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A Survey and Analysis on TDMA Based MAC Protocols for VANETs

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Abstract**: *Vehicular Ad hoc Networks, known as VANETs, are deployed to decrease the probability of road accidents and to improve passenger comfort by allowing vehicles to exchange different kinds of data messages between the mobile vehicles and the installed infrastructure. VANETs facilitate improved traffic safety and efficiency. Each vehicle can exchange information to inform other vehicles about the current status of the traffic flow or a dangerous situation such as an accident. Moreover, traffic safety applications need a reliable communication scheme with minimal transmission collision, which leads to the need for an efficient and reliable MAC. Design MAC for VANETs is a complex task due to the high mobility of the nodes, the frequent changes in topology, the lack of an infrastructure, and various QoS requirements. In the past years, various Time Division Multiple Access (TDMA) based medium access control protocols have been proposed for VANETs in an attempt to assure that all the vehicles have sufficient time to send safety messages with minimum collisions and to reduce the end-to-end delay and the packet loss ratio. In this survey paper a qualitative comparison provided in order to improve the performance of TDMA-based MAC protocols for V2V communication and also focused on the detailed characteristics of these protocols, their benefits and limitations.***
Keywords: Ad hoc, DSRC, IEEE 802.11p, MAC Protocols, TDMA, QoS, V2V, V2I, VANET.

I. INTRODUCTION

Vehicular ad hoc networks (VANETs) are emerging as a promising technology for providing safety and comfort applications for vehicular transportation. VANETs are receiving growing attention from the research community and from the transportation industry because of their great potential to improve traffic safety on roads. They can also be used to improve traffic management conditions and to provide on-board infotainment such as Internet access, video streaming, etc. VANETs are an example of Mobile Ad hoc Networks (MANETs) but with their own specification: high node mobility with constrained movements and the mobile nodes have ample energy and computing power (i.e. Storage and processing) [1]. In VANETs, communications can either be between vehicles V2V (Vehicle To Vehicle) or between vehicles and roadside units V2I [2] (Vehicle to Infrastructure). The applications for V2V and V2I can be divided into the following three services: safety services, traffic management and user-oriented services [3], [4]. Safety services have special requirements in terms of quality of service. In fact, bounded transmission delays as well as low access delays are mandatory in order to offer the highest possible level of safety. At the same time, user-oriented services need a broad bandwidth. Medium Access Control will play an important role in satisfying these requirements. In VANETs, the nodes share a common wireless channel by using the same radio frequencies and therefore an inappropriate use of the channel may lead to collisions and a waste of bandwidth. Hence, channel sharing is the key issue when seeking to provide a high quality of service. VANETs are designed to provide several services to enhance road safety. This objective can essentially be achieved by the use of efficient safety applications which should be able to wirelessly broadcast warning messages between neighboring vehicles in order to rapidly inform drivers about a dangerous situation such as an accident. To insure their efficiency, safety applications require reliable periodic data dissemination with low latency. Medium Access Control (MAC) schemes must be designed to share the medium between the different nodes both efficiently and fairly. However, due to the special characteristics of VANETs, traditional wireless MAC protocols are not suitable for use in VANETs which leads either to adapting these traditional MAC protocols or to design new mechanisms. Generally, MAC protocols fall into one of two broad categories: contention-based and contention-free. In contention-based protocols, each node can try to access the channel when it has data to transmit using the carrier sensing mechanism [5]. Several neighboring nodes can sense a free channel, and so decide to access and transmit their data at the same time, which generates collisions at the destination nodes.

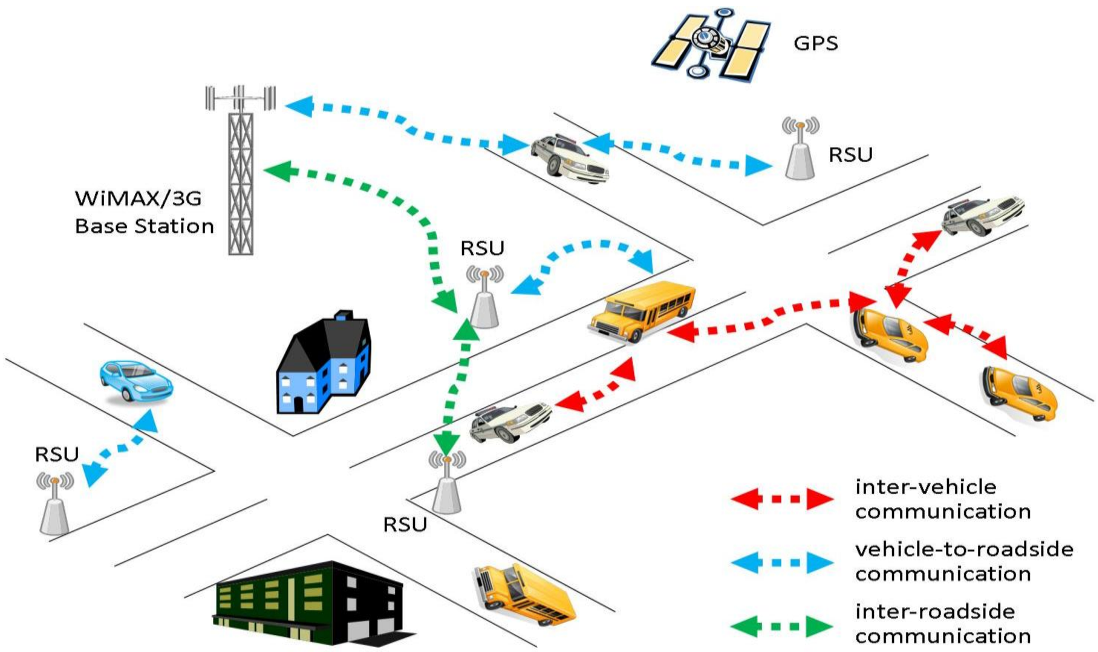

Fig. 1 VANET Scenario
(Source: https://i.ytimg.com/vi/DrH-1505-Mg/maxresdefault.jpg)

Contention-free MAC protocols try to avoid this by assigning access to the channel to only one node in a neighborhood at any given time. Contention-based protocols do not require any pre-defined schedule; each node will compete for channel access when it needs to transmit, without any guarantee of success. For real-time applications this may cause problems such as packet loss, or large access delay. On the other hand, contention-free protocols can provide bounded-delays for real-time applications, but require the periodic exchange of control messages to maintain the schedule table and require time synchronization between all the nodes in the network. In order to provide QoS and reduce collisions in VANET networks, MAC protocols must offer an efficient broadcast service with predictable bounded delays. They must also handle frequent topology changes, different spatial densities of nodes and the hidden/exposed node problem. They have to support multi-hop communication and nodes (vehicles) moving in opposite directions. The relevance of these issues has been confirmed by the development of a specific IEEE standard to support VANETs.

The IEEE 802.11p [6], which is the emerging standard deployed to enable vehicular communication, is a Contention-based MAC protocol, 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 [7]. The IEEE 802.11p standard does not provide a reliable broadcast mechanism with bounded communication delay. This disadvantage is particularly important in VANETs which are specially designed to improve road safety. Therefore, designing an efficient MAC protocol that satisfies the QoS requirements of VANET applications is a particularly challenging task. Currently, a great deal of research work on contention-free MAC protocols for VANETs is being carried out. These protocols help avoid the disadvantages of the IEEE 802.11p standard by eliminating the need for a vehicle to listen to the channel before it starts its transmission and by reducing the time to access the channel when node density is high. Several contention-free MAC protocols have been proposed in the literature for inter-vehicle communications, including Frequency Division Multiple Access (FDMA), Code Division Multiple Access (CDMA), and Time Division Multiple Access (TDMA). These protocols solve the collision problem as in the IEEE 802.11p standard by assigning respectively a unique frequency band, code sequence or time slot to each vehicle in a given channel contention area. Therefore, these protocols are suitable for VANET safety applications in terms of access delay and the collision rate. FDMA-based MAC protocols require that the transmitter and the receiver be synchronized the same channel frequency. Hence, a frequency synchronization mechanism is necessary to match the communicating vehicles to each other. The synchronization algorithm usually requires creating a dedicated control channel frequency which will be used by the vehicles to negotiate frequencies by exchanging control messages.

