A Survey of Media Access Control (MAC) Protocols for Vehicular Ad-hoc NETworks (VANETs)

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ABSTRACT

Recent advances of various wireless communication technologies and the emergence of computationally rich vehicles are pushing Vehicular Ad-hoc NETwork (VANET) research to the forefront in academia and industry. A lot of research results have been published in various areas (such as routing, broadcasting, security, and others) of VANET in the last decade covering both Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) scenarios. One specific area of VANET that still faces significant challenges is the design of reliable and robust Media Access Control (MAC) protocols for V2V communications. We present a survey of V2V MAC methods (including various VANET standards) that have been proposed for VANETs over the last few years. We focus on the benefits and limitations of the proposed MAC techniques as well as their ease of implementation in practice and future deployment. We also discuss some of the challenges that still need to be addressed to enable the implementation of highly efficient and high performance MAC protocols for V2V communications. Finally, we propose some innovative solutions that can be developed to address these challenges.

Key Words: Communication, VANET, Ad-hoc Networks, MAC, Performance, Protocol, Wireless

1. INTRODUCTION

Vehicular Ad-hoc NETworks (VANETs) have received increased industrial and research interests recently [1][2][3][4]. The major drive for this development has been the plethora of foreseen applications, as well as the emergence of wireless networking technologies [5][6][7][8][9]. VANETs are envisaged to provide a communication range of 1000 meters with roadside units and other vehicles, at relative speeds up to 200 km/h, irrespective of the environment [10]. Applications for VANETs can be divided into the following broad categories namely, safety related, traffic management and transportation efficiency, user infotainment services and Internet connectivity [2][9][11]. Safety related applications include lane change assistance, cooperative forward incident warning, intersection collision avoidance, emergency or incident warning [5]. Traffic management applications form part of a greater Intelligent Transportation System (ITS) and include toll collection, intersection management, cooperative adaptive cruise control, and detour or delay warning. The market impetus for VANETs is expected to be driven by user infotainment services rather than the safety or traffic applications [2]; government and industry investments are based on this premise. Applications in this area are typically classified as infotainment and range from multimedia delivery to email services and augmented reality services [12]. The applications envisaged for VANETs, vary significantly in their VANET requirements. Safety messages require fast and guaranteed access and a short transmission delay, while messages are relatively short. The infotainment services could require a heavier data load, with less severe timing requirements [2]. Due to the wide variety of expected VANET applications, VANET networks need to support a broad range of requirements. For safety applications a high level of Quality of Service (QoS) needs to be ensured, while for the user infotainment services this may not be a stringent requirement. Furthermore, for viable augmented reality applications, such as location information overlay, substantial processing and accurate location determination will be required, while for traffic management the requirement for these could be less stringent. An important goal of VANET implementations is to make roads safer and make driving more enjoyable. As stated earlier however, the market force is expected to be infotainment. It is clear that there is a potential conflict of outcomes, since infotainment is likely to be an additional driver distraction, which increases the safety risk, rather than reduce it.

1.1 Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) Communications

VANETs comprise of two main modes of communication, Vehicle to Infrastructure (V2I) and Vehicle to Vehicle (V2V). The former is for communication between the On Board Units (OBUs) on vehicles and an infrastructure, through Road Side Units (RSUs). The latter is between vehicles that connect through OBUs. OBUs are network nodes mounted to vehicles and therefore inherently mobile and wireless. RSUs are stationary network nodes and are usually mounted in an elevated position on existing transportation infrastructure, such as traffic lights, street lights and road signs [13]. RSUs provide a wireless link to vehicles and a wireless or wired link to the infrastructure.

In this paper we focus primarily on V2V, but relevant aspects of V2I are also covered where necessary.

1.2 Recent VANET Research Areas

VANET has attracted a lot of research attention recently. Table 1 summarizes some of the major VANET areas that have been recently investigated by researchers as proven by the number of publications (obtained from the IEEE Xplore database) in each of these areas. As Table 1 shows, we note that the area of Media Access Control (MAC) support for VANET has not really received a commensurate level of attention compared to the other VANET areas.

Table 1: Selected VANET research areas recently investigated

VANET Topic	**IEEE Xplore publications**
Broadcasting	646
Routing	253
Evaluation of existing wireless technologies (cellular, Wi-Fi and WiMAX)	98
Security	153
Medium Access Control (MAC)	***38***

Still, among the relatively few published works on MAC support for VANET (as shown in Table 1), many of these publications have focused on V2I communications. V2V MAC support remains fairly unexplored and several significant research challenges still remain. Consequently, in this work, our survey reviews mainly on V2V MAC approaches that have been recently proposed.

1.2.1 Heterogeneous Wireless Technologies

It is argued that vehicular networks will initially use a hybrid of existing wireless technologies which include cellular technologies, Wi-Fi (IEEE 802.11a/b/g/n) and WiMAX (IEEE 802.16) [2][15]. The proposed dedicated VANET standards would gradually emerge as the dominant VANET technology. The hybrid nature of such a network would require techniques and methods to hop between different wireless communications technologies.

1.2.2 Message Routing

A challenge created by the mobility of VANETs is network routing. Routing strategies need to make provision for the fact that vehicles, which make up the nodes of the network, continually change position, speed and direction [2]. Research on routing protocols has evaluated ways to select nodes (vehicles) in a multi-hop route. Routing protocols are typically based on the following properties of the source, destination and in-between nodes: position, direction of travel, speed, association with nearby nodes (e.g., whether it is the coordinator or member of a ring), relative routing authority (whether it has the right and ability to forward messages) [2][12][16][94]. These properties are obtained using vehicle positioning and localization techniques, and signal strength [12][16]. In the exclusively V2V communication scenario, message routing becomes an important determinant of efficient networking. If a message is to be sent from vehicle A to vehicle B, it is paramount that the routing decisions be made in such a way that the message will reach B despite the mobility of, and changing connections between all the nodes linking vehicle A and vehicle B. [2]. Duchourthial and Khaled [17] categorize routing protocols into the following categories: Topological (based on network topology) [18][81], Geographical (based on positional information) [19], Hierarchical (based on clusters) [20][86], Movement-Based (based on trajectory) [21] and Broadcasting [22][89]. Given that routing is not the main focus of this paper, further details can be found in [2][3][23][16][66][67][95].

