadcast this information in the CS in the next frame. If the vehicles did not receive their information in the CS packet, they will randomly choose time slots in the next frame in SCHI after finishing the previous frame. At the end of each SCHI, the RSU successfully receives the ID's vehicles and then includes them into Length Information (LI) packet to broadcast in the next synchronization interval. The LI contains information the length of CRP where vehicles will attempt to transmit data. The sender and receiver communicate via the three-way handshake with the Request (REQ), Response (RES), and RSU Coordination (RC) packets. During SCHI, the vehicles with the reserved SCHs will switch to the SCHs to transmit their data. The C-MAC allows the RSU to handle and minimize the length of the CRP. The C-MAC protocol is adaptive with regard to the number of vehicles. The length of CCHI can be optimized to provide the maximum throughput. Compared with the IEEE 802.11 and VCI MAC protocols, the C-MAC outperforms both in terms of the throughput and delays. However, the C-MAC was proposed for simple highway scenarios (one direction).

8.2.1.1.3. Coordinate with cluster-head The (CBMMAC) [65,95] protocol was proposed to improve not only QoS for real-time safety applications but also throughput for the non-safety application. The CBMMAC divides seven channels in DSRC [24] so that they can perform certain functions: Ch178 is Intercluster Control (ICC) channel, Ch174 is Intercluster Data (ICD) channel, Ch172 is Cluster Range Control (CRC) channel, and the remaining channels (Ch176, 180, 182, 184) are Cluster Range Data (CRD) channels [65]. Each vehicle operates in exactly one of the fol-

lowing fours states: Cluster-Head (CH), Quasi-Cluster-Head (QCH), Cluster-Member (CM), and Quasi-Cluster-Member (QCM). A cluster is organized with vehicles moving in the same direction, then CH is elected by vehicles. To operate on different channels, each vehicle must use two transceivers. One transceiver tunes the CRC channel to exchange safety messages, while the other transceiver tunes to the ICC channel to exchange safety messages with the CH vehicles. The CRC channel is divided into two periods: upstream using TDMA and downstream using CSMA/CA, as shown in Fig. 20. In an intra-cluster, the coordination and communication schemes are based on MMAC [96]. Initially, each CH depends on the luster members to create a reservation schedule for the TDMA slot on the CRC channel. The CBMMAC protocol outperforms the IEEE 802.11 and DCA [97] in terms of packet delay and system throughput. However, the CBMMAC has only been evaluated in the scenario with one direction, and the authors have not studied merging collisions. In addition, the system which applies CBMMAC is very expensive because of prices of two transceivers and one GPS system.

Unlike the IEEE 802.11p standard, the CBMCS [66] protocol divides the wireless medium into multiple control channels (CSMAbased mechanism) and one data channel (TDMA-based mechanism). Initially, each vehicle broadcasts its position, speed, and vehicle' ID through the control channel. The CH is a vehicle moving in the middle lane and has the highest probability (chosen randomly in [0, 1]). Once the CH is elected, it will decide the TDMA frame structure based on the number of cluster members and the number of neighboring CHs. Hence, the length of the TDMA frame is adjusted depending on the number of cluster members. To avoid collisions happened by exposed and hidden vehicles, each CH selects a different orthogonal code from one of its neighboring CHs. After the TDMA and CDMA codes are formed, each vehicle's information of position and speed must periodically be sent during its time slot on the data channel. In this protocol, the Vehicle Accident Avoidance Mechanism (VAAM) is included to warn of dangerous situations such as an accident and changing lanes. Compared with CBM-MAC [98], CBMCS allows vehicles to attempt fast channel and

Comparison of hybrid MAC protocols using dynamic intervals with centralized channel assignment methods.