This makes the FDMA mechanism, very complex and adds a high communication overhead. Unlike FDMA, the CDMA scheme uses the same channel frequency which is shared between different vehicles by assigning unique code sequences. At the beginning of each communication, the sender and receiver must agree on the code to use in a way that reduces the risk of collision as much as possible. A CDMA code assignment algorithm is therefore required to negotiate and allocate codes for every communication, which means that the CDMA scheme has a significant overhead and an increased transmission delay.

An emerging area of research in the field of VANETs is a TDMA-based MAC protocol where the time is divided into slots and only one vehicle can access the channel at each time slot. In TDMA all the vehicles use the same frequency channel without any code sequence, but at a different time. This means that the transmitter and the receiver have to be frequency synchronized. In contrast to the FDMA scheme, which can suffer from interference between vehicles using the same frequency band and start transmitting at the same time, the TDMA technique ensures that they will not experience interference from other simultaneous transmissions. Moreover, TDMA can efficiently support I2V communication, as fixed RSUs can be used to create and manage the TDMA slot reservation schedule. Another important feature of the TDMA scheme is that it allows a different number of time slots to be allocated to different vehicles. This means that the bandwidth resources can be assigned on-demand to different vehicles by concatenating or rescheduling time slots based on priority access. By providing, in principle, Collisions may, however, occur with TDMA, collision-free transmission with bounded access delay, and TDMA is better suited to the requirements of VANETs. Recently, MAC protocols, notably those that are based on the TDMA technique, have attracted a lot of attention and many protocols have been proposed in the literature. Although these protocols can provide deterministic access time without collision, in order to operate efficiently they must be aware of the neighbours slot allocation.

In addition, most of them make use of real-time systems that provide location and time information such as the Global Positioning System (GPS) which allow them to synchronize the communicating vehicles. However, many issues arise due to higher vehicle mobility in VANETs which can affect the performance of these protocols. Therefore, the scheduling mechanism in TDMA protocols should take into consideration the mobility features of VANETs so as to avoid collisions. Several TDMA-based MAC protocols such as VeMAC [8], TC-MAC [9] and ACFM [10] proposed in the literature address the TDMA issues in such mobility scenarios. These protocols will be discussed in the next sections. In this paper, we provide a survey of TDMA-based MAC protocols, and we discuss how well these protocols can satisfy the stringent requirements of VANET safety applications as well as how well they can handle the highly dynamic topology and the various conditions of vehicular density that are often present in VANETs.

II. VANET STANDARDIZATION

A. Dedicated Short Range Communication

DSRC was initially coined in USA by the FCC (Federal Communication Commission). It was developed to support V2V and V2I communications. This standard supports vehicle speeds up to 190 km/h, a data rate of 6 Mbps (up to 27 Mbps) and a nominal transmission range of 300 m (up to 1000 m). DSRC is defined in the frequency band of 5.9 GHz on a total bandwidth of 75 MHz (from 5.850 GHz to 5.925 GHz). This band is divided into 7 channels of 10 MHz (see Figure 2). These channels are divided functionally into one control channel and six service channels. The control channel, CCH, is reserved for the transmission of network management messages (re-source reservation, topology management) and it is also used to transmit high priority messages (critical messages relating to road safety). The six other channels, SCHs, are dedicated to data transmission for different services. Moreover the IEEE 802.11p standard was adopted as the Medium Access Control (MAC) and Physical Layer (PHY) specifications for the lower-layer DSRC standard.

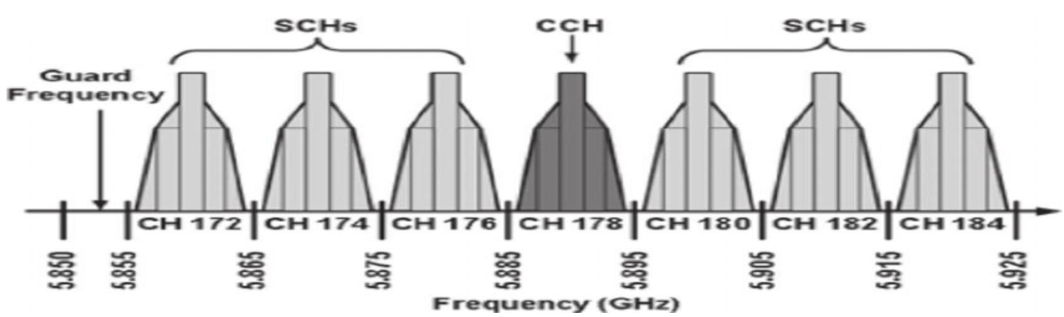

Fig. 2 Channel Assignment in DSRC
(Source: https://www.researchgate.net/figure/279163235_fig2_Fig-2-Channel-assignment-in-DSRC)

B. IEEE 802.11p

The IEEE 802.11p [6] standards, which improve the existing IEEE 802.11to support VANETs, have been proposed by the Task Group of the IEEE. This standard improves QoS by using the Enhanced Distributed Channel Access (EDCA) functionality, derived from the IEEE 802.11e standard [7]. The EDCA allows safety messages which have a higher priority to have a better chance of being transmitted than messages with a lower priority. Prioritization is achieved by varying the Contention Windows (CWs) and the Arbitration Inter-Frame Spaces (AIFS), which increase the probability of successful medium access for real time messages. The channel access time is equally divided into repeating synchronization intervals], and each synchronization interval is divided into CCH Intervals (CCHI) and SCH Intervals (SCHI). During the CCHI all the vehicles tune to the CCH to send/receive high priority safety messages or to announce a service that will be provided on a specific service channel. If a vehicle decides to use this service on a specific SCH channel, it tunes to this channel during its SCHI. In order to support different applications concurrently, IEEE 1609.4 defines multichannel operation for the MAC of the IEEE 802.11p standard. However, if there are two antennas, the first one is tuned to the CCH, while the second one is tuned to the SCH, which will eliminate the need for any channel switching operation and thus enable each vehicle to broadcast safety messages throughout of the CCHI without a Guard Interval.

C. Wireless Access in Vehicular Environment (WAVE)

WAVE is a mode of operation which is used by IEEE 802.11 devices to operate in the DSRC band. It is a protocol stack that defines the functions of protocols in each layer in VANETs, and describes the interaction between each layer and its upper and lower layers. As shown in Figure 3, the WAVE stack incorporates a number of protocols in conjunction with the family of the IEEE 1609 standards [7].