1.2.3 Medium Access Control

In any networking environment, one of the key aspects of the communication protocol stack is the Medium Access Control (MAC) layer. The MAC layer determines the node which is given access to the physical medium. MAC mechanisms could be categorized as *contention-based* and *contention-free*. Contention-based approaches rely on carrier sensing, back-offs and retry schemes, while contention-free approaches rely on time division multiple access and synchronization schemes. MAC mechanisms could also be categorized based on the entity in which the control of the medium access resides. The importance and the strong need for a highly optimized MAC layer is demonstrated by the fact that the time two vehicles are within communication range could be as low as 30 seconds for two vehicles each traveling at 120km/hr in opposite directions, with a range of 1000m [10][2][73]. The method used to coordinate medium access could range from a completely random access — where any of the nodes arbitrarily and asynchronously tries to access the medium without, or with little coordination (such as IEEE 802.11p intended for VANET [24]) - to a structured approach - where only certain time slots on certain frequency channels are allocated to a certain node [25]. Structured approaches could be a combination of the fundamental multiplexing techniques: Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), Code Division Multiple Access (CDMA) and Space Division Multiple Access (SDMA). For these approaches every node has a portion of the bandwidth, time, frequency, space, code or a combination of these for exclusive use and is therefore assured of collision free transmission. These MAC methods are referred to as contention-free, even though a level of contention is usually required to initially acquire a segment. It is possible to have a combination of contention-based and contention-free MACs [26][27]. For instance, a MAC could have a portion of its time allocated to particular nodes (contention-free) and the remainder allocated to contention-based operation. An advantage of the random access and contention-based methods is that little coordination is required. These MAC methods are therefore more robust to changes in network configuration and have lower overheads and consume less energy. However, the performance of random access and contention-based methods deteriorate significantly with increased traffic load, because of a corresponding increase in collisions. Any contention-based MAC method could also suffer from unbounded access delays. Contention-free MAC methods have the advantages that a QoS can be guaranteed and the performance is better under increased loads. They do, however, require more coordination to perform allocation, especially when the network configuration changes rapidly and portions need to be allocated and re-allocated frequently. According to Liu et al. [28], it has been demonstrated and is widely accepted that contention-free MAC schemes exhibit better channel utilization and are more reliable than Carrier Sense Multiple Access (CSMA) schemes.

A second category of MAC techniques is based on the location of the coordination control function. One approach, called distributed or decentralized control, is to have nodes that are self-organizing, whereas with another popular approach nodes are coordinated by a central entity. For distributed MAC, many nodes could autonomously organize themselves in an ad-hoc fashion to setup and maintain medium access coordination. The distributed control could either be done in groups, by group leaders deciding on the allotment, or with nodes claiming available portions and then declaring or advertising their allocations. The group leaders in the former could be self-appointed, or could be elected based on a set of criteria (such as signal strength).

1.2.4 Physical Layer Challenges

Another challenge caused by the mobile nature of vehicles is the *Doppler Effect*. If a vehicle transmitting an RF signal is moving at high speed relative to a receiving vehicle, the received frequency could differ from the transmitted frequency by as much as 300 Hz [29]. This is called the Doppler Effect and can also be observed by the change in audible frequency when a vehicle with a siren passes by. In order to correctly receive and interpret the transmitted information, the receiving vehicle has to compensate for the change in frequency.

When a radio wave follows more than one route to get from a transmitter at point A to a receiver at point B, there is a chance that the signal will experience positive or negative interference at point B due to the difference in traveling time along the different routes. Negative interference reduces the signal level and positive interference increases the signal level, which results in a varying signal at the receiver. This is referred to as multipath fading and is due to the mobile nature of VANETs, the varying levels of *multipath fading* is a significant challenge [29][96]. Other physical layer challenges include adjacent channel interference and interference from other RF sources (e.g. Wi-Fi).

A further challenge introduced by high mobility is the unpredictable and varying nature of the transmission medium. As vehicles move relative to each other and objects, such as buildings, pedestrians or trees, the physical properties of the link are continually perturbed [30].

1.3 Performance Metrics for VANET

The transportation scenarios used when VANET aspects are developed and evaluated are highway traffic, city traffic, intersectional traffic, and traffic moving in opposite directions. In one scenario, vehicles could travel on a highway. Vehicles on a *highway* tend to travel in a platoon, which means the relative speed between vehicles is low, while the relative speed between a vehicle and the infrequent RSUs is high. Highway traffic also tends to move in the same direction, limited by the available road. Another scenario is *city driving*, which tends to be at low speed and stop-start. It is reasonable to expect that there will be a higher density of RSUs in the city center. Routing in the city becomes tedious, since buildings represent large obstacles and driver behavior is less predictable in the city (e.g. whether a person would turn or continue). If a grouping method, such as token passing, is used to coordinate access to the medium, the group management scheme needs to be more agile for city driving.

To assess the performance of proposed MAC approaches for VANET, various performance metrics are used. They are summarized in Table 2.

Table 2: Common Performance Metrics used for Evaluating MAC Methods

Performance Metric	**Description of Performance Metric**	Reference
Maximum medium access delay	Measures how long a node has to wait to get access to the medium.	[27][28]
Payload delivery delay	Measures the time it takes to send either a packet or multiple packets from one point in the network to another. This metric could also include a measure of the time for a round trip.	[26][27][25]
Throughput (or goodput)	Measures the data transmitted from one point in the network to another in a given time. When goodput is measured, only the effective data throughput is measured, excluding management and overhead.	[27][25][31]
Overhead	Measures the ratio of data transmitted to manage or maintain the network, as opposed to goodput.	[26]
Fairness of access (Index of)	An index is used to measure fairness of access. The concept depends on the definition of fairness. Karamad et al. [1] based fairness on the premise that all nodes, despite their speed, should be able to send the same number of messages to an RSU in a given time. The faster moving nodes must therefore get more chance to transmit. The fairness metric in [1] measures the likelihood for each node to transmit relative to its speed.	[29]
Probability (or ratio) of successful delivery	Measures the probability of messages (especially safety messages) being successfully delivered.	[29][26][32][33]
Network stabilization time	Time it takes for all nodes to be allocated a transmission slot and for the network to reach a stable state.	[25][33]

2. MAC DESIGN CONSIDERATIONS FOR VANET

A unique characteristic of VANET that distinguishes it from other ad hoc networks is the high mobility of nodes (vehicles). Limited connections currently exist between vehicles and different types of infrastructure, such as the Internet and toll collection facilities. Whenever an occupant of a vehicle carries a mobile phone with a data connection to a cellular service, the user can access the

Internet from within the vehicle. Newer vehicles are equipped with built-in mobile phone connectivity that enables various Internet-based services to occupants [34][35][36]. These connections are, however, limited to Internet connectivity. Vehicles are also connected to infrastructure such as Electronic Toll Collection (ETC) systems in numerous countries (for example, AUTOPass in Norway, Via Verde in Portugal, I-PASS in Illinois US, Salik in Dubai) with ranges of ten to fifteen meters.

VANET solutions that have been developed using existing technologies (e.g. cellular phones or Wi-Fi) are not sufficiently robust to cope with the mobility inherent to VANETs [15][37]. The low bandwidth and relatively short range provided by ETC restricts its ability to host the VANET applications mentioned in this work. The cellular Internet connectivity is dedicated to Internet connectivity and is therefore inherently infrastructure-based and sluggish [1][15][38]. The applications envisaged for VANET require *fast association* and *infrastructure independent* communications.

As was mentioned earlier, one of the greatest challenges in making VANET a *cost-effective* technology that can be easily deployed and adopted, is the time it takes to establish connections between vehicles (nodes) and other vehicles, or between vehicles and RSUs, as well as the delays incurred during the management of access to the underlying wireless medium. The problem is most noticeable in the scenario where two cars travel in opposite directions at speed, attempt to establish a connection, and need to transfer information on a constantly changing medium, while managing the medium and accompanying data collisions. The bottleneck in this process is the Medium Access Control (MAC) layer [2][10][39]. This was also demonstrated to be the case for IEEE 802.11p [32]. Several design challenges still need to be addressed at the MAC level [10][29] to achieve fast, reliable, and fair access — these challenges are discussed in the next section.