| | ACFM | R-MAC | C-MAC | CBMMAC | CBMCS |
|-----------------------|---|--|---|---|--|
| Refer- ences | [69] | [68] | [67] | [65,95] | [66] |
| Pub- lished | 2012 | 2013 | 2016 | 2007 | 2009 |
| Optimal objective | Number of time slot | Slot allocation and reservation | Number of time slot | | |
| Solution method | Road side unit | SACT algorithm [68] and Markov chain | Road side unit | Cluster head | |
| Metric | Number of vehicles in RSU's coverage | Number of vehicles and traffic load | Number of vehicles in RSU's coverage | Number of cluster members | Number of cluster members |
| Benefits | - Fair channel access - Improves channel utilization | – Improves the Jain's fairness index – Increases packet delivery rate | Provides maximum throughput Improves the overall throughput and delay of non-safety applications | Improves real-time safety message delivery Improves throughput for non real-time traffic | Provides vehicle accident avoidance mechanism in order to enhance traffic safety Guarantees low end-to-end delay for intra-cluster communications |
| Draw- backs | Does not expand the seven DSRC channels Supports QoS for non-safety applications | Supports only to safety applications | – An interference signal can be occurred in the overlapping regions | – This system is very expensive because of using two transceivers and one GPS system | – Unclear whether CBMCS can control non-safety applications. |
| Com- pared with | – IEEE 802.11p and P3G | – IEEE 802.11p | – IEEE 802.11p and VCI MAC | – V2V DCA and IEEE 802.11 | – CSMA/CA, V2V-DCA and CBM-MAC |
| Simula- tor | NS-2 | NS-2 | N/A | MATLAB | C++ |

efficient safety transmissions. However, simulation results are only considered for safety applications without considering non-safety applications.

8.2.2. Summary and issues

All hybrid MAC protocols are presented in Table 8 according to the channel assignment methods. We now discuss issues and promising future research as follows.

- Inter-RSU interference: Due to vehicles moving at the overlapping area and RSUs use the same frequency band, inter-RSU communication is affected by interference between vehicles in these regions. Future MAC protocol should eliminate this interference to achieve efficient broadcast safety message.
- Cluster stability and inter-cluster inference: The hybrid MAC protocols using dynamic intervals with centralized channel assignment require stability of the cluster. In VANETs, vehicles can arrive/depart a cluster at any time. If the cluster head is absent, the centralized management will fail and packet collisions will occur.

9. VANET simulations

VANET simulations help to perform vehicular services and applications before being deployed in the real world [99,100]. Network simulations for VANETs mostly use NS2, NS3 [90], Matlab [101], or OMNeT++ [102]. Different works use different network scenarios which is created by the randomly generated traffic to the simulators. Examples of the realistic vehicle behavior and traffic simulators are SUMO [103], MOVE [104] for NS2, NS3, and VEINS [105] for OMNeT++. Moreover, various patches available for different tools that enable additional features for VANETs are proposed. One such patch is in [106], which enables the multichannel operation in VANET simulators in NS2.34. A comparison of VANET simulations is presented in Table 9.

For dynamic interval based MAC protocols, there are some issues in evaluating MAC protocols.

The comparison of the schemes with simulation results is unfair

- 1. In contention-free MAC protocols, ATSA [71,72] and CFR MAC [70] use distributed channel assignment method while CBMAC [73] and TM-MAC [16] use centralized distributed channel assignment method.
- 2. For contention-based MAC protocols, there are two main methods: 1) Markov chains method and 2) Other methods. First, Markov chains method bases on the WSA and safety packet transmissions to find the optimized interval. In [45, 51,52,9,53,57], different works use different metric to solve the optimized interval such as WSA classes [46,50], and access categories [51,52]. In addition, in each proposed MAC protocols, the authors studied the performance between new MAC protocols and existing protocols. Hence, we do not study simulation results in the same methods used.

Second, other methods based on different metrics to find optimized intervals such as network traffic load [45], end-toend delay and average packets [56], vehicle density and context [55], average contention delay and the link latency [57], randomly generate packets [58]. According to different solution methods, DID-MMAC [45], AAA [56], CAVI [55], DSI [57], and DAN [58] operate under different assumptions. For instance, DID-MMAC [45] performed simulations based on real freeway traffic data conducted by Berkeley Highway Lab. AAA [56] based on vehicular clouds which are used to manage coalitions of affordable resources in vehicles being in the same area in order to host infotainment applications used by other vehicles on the move.