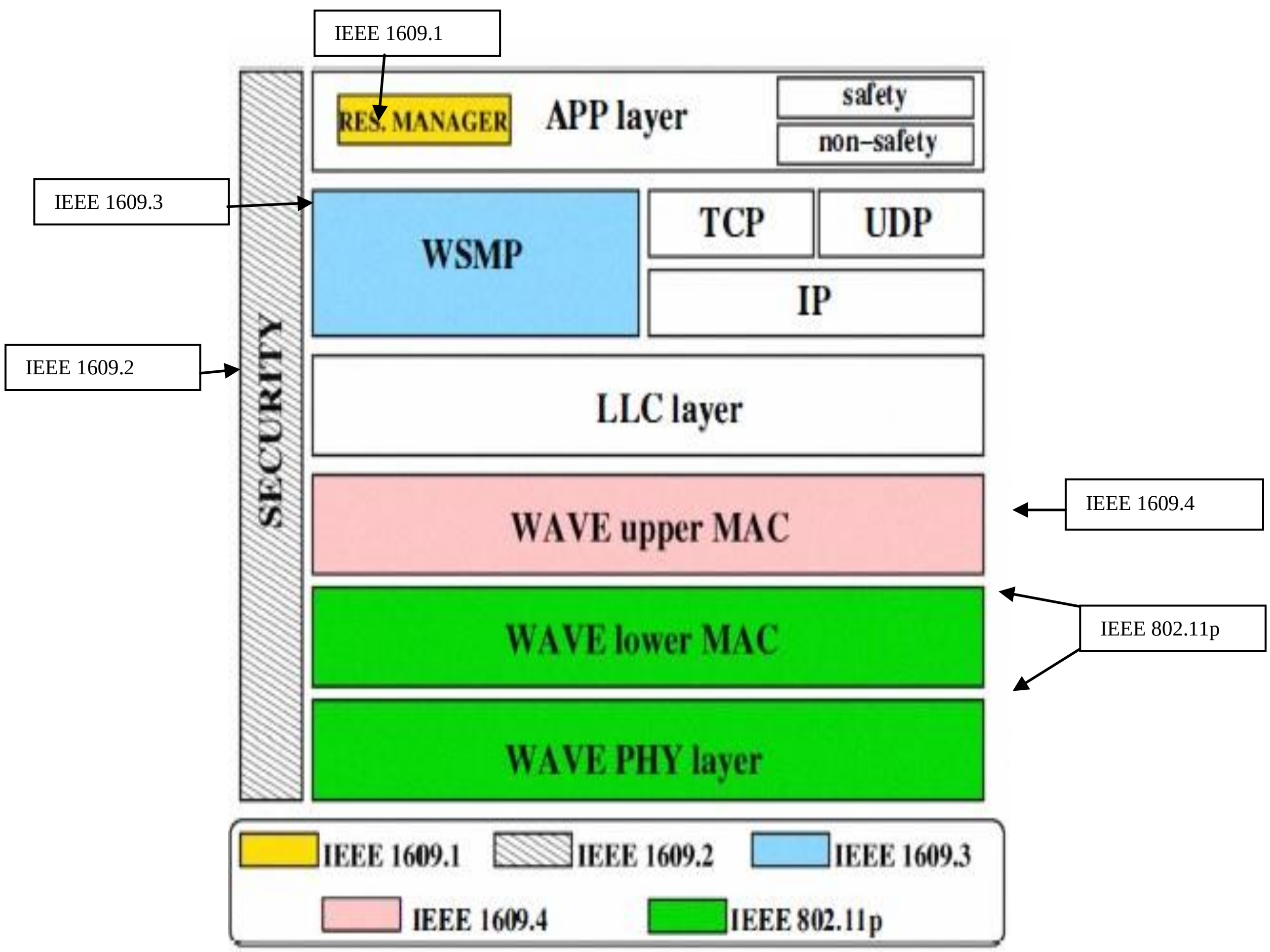

Fig. 3 WAVE stack architecture

Upper protocol layers, as defined by OSI architecture, are covered by IEEE 1609 specifications. Four 1609 sub-groups are defined as:

1) IEEE1609.1, Resource Manager, Upper layers.
2) IEEE1609.2, WAVE Security services.
3) IEEE1609.3, Network layer; WAVE short message protocol (WSMP) is responsible for addressing and routing. It ensuresthat communication system supports two protocols stacks. The two stacks supported by WAVE are traditional Internet Protocol version six (IPv6) and a proprietary one known as WAVE Short-Message Protocol (WSMP). The reason for having two protocol stacks is to accommodate high-priority, time-sensitive communications, as well as more traditional and less demanding exchanges, such as Transmission Control Protocol/User Datagram Protocol (TCP/UDP) transactions. WSMP enables the application to send short messages and directly control certain parameters of the radio resource to maximize the probability that all the implicated parties will receive the messages in time.
4) IEEE1609.4 is defined for multi-channel operations. Together with IEEE802.11p it takes care of the lower layers. This protocol defines a time-division scheme for DSRC radios and subsequently supports different applications concurrently.

III. RELATED WORK

Many survey papers in the literature have been written in order to summarize and categorize MAC QoS issues and solutions for VANETs. The work in [11], surveys some aspects and the role of MAC protocols in Vehicular Ad-Hoc Networks. The authors in this article outline MAC protocols in VANETs without any detailed analysis and classification. Menouar et al. in [12] survey a number of MAC protocols designed for MANETs. However, the most recent protocol discussed in this article was published in 2004. Then a qualitative comparison is given between those that can be adapted for VANETs, i.e. ADHOC MAC and IEEE 802.11. The two protocols are analysed according to certain characteristics such as time synchronization based, multicast/broadcast based, mobility-aware, and QoS and real-time capability. Booysena et al. in [13] provided an overview of many V2V MAC protocols including various VANET standards that were proposed for VANETs in 2009 and 2010. The authors focused on the benefits and limitations of the MAC protocols proposed. Their conclusions highlighted some challenges that still need to be addressed in future work to enable the implementation of highly efficient MAC protocols for VANETs. These challenges are outlined below:

1) Contention-free protocols can satisfy QoS requirements for real-time applications but they need a high level of coordination due to the special characteristics of VANETs.
2) Contention-based protocols are not suitable for important safety messages due to their unbounded delay and low performance in highly dense networks.

Finally, some multi-channel MAC protocols proposed both for MANETs and VANETs to take full advantage of the seven available channels were surveyed in [14]. The authors also provided a short overview of many issues involved in the design of multi-channel MAC protocols in VANETs. The novelty of our survey with respect to other survey papers in the same area is that it focuses on certain specific MAC protocols, namely those that are based on the TDMA method and it gives a novel topology-based classification of these protocols. We discuss and analyse them from a design perspective, i.e. how to coordinate channel access for neighboring vehicles, how to adapt the TDMA method to the particular characteristics of VANETs, how to optimize TDMA-based MAC protocols, what mobility scenarios and which metrics can be used to evaluate the performance of such protocols. In this paper, we provide an in-depth and comprehensive overview of many recent TDMA-based MAC protocols according to the nature of the topology of the network and we discuss how well these protocols address the above issues. The main contributions of the paper are listed below:

1) We review the features of VANETs and the recent standardization activities in the field, together with their shortcomings at the MAC layer.
2) We give an insight into general VANET MAC protocol design issues, and we set out the reasons for using collision-free medium access control, e.g. TDMA, in VANETs.
3) We classify the recent TDMA-based MAC protocols into three different categories based on the network topology. For each category, we identify and describe the TDMA problems that can occur in each topology. Review and discuss the available TDMA-based MAC protocols in the literature, and highlight their strengths and weaknesses. Provide a comparison of these protocols for QoS provisioning in VANETs.
4) We provide a statistical analysis to draw several important conclusions, e.g. to identify the most widely addressed MAC issues over recent years, and which QoS parameters have been the most studied.

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IV. MEDIUM ACCESS CONTROL IN VANETs

VANETs are designed to provide several services to enhance road safety. This objective can essentially be achieved by the use of efficient safety applications which should be able to wirelessly broadcast warning messages between neighboring vehicles in order to rapidly inform drivers about a dangerous situation such as an accident. To insure their efficiency, safety applications require reliable periodic data dissemination with low latency. Medium Access Control (MAC) protocols in VANETs play a primary role in providing efficient delivery. Medium access protocols are situated in the Data Link Layer, which is not only responsible for ensuring fair channel access, but also for providing multi-channel operation and error control.