2.1 MAC Design Challenges for VANET

The most important challenges of a MAC layer for VANET are discussed in [40]:

- The *hidden terminal* problem where two nodes are outside of each other's range, but both attempt to communicate with a node that is within the range of both. This problem is likely in pure V2V environments where there is no centralized communication coordination. The result of the hidden terminal problem is message collisions.
- The *dynamic nature* of VANETs. Given the changing conditions and vehicle positions, the frequency and propagation delays of a channel could vary significantly.
- VANETs need to be *scalable*, to ensure network performance in both low and high vehicle densities.
- The different applications expected for VANETs, result in *disparate requirements* on the system.

According to [10], the MAC should be robust against frequent disconnects between nodes, which could occur due to the highly mobile and varying nature of VANETs. Since nodes in a VANET are vehicles, which are inherently mobile, the MAC should be optimized for frequent disconnects and hand-offs with other OBUs and RSUs [10]. Since wireless transceivers cannot transmit and receive simultaneously, collision detection is not straightforward. The MAC layer needs to ensure fairness among all stations sharing the wireless medium and to offer predictable access to the shared medium.

In V2I VANET scenarios, centralized MAC methods could be employed, since an RSU could act as a coordinator. A crucial challenge for communication between vehicles (V2V) that are out of range of an RSU is the coordination of communication on the available channels. In pure V2V situations no central coordination is available to manage and coordinate access to the allocated channels [32]. The key challenges are to determine who, if any, assumes control of coordinating access to the medium on an ad-hoc basis, and how the time slots and channels are shared fairly between the vehicles that in range of each other [32].

Given the disparate nature of emerging VANET applications such as media streaming or sending of safety critical messages, another vital requirement for the MAC layer is to guarantee appropriate levels of QoS for various applications. The QoS requirements for safety messages are different to those of media streaming. A guarantee is required that the safety messages will be delivered such that the receiver has sufficient time to respond. Multimedia streaming applications require that the QoS is sufficient to allow clear and decipherable delivery to the end user.

3. STANDARDS FOR VANET SUPPORT

3.1 Dedicated Short Range Communication (DSRC)

Dedicated Short Range Communication (DSRC) [41] was initially used in Europe to describe the protocol used for only Electronic Toll Collection (ETC). These systems are now in use worldwide, in countries that include China, Australia, and South Africa. Current DSRC systems, mostly used for tolling, comply with different and incompatible standards in Japan, Europe, and the US. Current DSRC ETC systems are based on the European Committee for Standardization (CEN) standards EN 12253, EN 12795, EN 12834 and EN 13372. EN 12253 uses the frequency ranges 915 MHz and 5.795 — 5.815 GHz. In the US however, DSRC and Wireless Access for Vehicle Environments (WAVE) [42] are interchangeably used to broadly describe vehicular network technology, based on the on the IEEE 802.11 standard. In Europe this is referred to as Intelligent Transportation Systems (ITS) [43]. In the United States, the DSRC spectrum is regulated by the US Federal Communications Commission (FCC) [44]. The European Telecommunications Standards Institute (ETSI) and the EU are responsible for regulating usage of this spectrum and published a standard, EN 302 571 2008, which allocates the same frequency range as DSRC in the US [40].

The American Society for Testing and Materials (ASTM) developed a single standard for the PHYsical layer (PHY) and the Medium Access Control (MAC) called ASTM E 2213 [45] with the purpose of defining the over-the-air radio frequency protocol for a DSRC system. Further work on this ASTM E 2213 standard has recently been undertaken by task group p of the IEEE 802.11 working group. The IEEE has subsequently released standards P1609.1 through P1609.4 and a draft standard IEEE 802.11p, which is a derivative of IEEE 802.11a, for initial assessment in VANETs, which they call Wireless Access for Vehicle Environments (WAVE) [10]. These standards are summarized in Table 3 [42][24][13].

Table 3: IEEE standards for VANETs

IEEE std.	**Purpose and function**
1609.1	WAVE resource manager
1609.2	Security, secure message formatting, processing and message exchange
1609.3	Routing and transport (networking) services (alternative to IPv6). Provides management information base for the protocol stack
1609.4	Multiple-channel operation in the DSRC standard, supplementing the IEEE 802.11p
802.11p	Specification for the physical and MAC layer to enable operation in the WAVE (highly mobile nodes), based on 802.11a

The next generation of DSRC, as defined by the IEEE WAVE standards and the ETSI standards, uses the 5.9 GHz band. The US DSRC channel assignment, as per the U.S. Code of Federal Regulations (CFR) for telecommunications title 47 parts 90 and 95 [46][47], is listed in Table 4 [48]:

Table 4: DSRC Channel allocation by the FCC [2]

Channel number		**Frequency (MHz)**	**Description**	
172		5855-5865	Critical, safety of life	
175	174	5865-5875	Service channel	Service channel
	176	5875-5885	Service channel	
178		5885-5895	Control Channel	
181	180	5895-5905	Service channel	Service channel
	182	5905-5915	Service channel	
184		5915-5925	High power, public safety	

Figure 1 shows how the IEEE standards and layers relate to the well-known ISO layers. [10][13][39][49].

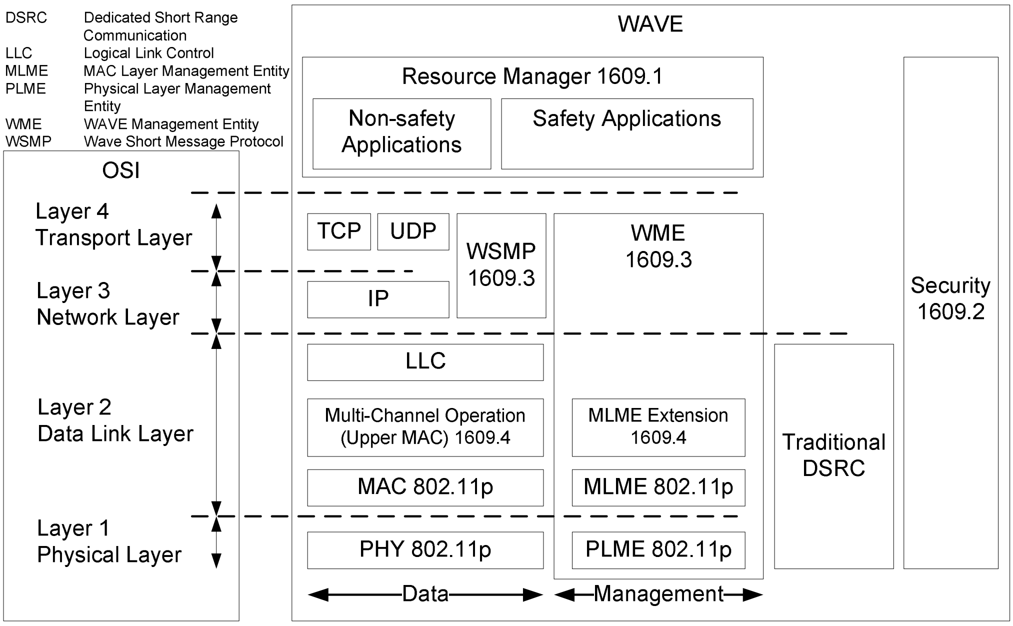


Figure 1: IEEE VANET standards

3.1.1 Europe

The EU spectrum allocation authority has allocated a frequency range of 30 MHZ, 5.875 - 5.905 GHz for ITS safety use in [50], with the intention to increase the range to 70 MHz.