3. Similarly, in hybrid MAC protocols, there are two methods used to channel assignment: centralized and distributed. First, comparisons of the schemes with simulation results using distributed channel assignment methods are studied in each hybrid MAC protocols such as DMMAC [61], HER-MAC [17], HTC-MAC [62], EFAB [63], Dynamic split [60], and CS-TDMA [64]. Hence, we summarized the hybrid MAC protocols using distributed channel assignment methods.

| Table 9 | Ta | bl | le | 9 |
|---------|----|----|----|---|
|---------|----|----|----|---|

Comparison of VANET simulations.

| | NS2(3) | Matlab | OMNET++ |
|--------------|--|---|--|
| MOVE | Yes | Yes | Yes |
| SUMO | Yes | Yes | Yes |
| VEINS | No | No | Yes |
| Advantage | - It has been used extensively over a long period of time | – It is easy to perform protocol evaluation | A higher range of networks protocols are embedded Provide powerful support to accurately simulate MAC and physical layer in addition to the very powerful graphical interface and modular core design |
| Disadvantage | High complexity in implementing the mobility models within the framework Consumes a higher percentage of the CPU and the Memory | – Cannot test for realistic networks | - To perform protocol evaluation, network sim- ulation and mobility scenario are running in a parallel manner |

Second, in centralized channel assignment methods, the optimized interval is calculated by either the road side unit (RSU) or the cluster head. These methods are designed based on the different formats for the repeated intervals (also called frames). For instance, in ACFM [69], the duration of each frame is 20 ms and is divided into a fixed number of time slots: one RSU time slot and 36 Data Slots (DSs). In RMAC protocol [68], a complete frame consists of an RSU segment and a vehicle segment. On the other hand, in CMAC [67], each CCHI is divided into three intervals: the Length Information Broadcast Phase (LIBP), the Safety Message Phase (SMP), and Channel Reservation Phase (CRP). Hence, the comparison of these schemes with simulation results is unfair because CMAC is based on the IEEE 1609.4 and 802.11p standards while ACFM and RMAC design a new format for intervals.

The different assumptions to design MAC protocols in VANETs for dynamic intervals

Some MAC protocols can operate under the specific assumption such as

- The ideal channel conditions (i.e., no exposed terminals and hidden terminals) (e.g., VCI MAC [9], Q-VCI MAC [53], DSI [57], and APDM [18]).
- The saturated (e.g., VCI MAC [9], Q-VCI MAC [53], CAMAC, CAMAC2) or non-saturated throughput conditions (e.g., APDM [18]).
- 3. One (e.g., VCI MAC [9], Q-VCI MAC [53]) or two transceivers used (e.g., ACFM [69]).
- 4. The use of digital map (DSI [57], ACFM [69]).
- 5. A platoon (AAA [56]).
- 6. Different context (CAVI-MAC [55]).

Therefore, the comparison of the schemes with simulation results is difficult to perform.

10. Conclusion

Both restricted control channel interval and the service channel interval are not able to adapt to the dynamically changing vehicle traffic conditions of VANETs. In recent years, a great deal of work has been done to address this issue. According to the vehicle density, the length of the interval can be adjusted by the vehicles themselves or a coordinator (such as an RSU or a cluster head). By leveraging information from Markov chains and stochastic process under different network conditions, MAC protocols can optimize either the length of the interval or the contention window. By adjusting the length of the interval, MAC protocols can support the maximum throughput of SCHs or reduce the access delay, end-toend delay, and packet loss ratio. Only a few MAC protocols using dynamic intervals can address both access and merging collisions. In this paper, we classify these protocols considering both channel access and the optimal method. We also performed a comprehensive survey of different techniques of MAC protocols using dynamic intervals. Our key contribution is that we discussed some existing mechanisms that dynamically adjust the interval length along with their benefits and limitations. In the future, designing MAC protocols using dynamic intervals can enable VANETs to adapt to time and space dimensions of the moving vehicles for efficiently supporting different VANET applications, as well as satisfy the QoS requirements at the MAC layer.

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