A. Classification of Medium Access Control Protocols

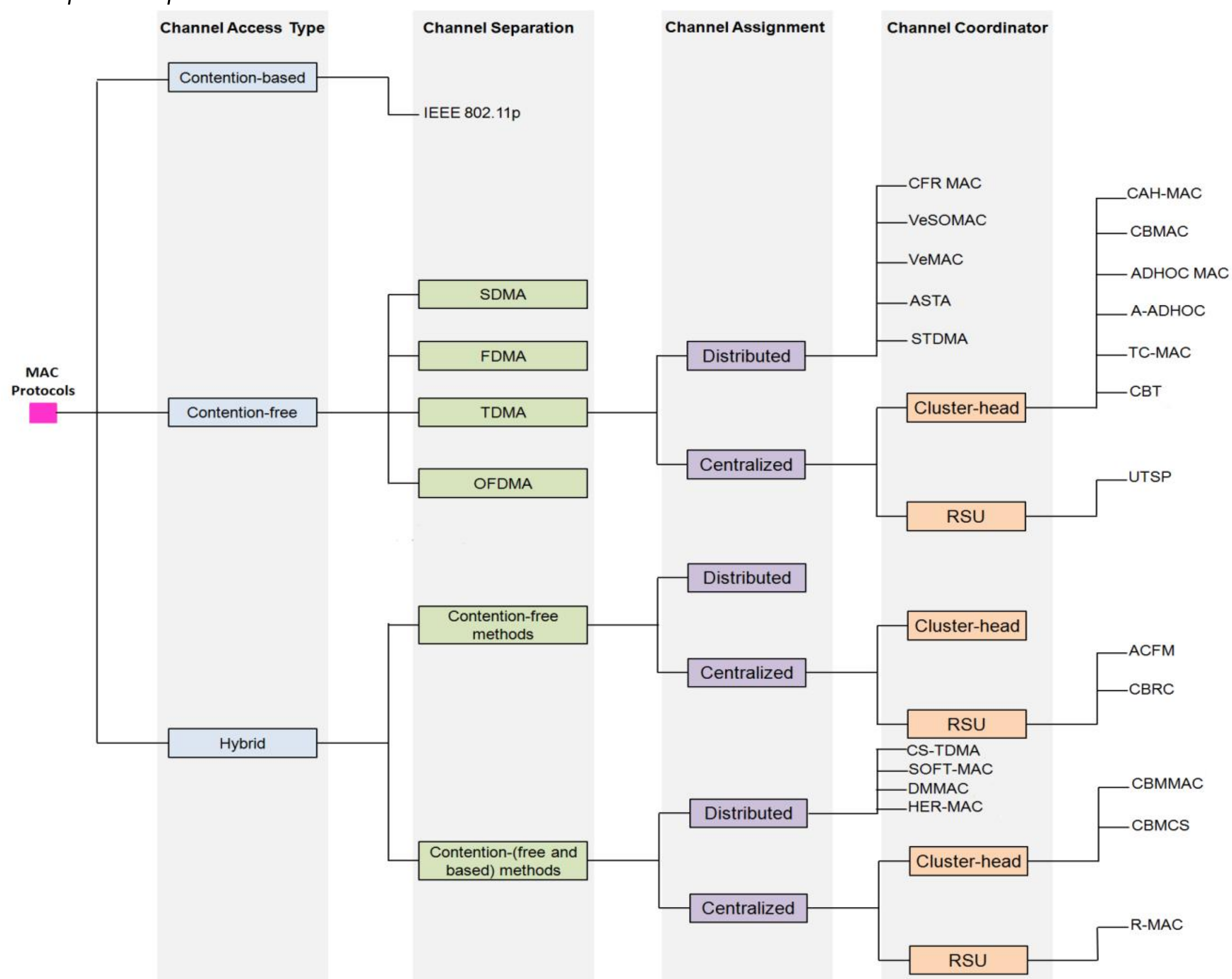

Fig. 4: Classification of TDMA-based MAC protocols

Several MAC protocols have been designed for inter-vehicle communications. They can be classified into three categories depending on the channel access methods used, namely the contention-based medium access method such as IEEE 802.11p [6], and the contention-free medium access method. The third category is a hybrid of the two previous methods. Figure 4 represents a classification of MAC protocols for VANETs. Contention-based MAC protocols represent the majority of MAC protocols proposed for VANETs. There is no predetermined schedule and they allow vehicles to access the channel, randomly when they need to transmit. As a result, transmission collisions are inevitable when the network load is high. The current IEEE 802.11p standard, which is presented in the previous section, is a contention-based protocol which cannot guarantee the QoS requirements for critical road safety applications. Several techniques have been proposed to improve the scalability of contention-based MAC protocols under heavy load conditions in VANETs, see [17], [18].

These mechanisms consist in adaptively adjusting the most important parameters of the IEEE 802.11p standard, namely the physical carrier sense threshold, the minimum contention window, and the transmission power control. Unlike contention-based MAC protocols, contention-free MAC protocols require a predetermined channel access schedule. Several contention-free MAC proto-cols have been proposed in the literature for inter-vehicle communications, including Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA) and Code Division Multiple Access (CDMA).

These protocols allow each vehicle to access the channel by a predetermined time slot, frequency band or code sequence, respectively. The major advantage of such protocols is that there are no message collisions between vehicles in the same two-hop neighborhood. Contention based and contention free MAC protocols each have their own specific tools to reduce the packet loss ratio. In recent years, there have been several hybrid proposals, which try to combine these two mechanisms into a single architecture to enhance their capabilities to provide a high QoS and reduce the collision rate. All these protocols divide the access channel into two periods (random access period and contention-free access period), in which the first period is used by the nodes to create a channel access schedule to be used in the second period. This paper will assess and highlight MAC protocols using Time Division Multiple Access (TDMA).

B. VANET MAC protocol design issues

Providing efficient MAC protocols in a VANET raises several key technical challenges:

1) *High speed:* Due to the high levels of speed, many vehicles can join a group of vehicles at any time. However, contention-free MAC protocols typically have a fixed parameter which specifies how many nodes can access the channel, whereas contention-less MAC protocols do not work well with high loads.
2) *Frequently changing network topology*: The open and important question is how MAC protocols can seamlessly adapt to frequent changes in topology. The MAC protocols must also be able to operate at highway and urban scenarios.
3) *No central coordination:* due to the lack of infrastructure in VANETs, there is generally any centralized coordinator. Therefore, the medium access control protocol must take this constraint into consideration and the control must be distributed among the vehicles. In order to ensure fair channel utilization without access collisions, neighboring vehicles must exchange control messages. Therefore, the MAC protocol must make sure that this overhead does not consume too much precious bandwidth.
4) *Scalability:* MAC protocols should be designed to support an efficient channel utilization mechanism under different traffic load conditions (large and/or dense VANETs).
5) *Broadcast support:* The open question is how to support an efficient broadcast service in MAC protocols in order to announce some information with a regional scope.
6) *The hidden and exposed node problems:* these two problems are the result of the broadcast nature of VANETs, since it is not possible to use RTS/CTS messages to prevent collisions for broadcast messages. The hidden node problem occurs when two vehicles that are not within transmission range of each other perform a simultaneous transmission of a vehicle that is within the transmission range of each of them. On the other hand, the exposed node problem occurs when a vehicle is prevented from sending packets to other vehicles due to a neighboring transmitter.
7) *Different QoS requirements:* Due to different QoS requirements in VANETs, MAC protocols should provide transmission services without collisions and with a bounded delay for high priority safety applications while, at the same time, ensuring a high throughput for infotainment applications. When safety messages are broadcasted, they should be given a higher access priority than other data messages.
8) *Time synchronization:* In order to be able to implement time-slotted MAC protocols, clock synchronization between vehicles in VANETs is an important issue. Most contention-free TDMA-based MAC protocols assume that all the vehicles can be synchronized at the start of each TDMA frame by using the 1PPS signal provided by the Global Positioning System (GPS) in each vehicle. It is generally assumed that each vehicle is equipped with a positioning system, e.g. GPS, which is not guaranteed to operate correctly in all the scenarios, for example when there are tunnels, high buildings, etc.
9) *Multichannel operation:* Typically, a node in an ad hoc network has a transceiver allowing it to listen or transmit on one channel at a time. To ensure maximum connectivity, all the nodes tune their transceivers to the same channel. However, as the node density increases the collision rate increases. To reduce collisions, the neighboring nodes can potentially transmit on different channels simultaneously. Therefore, the MAC protocols should implement a dynamic multichannel operation algorithm which is able to switch between different channels quickly to increase network throughput without a central coordinator.

Although the FCC (Federal Communication Commission) has established the DSRC service defined on the frequency band of 5.9 GHz divided into seven channels, there are many MAC protocols which are limited to using a single channel.

10) *Adjacent Channel Interference*: The parallel usage of the Control Channel (CCH) and the Service Channels (SCHs) in order to increase the transmission rate and decrease the packet loss ratio impacts communication by generating interference signals. This problem is known as Adjacent Channel Interference (ACI) which has been evaluated for VANETs.

C. Performance metrics

Due to the wide range of MAC protocols that have been proposed for VANETs, it is important to understand the metrics that will be used in the following sections to compare these MAC protocols. Naturally, these metrics are delay, packet loss, throughput, fairness, stability and support for real-time and for user-oriented applications.