Additionally, in Europe, the International Organization for Standardization (ISO) set up Technical Committee (TC) 204 that is made up of a number of working groups. The ISO TC has developed a framework for ITS called Communications Access for Land Mobiles (CALM) encapsulating VANET standards from IEEE, ETSI, CEN and the Society of Automotive Engineers (SAE) [51]. CALM includes various types of wireless technologies including WiMAX, Wi-Fi, EDGE, GPRS, 2G, and 3G. The CALM equivalent in the 5.9 GHz range is called CALM M5 and occupies the same frequency range as DSRC in the US.

3.1.2 Japan

In Japan, the Association of Radio Industries and Businesses (ARIB) standard T75 is used for ETC. This standard prescribes the frequency range 5.77 - 5.85 GHz, with the uplink and downlink channels separated by 40 MHz [52].

The frequency ranges for DSRC for different regions of the world alongside the ITU-R Industrial Scientific and Medical (ISM) radio band are summarized in Figure 2.

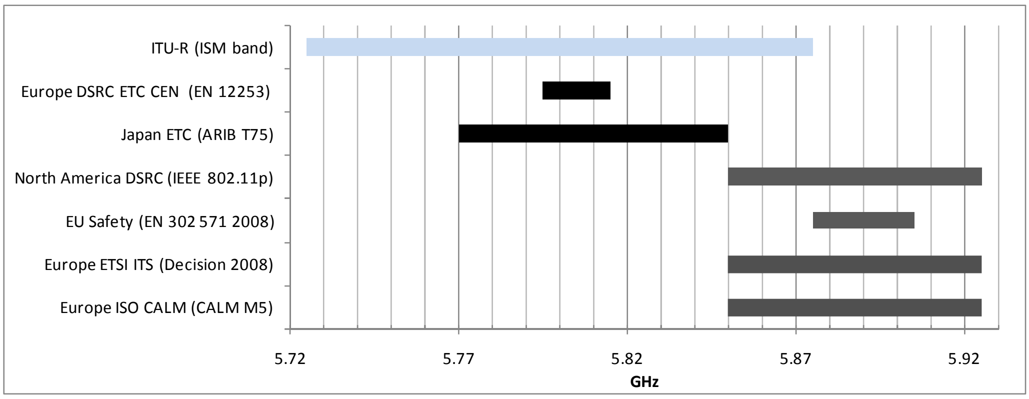


Figure 2: VANET and traditional DSRC frequency allocations for different parts of the world.

3.2 IEEE 802.11p/IEEE 1609.4 Standards

The basic MAC technique used by 802.11 networks is the Distributed Coordination Function (DCF). The contention-based scheme employed in IEEE 802.11 networks, including IEEE 802.11p, is CSMA/CA. Nodes wait for a random period, ranging from zero to a maximum value, called the Contention Window (CW), before transmitting. If activity is sensed during the CW, the countdown pauses. Every transmit attempt expects an ACKnowledge (ACK) to confirm successful transmission. The CW is doubled in the event of unsuccessful transmission, up to the maximum value. To avoid the hidden or exposed terminal problems, a Request To Send, Clear To Send (RTS/CTS) handshaking method is employed along with a Network Allocation Vector (NAV) [53]. Each node maintains a NAV, which is extracted from the RTS, CTS, Data and ACK packets. NAV acts as a virtual carrier sense by predicting when the medium will be busy and not transmitting then (similar to normal carrier sense that waits until it senses a free medium before attempting to transmit).

In contrast to the traditional IEEE 802.11 network, IEEE 802.11p does not contain authentication and association in the MAC and PHY layers. This is because the normal modes of authentication and association would not meet the stringent timing requirements set by the VANET environment (for example for the scenario where two vehicles move at normal speed in opposite directions). Moreover, the notion of the 802.11 Basic Service Set (BSS) is replaced in 802.11p with a WAVE-BSS (WBSS). In a traditional 802.11 network, a BSS is the collection of nodes that are connected and are able to communicate. Two types of BSSs could exist in a conventional 802.11 network, namely an Infrastructure BSS, which includes an AP, or an Independent BSS, which is formed without an AP on an ad-hoc basis. For WAVE, however, any node is allowed to transmit in a WBSS before any authentication or association, as long as the node has received a WBSS announcement from a WBSS provider [10][54]. Network synchronization is achieved by dividing channel time into 100 milliseconds intervals. Every interval has a Control CHannel (CCH) and a Service CHannel (SCH) allocation, both with a guard band [42], as indicated in Figure 3.

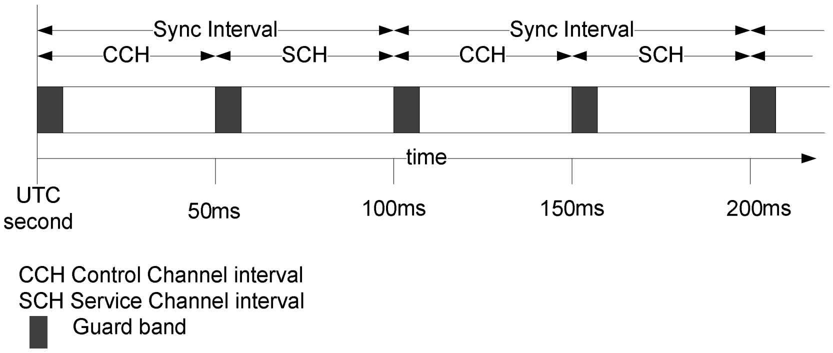


Figure 3: WAVE Synchronization

IEEE 802.11p uses Enhanced Distributed Channel Access (EDCA) functionality, derived from the IEEE 802.11e standard [13]. The EDCA resides in the MLME Extension and allows messages with a higher priority (there are 4 categories) to have a better chance of being transmitted than messages with a lower priority. To achieve this, the Contention Window (CW) and the Arbitration Inter-Frame Space are shortened. EDCA also provides contention-free periods, called Transmit OPportunities (TXOP).

IEEE 1609.4 specifies the multiple channel operation for the MAC and PHY of an IEEE 802.11p WAVE system using the Control Channel (CCH) and Service CHannels (SCHs). It also provides for prioritization, routing, and coordination. The WAVE service advertisements and channel coordination are to be performed on the control channel (Channel 178 as designated by the FCC) [48][40].

The IEEE 802.11p MAC does not adequately address the requirements imposed by VANET applications, since it uses a standard contention-based MAC approach. QoS cannot be guaranteed for safety critical messages and other real-time transmissions.

4. PROPOSED (NON-IEEE 802.11P OR IEEE 1609.4-BASED) MAC SOLUTIONS FOR VANET

In this section we review MAC techniques (not based on either IEEE 802.11p or IEEE 1609.4) for VANET that have been recently proposed in the literature.