1) *Access Delay: The* access delay is defined as an average time from the moment when a vehicle starts trying to send a packet until the beginning of its successful transmission. It is also defined as the average time spent by a frame in the MAC queue. However, the access delay depends not only on the MAC protocol, but also on the traffic rate produced by the other vehicles sharing the same channel. It is necessary to know which MAC protocols can support safety and real-time applications.
2) *Packet loss:* Packet loss occurs when one control/data packet fails to be transmitted successfully. There are a variety of reasons that lead to packet loss, including exposed/hidden nodes, collisions, low power signal, etc. The packet loss ratio can be defined as the ratio of the number of lost packets to the total number of packets sent.
3) *Throughput:* Throughput can be defined as the fraction of the channel capacity used for the data transmission. The goal of an efficient MAC protocol in a VANET is to maximize the throughput for user-oriented applications while minimizing the access delay for safety applications.
4) *Fairness:* A MAC protocol is fair if all the vehicles have equal access to the medium during a fixed time interval. However, fairness can also be defined as the ability to distribute bandwidth according to traffic priority when priorities are supported.
5) *Stability:* Generally, VANETs become unstable when the vehicles' movements are high. Thus a MAC protocol is considered to be stable if it is able to operate under different vehicular traffic conditions.
6) *Support for safety Applications:* In VANETs, each vehicle can exchange information to inform other vehicles about dangerous situations such as an accident or an event-triggered warning. These types of data have strict requirements in terms of access delay and transmission collision rates. This increases the need for an efficient MAC protocol.
7) *Support for user-oriented Applications:* With the convergence of multimedia applications in VANETs (e.g., video/audio) and data (e.g., e-maps, road/vehicle traffic/weather information), it is now necessary for MAC protocols to support multimedia and data traffic. Since multimedia applications require lower latency than data applications, the MAC protocols should satisfy these latency requirements. Two methods can be used to process packets from various applications based on their latency constraints: access priority and scheduling. An access priority scheme provides differentiated services by allowing certain vehicles to access the medium with a higher probability than others, while scheduling can guarantee the required delay (e.g. TDMA-based MAC protocols).

V. CLASSIFICATION OF TDMA-BASED MAC PROTOCOLS

VANETs usually include nodes that are moving fast and at different speeds, so the topology can change frequently. Therefore an efficient MAC protocol must be able to adapt to frequent topology changes and must assume as general a topology as possible, for instance the Road Side Units (RSUs) can access the channel via the same MAC protocol as the vehicles. A VANET topology can be described in terms of a hierarchy. In a centralized case, a base station (e.g., RSU) controls or manages all the vehicles in the network, whereas in a clustered topology one vehicle in each cluster is elected to act as a local central control entity of the group. In a fully distributed VANET, the centralized control notion is absent and all the nodes can be both nodes and routers. We make a further and new classification of TDMA-based MAC protocols according to their topology. These protocols consider a wide spectrum of topologies based on the communication architectures (e.g. V2V or V2I) or applications for which they are designed. The majority of the MAC protocols considered in [11] – [14] have a common fully distributed network topology. Thus, in our classification, the topology for which a MAC protocol was developed is considered to be another key design element in a VANET.

TABLE 1: Comparison of contention-based and TDMA-based MAC protocols in high load conditions

	Channel Utilization	Collision Rate	Throughput	Access Delay	Fairness	Packet Loss
Contention Based MAC (CSMA/CA)	Inefficient	High	Medium	Unbounded	No	High
Contention Free Based MAC (TDMA)	Efficient	Low	High	Bounded	Yes	Low

In order to categorize the protocols, in this paper, we propose the three following classes:

1) Protocols operating on a fully distributed VANET: These protocols coordinate channel access in a distributed way. They assume that each vehicle only needs to communicate with its one-hop neighbours in order to access the channel.
2) Protocols operating on a cluster-based topology: This category of protocols assumes that one vehicle in each group is elected t act as a local channel access coordinator.
3) Protocols operating on a centralized topology: These protocols assume that there are central points (RSUs) which are used to coordinate channel access for the vehicles in their coverage area.

TDMA-BASED MAC PROTOCOLS IN A FULLY DISTRIBUTED VANET (TDV)

In order to make the implementation of a time-multiplexed protocol more efficient in a distributed network topology, there are some issues that must be addressed. In this section, we identify the TDMA problems that may occur in a fully distributed VANET due to the high mobility of the nodes, and we survey the main TDV protocols that have been proposed in the literature.

A. TDMA problem statement in a fully-distributed VANET

When a distributed scheme is used to allocate a time slot, two types of collision can occur [19]: access collision between vehicles trying to access the same available time slots, and merging collisions between vehicles using the same time slots.

As shown in Figure 5, an access collision problem [20] occurs when two or more vehicles within the same two-hop neighborhood set attempt to access the same available time slot. This problem is likely to happen when a distributed scheme is used.

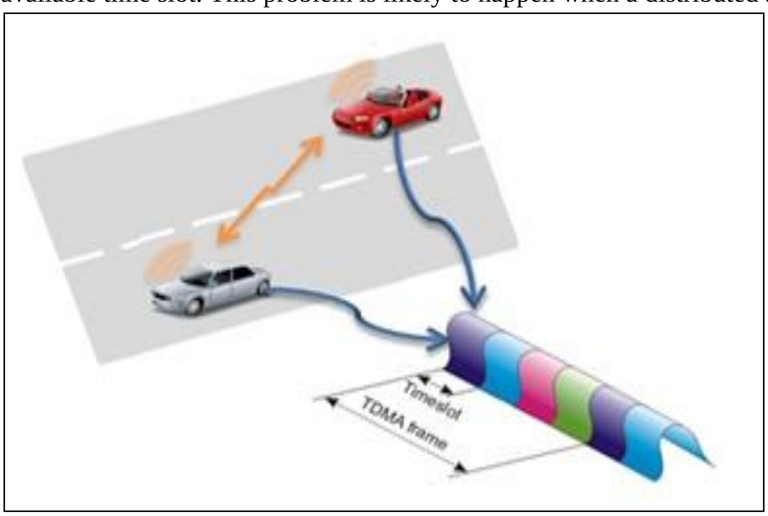

Fig. 5 Access Collision Problem

On the other hand, merging collisions [19] occur when two vehicles in different two-hop sets accessing the same time slot become members of the same two-hop set due to changes in their position. Generally, in VANETs, merging collisions are likely to occur in the following cases:

1) Vehicles moving at different speeds.
2) Vehicles moving in opposite directions.
3) There are RSUs installed along the road.

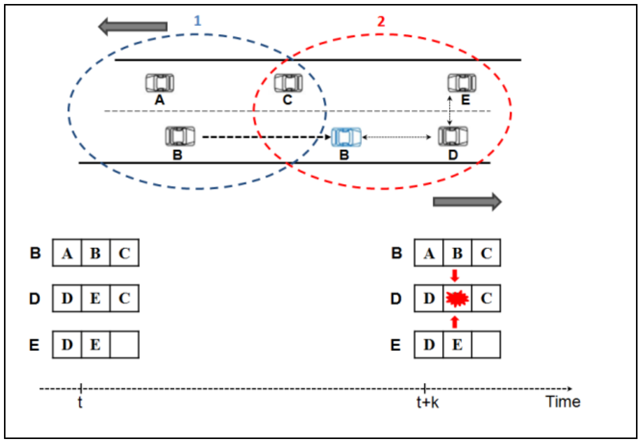

Figure 6: Merging collision problem

Figure 6, shows an example of the second case of the merging collision problem, when vehicle B in the first two-hop set moving in the opposite direction to vehicle E in the second two-hop set is using the same time slot as B. Since B and E become members of the same two-hop set, a collision occurs.

B. TDV protocols

In the literature, various distributed TDMA-based MAC protocols have been proposed for VANETs. Each of them focuses on certain issues in specific mobility scenarios.

1) *Space-Orthogonal Frequency-Time Medium Access Control (SOFT MAC):* Abu-Rgheff et al. [16] proposes a MAC protocol for VANET networks based on a combination of CSMA, SDMA 5, OFDMA6 and TDMA techniques. TDMA is used to ensure contention-free channel access, while OFDMA and SDMA are used to perform simultaneous transmissions. In SOFT MAC, the frequency bands and slots are pre-assigned according to the vehicles' locations by dividing the road into the cells of radius R and a portion NC of the available sub-carriers are assigned to each cell. Maps are pre-installed in the vehicles identifying which sub-carriers are allocated to each portion of the road. Then, these sub-carriers are shared between vehicles within the same cell via a TDMA. Each vehicle uses its current position, obtained by the GPS system, to know the set of sub-carriers.