In [29] a contention-based MAC for V2I is developed by Karamad et al., with the purpose of increasing access fairness. Although this MAC is developed for RSU based communication, we include it in this paper to highlight the alternative interpretation of fairness and the resulting MAC approach. Since vehicles do not travel at the same speed, yet they have an approximately equal communication range, all vehicles do not have the same residence opportunity at RoadSide Units (RSUs). Furthermore, faster nodes are less likely to be able to communicate with a given RSU than slower nodes in the same travel path. The approach is based on IEEE 802.11, with DCF adjusted for node speed. In the proposed MAC approach, the contention window of each vehicle is increased for higher vehicle speeds, which enables fairer access of the shared medium. The approach has a number of shortcomings and is not suited for V2V communication: A high level of coordination, awareness, and overhead are required to be able to actively adjust the DCF for each node relative to other nodes. Moreover, the speed of other nodes is only known once within range. In the V2V scenario, contact time is already very short. It is difficult to justify the cost of data transfer time given the small benefit or increased fairness as defined in [29].

A Self-organizing TDMA-based (STDMA) MAC method is evaluated in the vehicular communication environment by Bilstrup et al. in [32], with the aim of guaranteeing the timely delivery of safety critical messages. The method is presently employed in aviation and naval surveillance as part of the Automatic Identification System (AIS) and VHF Data Link Mode 4 respectively [55][56]. STDMA provides decentralized coordination and nearly contention-free communication. A frame is a repeated sequence of a fixed number of slots and every node synchronizes its slots to Global Positioning System (GPS) time. The frames are not synchronized. Every node selects a range of slots to choose from and at random intervals chooses a different and unoccupied slot from this range. The structure as perceived by a node is demonstrated in Figure 4. The number of times a node transmits per frame is determined by its speed.

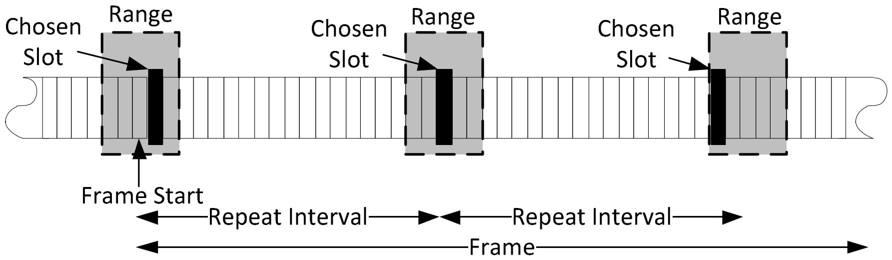


Figure 4: STDMA Message Structure

Once slots are chosen, the method essentially uses standard TDMA, avoiding transmission collisions. During a slot, a node transmits the positional information of the transmitting node and an optional short emergency message. The STDMA approach exhibits some inadequacies when considered as a complete solution for the various VANET applications and scenarios: STDMA AIS was developed for very low data rates to announce only positional information. It is not suited to high volumes of data such as multimedia. Since the method employs TDMA, a slot is wasted for every node that does not need to transmit. The system is more suited to highway traffic than urban, since the former has fewer changes of relative direction and relative speed between nodes. Accordingly, the authors evaluated the system for safety applications with short data spurts requiring high reliability, and in a highway scenario. The system is absolutely reliant on GPS, both for synchronization and for viable slot sharing and STDMA will not work without GPS support [32]. In a node overload condition, slots are overloaded since nodes that are furthest apart start to share slots. If these slots are not sufficiently separated in space, collisions will occur, which could lead to unbounded delays. The system only uses one of the seven available WAVE channels.

A self-organizing contention-free TDMA MAC, called VeSOMAC, is developed and evaluated by Yu et al. [25]. The goal of the research is to develop a contention-free MAC method with distributed control, which delivers increased data transfer between platooning vehicles in highway scenarios. VeSOMAC can operate with all nodes synchronized with GPS time, or with nodes self-adjusting asynchronously. We will focus on the asynchronous operation, since that is what the paper describes in detail. The message structure for three nodes (X, Y, and Z) is illustrated in Figure 5.

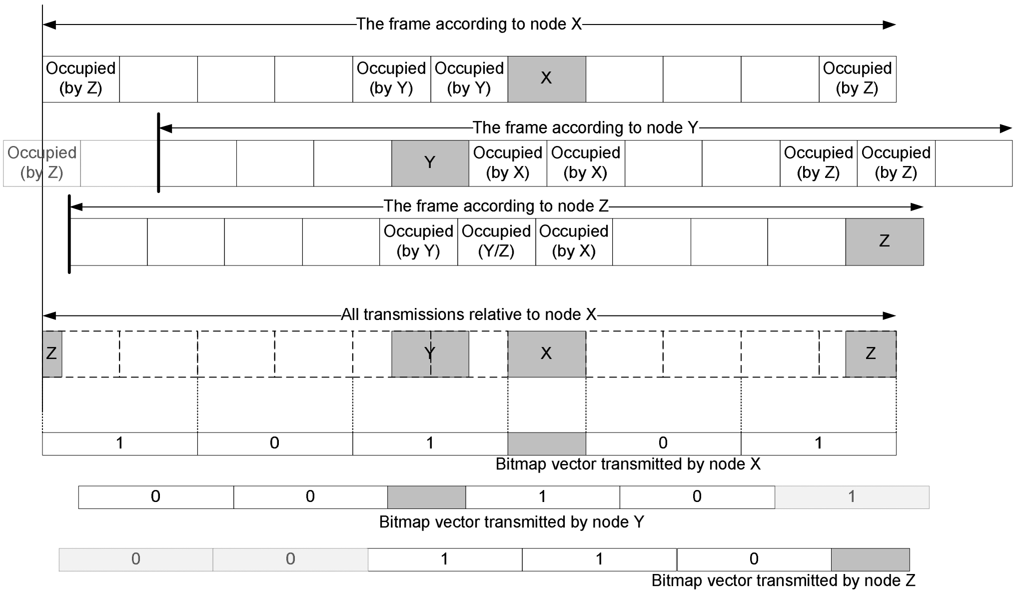
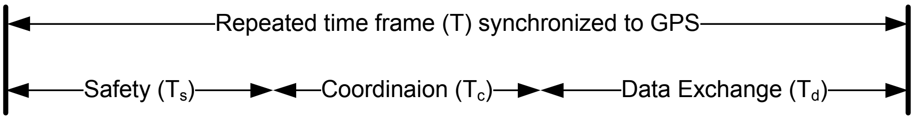


Figure 5: VeSOMAC Message Structure for three nodes. Adapted from [25].

Every slot is a segment of equal time within a repeating superstructure called a frame. Each node is allocated a transmission slot. The frame is essentially a period of time in every node, rather than a structured superset of all slots for all nodes. All frames have the same duration, but are not synchronized to that of other nodes. A node is compelled to use its allocated transmission slot, and to send what is called a bitmap vector that announces which slots are used by its one-hop neighbors. The bitmap vector contains 1s and 0s to indicate the occupancy of slots, relative to the node's own slot and as perceived by the node. Since the nodes' frames are not synchronized, a worst case synchronicity (marginally less than two slots) has to be assumed and therefore each bit in the bitmap represents two slots to avoid collisions. Since all nodes transmit the transmission slots of all their one-hop neighbors, it is claimed that a new node can avoid collisions with all its two-hop neighbors by choosing a slot that is unoccupied according to the combination of all one-hop neighbor time slots. It is not clear from the paper how a node combines the unsynchronized bitmaps from other nodes to form this timing-dependent decision, since the new node has to assume the worst-case synchronicity between all neighboring nodes, which significantly reduces the available slots. Every vehicle continuously attempts to reallocate its own transmission slot to follow immediately after (in time) the node traveling in front of it (in space). For this purpose, GPS information is added to the header transmitted in every allocated slot. Slot relocation is done by means of a collision resolution mechanism. When a node repeatedly detects that its neighbors do not acknowledge its allocated transmission slot, it assumes a collision is taking place and reallocates its transmission slot. The approach has some shortcomings: The system is designed for highway scenarios, and the evaluation is accordingly done for highways only. The system performance is expected to degrade significantly under urban conditions with numerous vehicles traveling in varying directions. The paper reports a round-trip delay that is longer than that of IEEE 802.11p. The assumption is made that clocks in each vehicle, even though asynchronous, are not drifting relative to each other. Drifting could have the effect that node transmissions collide during one interval and not during the next, thereby not reaching the collision detection threshold necessary to reallocate a new slot to avoid collisions. The overhead in the system is significant, since each node has to occupy a full transmission slot even if has no data to transmit. The scenario where two nodes collide and then iteratively and repeatedly jump to the same transmission slot in an attempt to relocate is not addressed. The size of a frame is a design parameter and does not cater for a congested group seceding to form a new group. The frame will therefore have to be designed for full capacity all the time, leading to severe underutilization if only a few nodes are present. In addition, there is no provision for utilizing the multiple channels allocated by the FCC [48].

Bi et al. [27] developed and evaluated a Multi-Channel Token Ring Protocol (MCTRP) for VANET. The research goal was to develop a contention-free MAC method that autonomously organize nodes into token passing rings to achieve low latency for safety messages and increased network throughput for non-safety applications. MCTRP works by grouping nodes with similar velocities into rings, each with a founder-leader node. A token passing TDMA scheme is used to control access to the medium for intra-ring data transmission, and CSMA/CA is used to control access to the medium for inter-ring data, emergency, and ring administration transmissions. Every node is equipped with two radios. The MCTRP message structure is illustrated in Figure 6. One is permanently tuned to WAVE channel 178, as allocated by the FCC [48], for inter-ring data communication, inter-ring safety message transmission and ring setup. The second radio is tuned to one of the six remaining WAVE channels that every ring uses for intra-ring transmissions of safety, coordination and data messages. MCTRP employs GPS synchronization and partitions its equal and repeating time segments (T) into safety periods (Ts), coordination (Tc) periods, and data exchange (Td) periods. This timing sequence is shared between Radio 1 and 2.



Inter-ring communications and ring founding - Radio 1 on CH 178

CSMA/CA	CSMA/CA with some NAV	CSMA/CA with RTS/CTS.

Intra-ring - Radio 2 on one of CH {172, 174, 176, 180, 182} as per RFN instruction

CSMA/CA	CSMA/CA	Token passing ring topology, coordinated by RFN during T_c

Figure 6: MCTRP Message Structure

MCTRP suffers from the following weaknesses: The ring topology with ring founder-leader nodes makes the system heavily reliant on these nodes. If a ring leader node departs, or goes out of range, the ring collapses and association has to be reinitiated. This makes the MAC more suited to scenarios where vehicles tend to platoon, rather than more erratic and unpredictable mobility patterns. The rules for ring organization and channel communication are computationally expensive, especially when faced with heavy traffic load and high node mobility. The ring topology is also fairly static since ring size is fixed. Given the ring topology, fixed ring sizes and fixed joining speed thresholds, it is likely that many nodes may not be able to join the rings. The system relies on connectivity between all nodes in the ring since the token needs to be passed between nodes and the founder-leader needs to be aware of all interactions. This scenario is idealistic and not likely because of the high mobility of vehicles, varying separation between vehicles, and harsh communication conditions. MCTRP uses CSMA/CA for safety messages and token passing TDMA for data transfers. This leads to a scenario where safety messages could face unbounded delays under heavy loads. The system depends on GPS for external timing as well as positional information. MCTRP is dependent on two radios per vehicle and full transmission slots are used even though a node may not need to transmit.

In [26] Su et al., developed and evaluated a clustering-based multichannel MAC (CBMMAC) that is similar to the MCTRP developed by Bi et al. [27]. The goal of this research was to develop a MAC for timely delivery of safety messages and increased throughput for non-real-time data. The protocol pools cars in close proximity and traveling in the same direction into groups called clusters. The seven WAVE channels are divided into four categories: An Inter-Cluster Control (ICC) channel, an Inter-Cluster Data (ICD) channel, a Cluster-Range Control (CRC) channel, and four Cluster-Range Data (CRD) channels. Each cluster has a self-elected leader, called the Cluster Head (CH), which controls the cluster and is also the source of synchronization. Every node is equipped with two transceivers. Channel allocation and MAC methods used by CBMMAC are summarized in Table 5.

Table 5: CMMAC Channel Categorization

	Transceiver	**Channel**	**MAC method**
Cluster Head (CH)	1	CRC	Contention-free TDMA & Broadcast
	2	ICC	Contention-based (e.g. IEEE 802.11)
Cluster Member	1	CRC	Contention-free TDMA & Broadcast
	2[1]	CRD	Contention-free (allocated channels)
		ICD	Contention-based (e.g. IEEE 802.11)
Non-member	1	ICC	Contention-based (e.g. IEEE 802.11)

One of the CH transceivers operates on the ICC channel using IEEE 802.11-based contention and the other on the CRC channel using contention-free TDMA and scheduled broadcast. The CRC is used to coordinate intra-cluster real-time traffic and non-real-time channel allocations using scheduled TDMA (from member nodes) and scheduled broadcasting (to member nodes). The message structure for the CRC communication is illustrated in Figure 7.

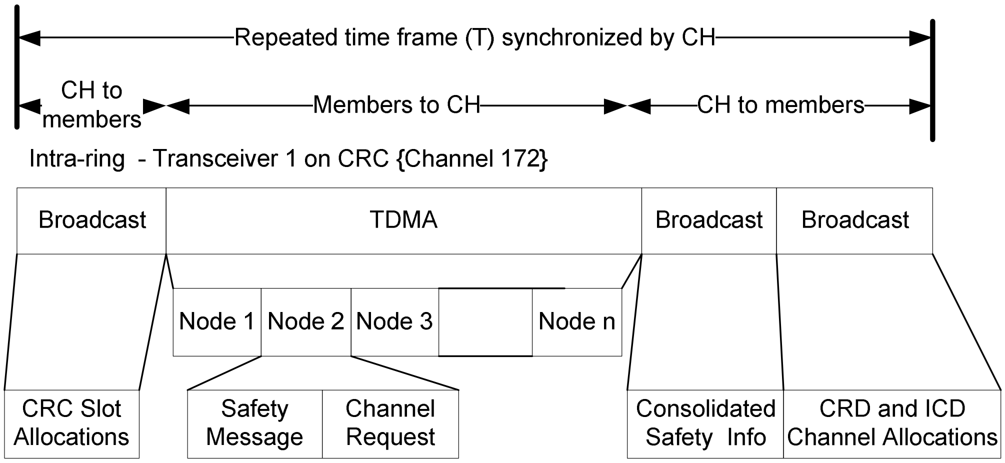


Figure 7: CMMAC CRC message structure. Adapted from [26].