The SOFT MAC protocol has two periods, namely the reservation period RS of duration dR and the transmission period TS of NT S transmission slots. The RS period is accessed via a contention-based CSMA, while the TS period is accessed via a prior reservation. The RS period is used to transmit short messages and to reserve the channel resource for the coming TS period, which is used to transmit a large amount of data. Transmissions made in the TS period also contain the information about the status of each slot (Busy or Free) in the frame, the current number of TS slots NT S , the ID of the vehicle transmitting in a busy slot and other information required for the SOFT MAC protocol (see Figure 7). Each node wishing to reserve a slot during the RS period checks the status of the slots in the current frame and initiates a reservation request.

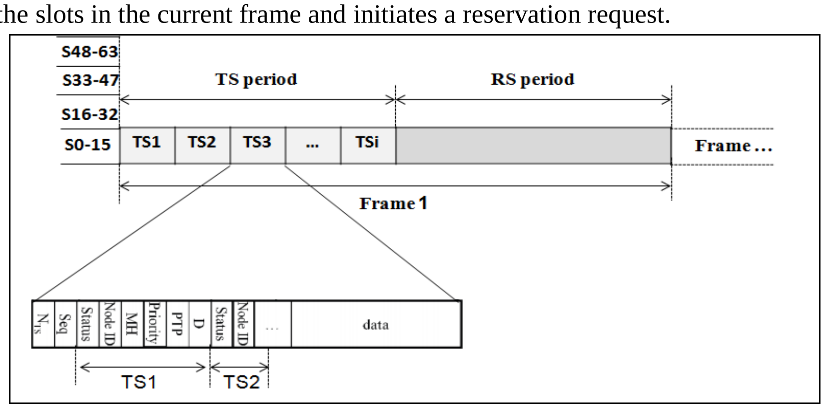

Figure 7: SOFT MAC Frame Structure [16]

Although this protocol shows improvements in throughput compared to the IEEE 802.11 standard and can support QoS requirements, the use of SDMA, CDMA and OFDMA techniques make SOFT MAC a very ex-pensive and complex MAC mechanism. Bad choices of parameters (NT S , dR, R and Nc) are likely to degrade the performance of SOFT MAC. Moreover, SOFT MAC assumes that all vehicles are equipped with digital road maps and, therefore, this protocol cannot ensure its interoperability in environments where vehicles without digital maps are present.

2) *Dedicated Multi-channel MAC with Adaptive Broadcasting (DMMAC):* The DMMAC protocol [21] is an alternative to the IEEE 802.11p standard. DMMAC is designed for VANETs to support an adaptive broadcasting mechanism which provides collision-free and delay-bounded transmissions for safety applications under various traffic conditions. As shown in Figure 8, the DMMAC architecture is similar to IEEE 802.11p with the difference that, the CCH Interval is divided into an Adaptive Broadcast Frame (ABF) and a Contention-based Reservation Period (CRP).

The ABF period consists of time slots, and each time slot is dynamically reserved by a vehicle as its Basic Channel (BCH) for collision-free delivery of safety messages or other control messages. The CRP uses CSMA/CA as its channel access scheme. During the CRP, vehicles negotiate and reserve the resources on SCHs for non-safety applications. DMMAC implements a dynamic TDMA mechanism for BCH reservation based on the distributed access technique R-ALOHA (Reliable R-ALOHA [22]). The length of the ABF frame is not uniform over the entire network. Each vehicle dynamically adjusts its ABF length according to its neighbours.

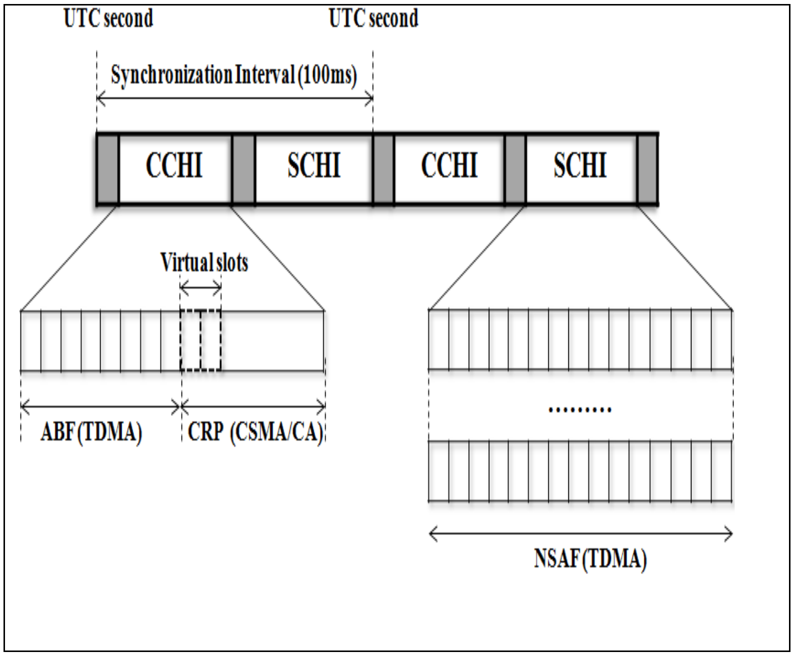

Fig. 8: Architecture of DMMAC

The simulation model used to evaluate DMMAC does not take into account velocity variations, the joining/leaving of vehicles and bidirectional traffic. It was limited only to the case of a straight road scenario with a number of slots that was significantly smaller than the maximum number of vehicles in the network.

Moreover, its random slot assignment technique does not perform a contiguous slot allocation. In addition, there are some issues that have not been studied, such as access collisions and merging collisions which can degrade the performance of DMMAC in highway scenarios where the vehicles are moving in opposite directions and under different traffic conditions.

3) *Vehicular Ad Hoc Networks MAC (VeMAC):* VeMAC [8], [23]–[24] is a contention-free multi-channel MAC protocol proposed for VANETs. In contrast to DMMAC and SOFTMAC, VeMAC is completely contention-free. This protocol supports efficient one-hop and multi-hop broadcast services on the control channel, which provides smaller rates of access collisions and merging collisions caused by node mobility. These broadcast services are presented in [25] for ADHOC MAC. In VeMAC, the merging collision rate is reduced by assigning disjoint sets of time slots to vehicles moving in opposite directions Left, Right) and to road side units (RSUs), see Figure 9.

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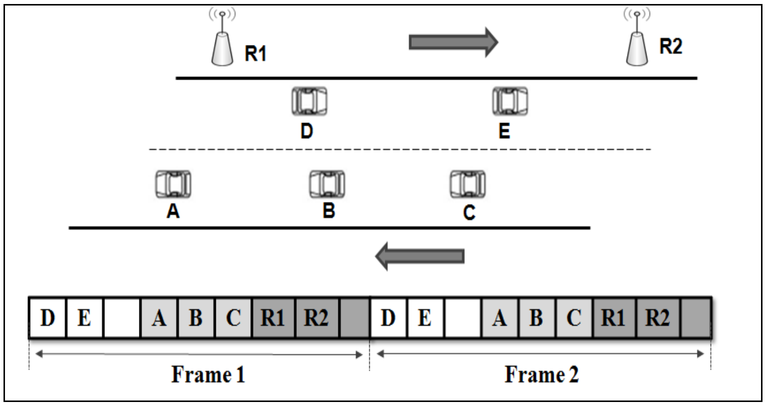

Figure 9: Partitioning of each frame into three sets

In VeMAC, each node has two transceivers, the first one is always tuned to the control channel while the other can be tuned to any service channel. Synchronization between nodes is performed using the 1PPS signal provided by the GPS in each vehicle. Each frame transmitted on the control channel is divided into four main fields: header, announcement of services (AnS), acceptance of services (AcS) and high priority short applications. As for ADHOC MAC [25], to avoid any hidden terminal problem, the header field of each message transmitted must include the time slots used by all the other vehicles within its one-hop neighborhood. Thus by reading the packet received from its one-hop neighborhood, each vehicle can determine the set of time slots used by all the vehicles within its two-hop neighborhood and the set of accessible time slots. It can attempt to acquire a time slot by randomly accessing any free time slot. The assignment of time slots to nodes on the service channels is performed by the providers in a centralized way. A provider is a vehicle which announces a service offered on a specific service channel in the AnS field on the control channel. A user is a vehicle which receives the announcement for a service and decides to make use of this service. It is the responsibility of the provider to assign time slots to all the users and it announces this slot assignment on the service channel in a specific time slot called the provider's main slot. When the provider receives the acceptance of the service in the AcS field, it tunes its second Transceiver to the specific service channel and starts offering the service in the time slots announced in the AnS field. In contrast to the other protocols, VeMAC can make use of the seven DSRC channels; it supports the same broadcast service on the control channel and on the service channels, and decreases the rates of merging and access collisions. Although communications over the service channels are overhead-free, the overhead of the VeMAC protocol on the control channel is considerable due to the size of the control frame transmitted on the CCH. Moreover, in VANETs, particularly in a highway environment, the number of vehicles in each direction is not equal. Thus, the size of the slots sets should be adjusted according to vehicle density. In addition, the merging collision problem can occur when vehicle density is high. Indeed, if a moving vehicle detects that it cannot access a time slot from the set of slots reserved for vehicles moving in its direction, then it will attempt to access any available time slot reserved for vehicles moving in the opposite direction.