For non-real-time data transfers within a group, the member nodes request transmission slots from the CH during their assigned real-time transmission slots. One of the member nodes' transceivers operates on the CRC channel and the other on one of the CRD channels. Non-member nodes, i.e. unassociated nodes, operate the first transceiver on ICC. One of the nodes in a cluster is assigned the role of gateway for inter-cluster data transmission on the ICD channel, and this node uses 802.11-based contention to gain access to the medium. It is not clear how this gateway node still takes part in intra-cluster communication with only one transceiver remaining since the paper does not describe the inter-cluster data transmission process in detail. Although the clustering-based multichannel MAC is meticulously planned, it also has some inadequacies: The system is exclusively designed for highway traffic, in fact, the system only activates once a highway is

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[1] The CH grants the member node use of its transceiver 2 for either CRD or ICD communication.

entered. The approach is intensely dependent on the CH, just as MCTRP, for coordination in the cluster. This dependence relies on vehicles flocking at low levels of relative mobility. One of the key benefits of using clusters or groups is diminished by using all 7 channels within one group. This will lead to high channel utilization when only one group is present, but high collision levels when two groups are in close proximity. Another weakness is the dependence on two radios per vehicle and GPS.

A Dedicated Multi-channel MAC (DMMAC) with adaptive broadcasting is proposed by Lu et al. [33]. The goals of this approach were to provide collision free and delay bounded delivery of safety messages with an adaptive broadcasting mechanism. In contrast to several of the proposed MAC approaches discussed earlier, only one radio is used per node. DMMAC builds on the WAVE structure by segmenting the 100 milliseconds synchronized interval into a CCH interval and an SCH interval of 50 milliseconds each (see Figure 3). The CCH is partitioned as a variable length Adaptive Broadcast Frame (ABF), made up of equally sized contention-free TDMA slots, and a Contention-based Reservation Period (CRP). Slot allocation is achieved by using a distributive control approach described below. The SCH, used for non-critical transmission, is called the Non-Safety Application Frame (NSAF). The ABF is used for safety and time-critical transmissions, while the CRP is used to coordinate resources (channel and time) allocation in the NSAF. Each node reports the slot allocation of all its one-hop neighbors (free/busy status and occupier ID) every time the node transmits.

A new node can thereby determine which slots in the ABF are not used by its two-hop neighbors and use the CRP to accordingly contend for a slot in the NSAF. Confirmation of successful occupation is achieved by inspecting slot allocation according to neighboring nodes’ transmissions. When a node has an allocated slot, it attempts to reallocate a slot nearer to the beginning of the frame in order to free slots at the end of the frame, which will become part of the CRP. During the NSAF, the channels are divided into slots of equal duration. The message structure employed by DMMAC is indicated in Figure 8.

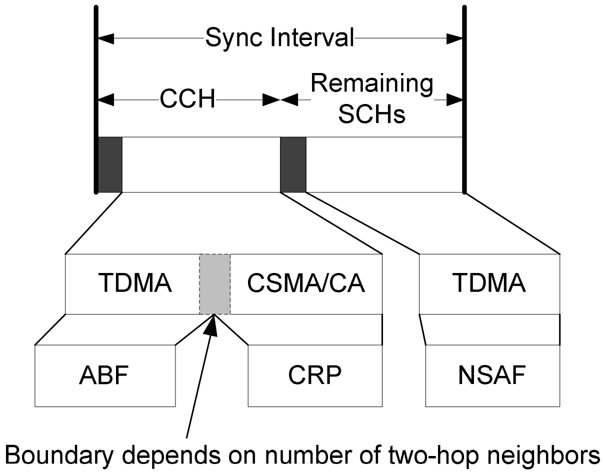

Figure 8: DMMAC Message Structure

Since [33] is only a working paper, the CRP and SCH processes are not explained and simulations are based on a limited set of simplistic highway scenarios. The approach proposed by Lu et al. has some serious drawbacks: The concept of making the ABF smaller when demand is less makes sense, since it releases unused bandwidth. Unfortunately the freed time is only in the negotiation and the coordination period (CRP) instead of the NSAF. NSAF has fixed slot sizes and slot numbers which will lead to under-utilization if few vehicles impose a heavy traffic load. The authors of this approach do not discuss what happens if a node falls out of range, and how its allocated slot will be freed. If all units reallocate to the beginning of ABF, and the ABF is shrunk accordingly, new nodes will not have slots available to contend for. The design allows nodes to negotiate for multiple channels in a geographically-unstructured way, which could lead to collisions (since only the ABF allocation of the two-hop neighbors is known, not the NSAF allocation).

We present in Table 6 a summary of the goals, salient features, and some benefits and drawbacks of each of the proposed MAC approaches discussed above.

Table 6: Summary of Recently Proposed MAC Protocols

	WAVE MAC [24][42]	**STDMA** [32]	**VeSO-MAC** [25]	**MCTRP** [27]	**CBM-MAC** [26]	**DMMAC** [33]
Goals of alternative MAC approaches	—	Maritime collision avoidance	Improved data throughput	Decreased emergency message latency and increased network throughput	Guarantee safety message delivery with non-critical data support	Collision-free and delay bounded safety message delivery with adaptable data throughput
Intended and simulated for highway scenarios	YES	Partially[1]	YES	YES	YES	YES
Intended and simulated for urban scenarios	YES	Partially[1]	NO	NO	NO	NO
Delay bounded time-critical transmission	NO	Partially[2]	Partially[3]	YES	YES	YES
Provision for non-critical transmission	YES	NO	YES	YES	YES	Partially[4]
Leaderless time and channel coordination (independent of leader node)	YES	YES	YES	NO	NO	YES
Self-synchronous (independent of GPS for timing)	NO	NO	YES	NO	YES	NO
WAVE MAC timing compliance (Figure 3)	—	NO	NO	NO	NO	YES
Bandwidth allocation adapts to demand	NO	Partially[5]	NO	NO	NO	Partially[6]

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[1] STDMA is used for maritime and aviation surveillance and collision avoidance.

[2] STDMA overloads slots, assigning a slot to nodes furthest apart if the medium becomes full.

[3] Distinction not made for safety messages, but due to the TDMA used, bounded transmission can be expected.

[4] The timing structure makes provision for non-critical transmission, but the process is not covered in the paper.

[5] STDMA overloads slots, assigning a slot to nodes furthest apart if the medium becomes full.

[6] DMMAC does modify the contention-free period based on the number of vehicles, but the non-critical transmission opportunity is not increased accordingly, the contention-based coordination time is.

	WAVE MAC [24][42]	**STDMA** [32]	**VeSO-MAC** [25]	**MCTRP** [27]	**CBM-MAC** [26]	**DMMAC** [33]
Multi-channel operation (exploits the WAVE channels)	TBD	NO	NO	YES	YES	YES
Radios per vehicle [1]	TBD	1	1	2	2	1
Complexity (level of coordination and management required)	Simple	Fairly simple	Fairly simple	Fairly complex	Fairly complex	Complex

5. FUTURE MAC CHALLENGES FOR VANET AND DISCUSSIONS

The MAC method is at the core of sharing the wireless medium with limited bandwidth efficiently among all vehicles, most of which are highly mobile. We have presented a survey of the various MAC approaches that have been proposed in the literature to enable efficient sharing of the wireless medium for VANET environments. In this section, we present and discuss some of the MAC research challenges that still need to be addressed through innovative solutions to enable the diverse range of VANET applications.

5.1 Contention, Location of Control, and Node Dependence

As was noted earlier, MACs can be categorized in terms of how nodes engage the medium and who controls access to it. Contention-based approaches are more suited to the inherently mobile nature of VANETs, since coordination is kept to a minimum. However, unbounded delays could exist, which is problematic for safety critical messages as well as infotainment that relies on a minimum QoS. Contention-free MACs tend to require coordination, frequent updating, and grouping and is susceptible to changes introduced by node mobility. It does, however, guarantee QoS. The control of this coordination needs to reside somewhere. The control can be distributed between the nodes with a shared algorithm or it can reside with a group leader. For the latter, the reliance is problematic given the unpredictable and mobile nature of vehicles, especially in urban areas. One possible approach would be where the safety and other time-critical messages are transmitted using a contention-free method. Other transmissions should either be contention-based or contention-free in a subdivided timeframe with slots allocated proportionally to nodes based on demand, which will ensure high channel utilization. The coordination control should preferably be distributed and as lightweight as possible.

5.2 Synchronization and Dependence on External Timing (GPS)

Based on the literature survey, we found that several of the available MAC methods rely on external GPS synchronization in order to achieve contention-free communication. Although many cars are expected to be equipped with navigation devices in future, this reliance could be problematic in scenarios where GPS reception is hampered (such as tunnels, between high buildings, etc.) making it difficult for GPS-based proposed approaches to continue to operate.

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[1] Where two radios are used, one is used for inter-group communication or group coordination, and the other for intra-group communication.

5.3 Channel Utilization and Fairness

The FCC prescribes seven WAVE channels for VANET use. Some of the available MAC approaches that were reviewed are limited to using a single channel. To make these approaches viable they need to expand to use all seven channels. Even though some of the approaches use all seven channels, channel utilization still needs to be addressed. Multi-channel support leads to the problem of how many radios to include. Current multi-channel solutions use two radios per vehicle. The automotive industry is exceedingly cost driven and a solution with multiple radios may not be cost-effective.

An issue that has not received attention with the available V2V MACs is fairness. A fundamental requirement for MAC is whether it fairly allocates access to the medium. There are numerous ways to define fairness. Contention-based MACs could be considered fair, since all nodes equally contend for the medium. A contention-free, pure TDMA approach could be considered fair, since all nodes have an equally long time slot. An equality of opportunity approach to fairness could be to allow every node to express its demand using a pure TDMA approach and then subdivide the remainder of the transmission period equally as required with another TDMA session.

5.4 Dynamic Adaptation Based on Varying Number of Nodes

Due to the high levels of mobility and the flocking nature of vehicles, the number of nodes in a given range could vary significantly. The contention-free MACs typically have a design parameter specifying how many nodes could be allowed into a group, token ring or TDMA sequence. This approach suffers from a limitation since the group size is optimized a priori for a traffic load and scenario, and if possible this limitation should be avoided.

5.5 Supporting Emergency Messages and Infotainment

The majority of MACs reviewed focused on safety message transmissions, rather than on non-time-sensitive message transmission. As was mentioned earlier, a great market driver of VANET deployment is expected to be non-safety applications such as infotainment and Internet connectivity. Future MAC methods should address this requirement by explicitly providing a means of transmitting high volume information with less stringent time-critical requirements while still providing timing guarantees for those with time-sensitive characteristics.

5.6 Coverage of Traffic Scenarios

A large number of the available MAC methods are purpose-made for highway scenarios and do not address the different requirements presented by urban and sub-urban traffic scenarios. Future MAC solutions for VANET should take into account these additional traffic scenarios in their designs and architectures.

6. CONCLUSION

Fast and reliable MAC protocol support is crucial to enable the broad range of envisioned VANET applications. In this work, we focused primarily on a review of MAC approaches that have been recently developed for V2V VANET scenarios. We discussed the details of recent VANET standards such as IEEE 802.11p/IEEE 1609.4 and we described the MAC support provided by each of these standards. We discussed the benefits and shortcomings of various MAC approaches that have been proposed in the literature. Such approaches include a novel 802.11 implementation with adaptive DCF, and a self-organizing collision-free TDMA approach called VeSOMAC. We also presented a self-organizing TDMA approach (STDMA) used in aviation and marine environments, MCTRP that combines a token-based contention-free intra-ring MAC with contention-based inter-ring communication, a clustering method with a cluster head that combines scheduled contention-free intra-cluster communication with contention-based inter-ring communication, and lastly, a dedicated multi-channel MAC with adaptive broadcasting. We also outlined some of the challenges not yet addressed by past proposed MAC methods that need further investigations and novel solutions.

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ACRONYMS

Table 7: List of Acronyms

2G	2nd Generation International Mobile Telecommunications
3G	3rd Generation International Mobile Telecommunications
ABF	Adaptive Broadcast Frame
ACK	ACKnowledge
AIS	Automatic Identification System
AP	Access Point
ARIB	Association of Radio Industries and Businesses
ASTM	American Society for Testing and Materials
BSS	Basic Service Set
CA	Collision Avoidance
CALM	Communications Access for Land Mobiles
CCH	Control CHannel
CDMA	Code Division Multiple Access
CEN	European Committee for Standardization
CFR	Code of Federal Regulations
CH	Cluster Head
CRC	Cluster-Range Control
CRD	Cluster-Range Data
CRP	Contention-based Reservation Period
CSMA	Carrier Sense Multiple Access
CTS	Clear To Send
CW	Contention Window
DCF	Distributed Coordination Function
DMMAC	Dedicated Multi-channel MAC
DSRC	Dedicated Short Range Communication
EDCA	Enhanced Distributed Channel Access
EDGE	Enhanced Data Rates for GSM Evolution
ETC	Electronic Toll Collection
ETSI	European Telecommunications Standards Institute

FCC	Federal Communications Commission
FDMA	Frequency Division Multiple Access
GPRS	General Packet Radio Service
GPS	Global Positioning System
ICC	Inter-Cluster Control
ICD	Inter-Cluster Control
ISM	Industrial Scientific and Medical
ISO	International Organization for Standardization
ITS	Intelligent Transportation System
LLC	Logical Link Control
MAC	Media Access Control
MCTRP	Multi-Channel Token Ring Protocol
MLME	MAC Layer Management Entity
NAV	Network Allocation Vector
NSAF	Non-Safety Application Frame
OBU	On Board Unit
PHY	PHYsical layer
PLME	Physical Layer Management Entity
QoS	Quality of Service
RF	Radio Frequency
RSU	Road Side Units
RTS	Request To Send
SCH	Service CHannel
SDMA	Space Division Multiple Access
TC	Technical Committee
TDMA	Time Division Multiple Access
TXOP	Transmit OPportunities
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
VANET	Vehicular Ad-hoc NETworks
VeSOMAC	Vehicular Self-Organizing MAC
WAVE	Wireless Access for Vehicle Environments
WBSS	WAVE Basic Service Set
Wi-Fi	Wireless Communication Based on IEEE 802.11
WiMAX	Worldwide Interoperability for Microwave Access
WME	WAVE Management Entity
WSMP	WAVE Short Message Protocol

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