4) *Near Collision Free Reservation based MAC (CFR MAC):* Zou et al. in [28] have proposed a near collision-free reservation based MAC protocol to further address the merging collision problem and to provide near collision-free channel access. The scheduling mechanism of CFR MAC is based on the VeMAC protocol which takes into consideration the traffic flow and the relative speeds of each vehicle. Each frame is divided into two sets of time slots Left and Right which are assigned to vehicles that are moving to the left and right. However, the merging collision problem can occur in VANETs when vehicles are moving at different speeds. Therefore, in order to solve this problem, each slot set is further divided into three subsets associated to three speed intervals: High, Medium and Low. The CFR MAC protocol dynamically adjusts the number of time slots reserved for each direction and speed level. The simulation results show that CFR MAC significantly reduces the access delay and the collision rate compared with to VeMAC and IEEE 802.11p.
5) *CSMA and Self-Organizing TDMA MAC (CS-TDMA):* Zhang et al. in [29] have proposed a novel multichannel MAC protocol called CS-TDMA combining CSMA with TDMA and SDMA to improve the broadcast performance in VANETs. CS-TDMA is a multichannel version of the SOFTMAC protocol and it implements the same MAC frame structure as SOFTMAC. Moreover, CS-TDMA differs from all the other multichannel protocols in that the ratio between the CCH and SCH intervals is dynamically adjusted according to traffic density. When the density of vehicles is low, the CCH interval is reduced to guarantee a high throughput for non-safety applications.

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When the traffic density is high, the CCH duration is maximized to guarantee a bounded transmission delay for real-time safety applications. CS-TDMA achieves a significant improvement in DSRC channels utilization, but the performance evaluation of the CS-TDMA protocol has been limited only to a medium density of vehicles (80 vehicle/km). Moreover, Access collision and merging collision problems are not studied in [29].

6) *Hybrid Efficient and Reliable MAC (HER-MAC) for Vehicular Ad hoc Networks:* Dang et al. [30] developed and evaluated a Hybrid Efficient and Reliable MAC for Vehicular Ad hoc Net-works, called HER-MAC, which is similar to the DM-MAC protocol. The goal of this research work is to develop a contention-free Multichannel MAC protocol with an adaptive broadcasting algorithm, which improves data transfer rates for non-safety applications while guaranteeing timely delivery for safety applications in highway scenarios. The architecture and the operation of HER-MAC are similar to DMMAC, differing in that the CRP period is used by a vehicle to reserve a time slot during the ABF period or to exchange a 3-way WSA/RFS (WAVE Service Announcement/Request for Service) handshake. In fact, if a vehicle wishes to exchange non-safety messages, it has to broadcast the WSA during the CRP period to reserve a time slot on a certain SCH. Then, when a vehicle decides to use the service, it sends the RFS to the service providers which will confirmed it with an ACK message. On receiving the ACK packet, the vehicles can start exchanging non-safety messages without any risk of collisions with messages from their neighboring vehicles.

TABLE 2: Qualitative comparison of TDMA-based MAC protocols in fully distributed VANET

	CFR MAC	HER-MAC	VeMAC	ATSA	CS-TDMA
References	[28]	[30]	[8] and [23]	[26]	[29]
Published	2014	2014	2011	2013	2014
Channel	Single	Multiple	Single/Multiple	Single	Multiple
Pure TDMA	Yes	No	Yes	Yes	No
Merging collision	Solved	Possible	Solved	Solved	Possible
Access collision	Solved	Possible	Solved	Possible	Possible
Mobility	High	N/A	High	N/A	N/A
Density (scalability)	High	Low	High	Medium	Medium
Broadcast service	Yes	Yes	Yes	No	Yes
Mobility model	Highway	Highway	Highway/Urban	Highway	Highway
Vehicular traffic	Bidirectional	Bidirectional	Bidirectional	Bidirectional	Bidirectional
Data Traffic load	High load	High load	High load	N/A	High
Control overhead	Medium	High	Low: SCH/High: CCH	Low	Medium
Transmission range	Low	N/A	Short	N/A	N/A
Multimedia applications	No	Yes	Yes	No	Yes
Real-Time applications	Yes	Yes	Yes	Yes	Yes
Positioning System GPS	Yes	Yes	Yes	Yes	Yes
Time Synchronization	Yes	Yes	Yes	Yes	Yes
Simulator	N/A	Matlab	MATLAB and NS2	MATLAB	Matlab

TABLE 2 (continued): Qualitative comparison of TDMA-based MAC protocols in fully distributed VANET

	VeSOMAC	STDMA	SOFTMAC	DMMAC
References	[34]	[31] and [32]	[16]	[21]
Published	2007	2009	2009	2010
Channel	Multiple	Single	Single	Multiple
Pure TDMA	Yes	Yes	No	No
Merging collision	Possible	Possible	Possible	Possible
Access collision	Possible	Possible	Possible	Possible
Mobility	Low	High	N/A	High
Density (scalability)	Low	High	Low	Medium
Broadcast service	No	Yes	N/A	Yes
Mobility model	Highway	Highway	Highway	Highway
Vehicular traffic	Unidirectional	Bidirectional	Unidirectional	Unidirectional
Data traffic load	High load	High load	High load	High load
Control overhead	Low	Low	Low	Medium
Transmission range	Medium	Long	N/A	Short
Multimedia applications	Yes	No	Yes	N/A
Real-Time applications	No	Yes	Yes	Yes
GPS System	No	Yes	Yes	No
Time Synchronization	Yes/No	Yes	Yes	No
Simulator	NS2	MATLAB	N/A	NS2

7) *Adaptive TDMA Slot Allocation:* An efficient MAC approach called ATSA [26], [27] is an improvement of the previously proposed MAC protocol named the Decentralized Adaptive TDMA Scheduling Strategy DATS. ATSA enhances the VeMAC protocol when the densities of vehicles moving in opposite directions are not equal (unbalanced traffic). Like VeMAC, ATSA divides the frame into two sets of time slots Left and Right. However in ATSA, when a vehicle accesses the network, it chooses a frame length and competes for one of the time slots available for its direction. To solve merging collisions under unbalanced traffic conditions, the frame length is dynamically doubled or shortened based on binary tree algorithm.
8) *STDMA (Self-organizing Time Division Multiple Access)* [31], [32] was developed for real-time communications. The method is currently employed in automatic identification systems [33]. STDMA is a decentralized scheme where the network members themselves are responsible for sharing the communication channel, and due to the decentralized net-work topology, synchronization between the nodes is done through a global navigation satellite system, GPS.
9) *VeSOMAC (Self-Organizing MAC Protocol for DSRC based Vehicular Ad Hoc Networks)* [34] uses an in-band control mechanism to exchange TDMA slot information during distributed MAC scheduling. The aim of this work is to develop a contention-free MAC protocol that can achieve fast TDMA slot reconfiguration without relying on roadside infrastructure or Virtual schedulers such as leader vehicles, which can deliver improved throughput for such applications in highway scenarios. VeSOMAC can operate in both synchronous and asynchronous modes. In the synchronous mode, all the vehicles are assumed to be time-synchronized by using GPS where they share the same frame and slot boundaries. In the asynchronous mode, each vehicle maintains its own frame boundaries.

C. TDMA-BASED MAC Protocols In A Cluster-Based Topology (TCBT)

Cluster-based TDMA MAC protocols have attracted attention for VANETs because they avoid access collisions due to concurrent access to the same available time slot, and limit channel contention as the number of vehicles increases. They also provide fair channel access within the cluster and effective topology control. In a cluster-based TDMA, one vehicle is elected to serve as the local network coordinator for each group. The elected cluster head is responsible for assigning time slots to its cluster members. Nevertheless, the main challenge in cluster-based TDMAs is the overhead generated to elect the cluster head and to maintain the cluster members in a highly dynamic topology.

1) *TDMA problem statement in a clustered topology:* When a cluster-based TDMA scheme is used to schedule and manage the time slots, an inter-cluster interference problem can occur. There are two types of inter-cluster interferences [41]: One-Hop Neighboring Collision and the Hidden Node Collisions.
2) *One-Hop Neighboring Collision (OH-Collision)* occurs when a time slot is used by two neighboring vehicles belonging to neighboring clusters. Figure 10 shows an example of an OH-collision situation when vehicle C in cluster 1 and vehicle D in cluster 2 are using the same time slot. Since C and D are within transmission range of vehicle B, a collision will occur at vehicle B.

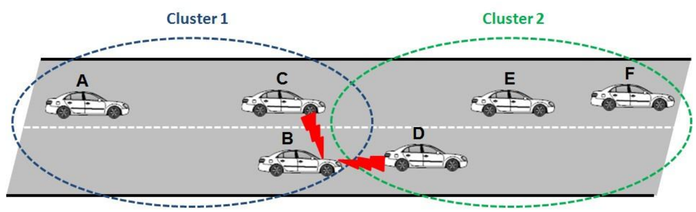

Figure 10: One-Hop neighboring Collision (OH-Collision).

*On the other hand, Hidden Node Collision (HN-Collision***)** occurs when two vehicles are in communication range of another node, but not within transmission range of each other. Let us consider the situation in Figure 11, when vehicle B in cluster 1 and vehicle D in cluster 2 are using the same time slot. Since these two vehicles are outside transmission range of each other, a collision will occur at vehicle C of cluster 1.

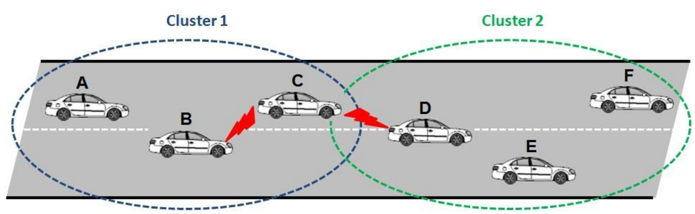

Figure 11**:** Hidden Node Collision (HN-Collision).

TCBT protocols

Several cluster-based MAC protocols have been pro-posed in the literature for inter-vehicle communications in order to provide efficient and fair channel utilization while minimizing intra-cluster and inter-cluster transmission collisions.

a) *AD HOC Medium Access Control (ADHOC MAC):*ADHOC MAC [25] is a MAC architecture where the vehicles are grouped into a set of clusters with no cluster head; each cluster contains a restricted number of vehicles that are one-hop away. ADHOC MAC provides an efficient broadcast service for inter-vehicle communications and solves MAC issues such as the hidden-exposed terminal problem and QoS provisioning. ADHOC MAC is a contention-free medium access protocol which implements a dynamic TDMA mechanism that is able to provide prompt access based on distributed access technique, R-ALOHA (Reliable R-ALOHA [22]), where the time is divided into frames and each frame is divided into N slots. Each vehicle can access the channel at least once in each frame by randomly selecting a time slot as its basic channel (BCH). To resolve the hidden node problem, each node should know the status (BUSY or FREE) of the N slots in a two-hop neighborhood. Thus, each vehicle broadcasts an additional frame to its two-hop neighborhood called the Frame Information (FI) during its BCH which is a vector with N entries specifying the status of each of the preceding N slots, as observed by the vehicle itself.

ADHOC MAC also implements an optimal multi-hop broadcast service and parallel transmissions that use a minimum set of relaying terminals able to cover the whole network. In ADHOC MAC, each vehicle can access the channel if and only if N is larger than the maximum number of terminals M in any two-hop neighborhood. The simulation results show that if M = N, the acquisition of an available slot by each vehicle is more contentious and takes a long time. Unlike the IEEE 802.11p standard, ADHOC MAC is a single channel protocol, not suitable for the DSRC architecture.

b) *Adaptive Real-time Distributed MAC (A-ADHOC):*A-ADHOC [42] is based on the previous ADHOC MAC protocol. The A-ADHOC protocol is intended for real-time applications in large-scale wireless vehicular net-works, offering another option of adaptive frame length. The simulation results show that A-ADHOC has surpassed the ADHOC MAC in both channel resource utilization and response time. In particular, the new protocol can avoid network failure regardless of traffic density, which is an inherent problem in the ADHOC MAC protocol.

c) *Cooperative ADHOC MAC (CAH-MAC) for Vehicular Networks:* Bharati and Zhuang propose in [40] a Cooperative ADHOC MAC protocol, with the aim of improving throughput for non-safety applications. The scheduling mechanism developed by the CAH-MAC protocol is based on distributed TDMA similar to the one in AD-HOC MAC in that the channel access time is divided into periodic frames and each frame is further divided into time slots. The goal of the research work is to propose a new way to overcome the transmission failure problem when it occurs due to poor channel conditions. In fact, upon detecting a transmission failure between the transmitter and the receiver, a neighboring node called a ”helper node” offers cooperation to relay the packet that failed to reach the destination during an idle time slot. Compared to the ADHOC MAC protocol, the main disadvantage of CAH-MAC is that the use of any free time slots by the helper nodes for cooperative relay transmissions can lead to the access collision problem with the vehicles that attempt to obtain an available time slot.

d) *Cluster-based TDMA system for inter-vehicle communications (CBT):* Sheu and Lin [36] have proposed and evaluated a Cluster-Based TDMA system (CBT) for inter-vehicle communications. The goal of this system is to develop contention-free intra-cluster and inter-cluster communications while minimizing collisions when two or more clusters are approaching each other. The protocol uses a simple transmit-and-listen scheme to quickly elect a VANET Coordinator VC. The CBT system assumes that each vehicle is equipped with a GPS positioning system and synchronization between the vehicles can be performed by using GPS timing information. The access time is divided into frames and each frame consists of n time slots. The CBT protocol certainly has some shortcomings: the VANET Coordinator is randomly selected based on the simple transmit-and-listen scheme and, in fact, the life time of a VC may be very short and thus the resulting clusters will be unstable, which degrades the performance of CBT. The CBT protocol is limited to using only a single channel. The authors do not study the problem of merging collisions when vehicles are moving in opposite directions and do not discuss what happens if a new vehicle joins a cluster or when a vehicle leaves the cluster and how its allocated time slot will be released and reallocated.

Summary of TCBT protocols

Four cluster based TDMA MAC protocols have been presented. Table 3 gives a comparison of these protocols and contrasts their performances and features. All these TCBT protocols have been proposed only for one specific scenario (Highway) and do not address the different requirements presented by urban scenarios where it is more difficult to form stable clusters when there are traffic lights, crossroads, and traffic-jams, as well as a high density of vehicles. ADHOC MAC and A-ADHOC, CBT, CAH-MAC and CBMAC do not support delay-sensitive applications and are limited only to throughput-sensitive applications as they are efficient only for data messages. However, A-ADHOC can operate well under different traffic conditions, as it implements an adaptive frame length mechanism according to vehicle density.

Table 3 Qualitative comparison of TDMA-based MAC protocols in cluster-based

	ADHOC MAC	A-ADHOC	CAH-MAC	CBT
References	[25]	[42]	[40]	[36]
Published	2004	2009	2013	2014
Channel	Single	Single	Single	Single
Pure TDMA	Yes	Yes	Yes	Yes
Access collision	Possible	Possible	Possible	Solved
Inter-cluster interference	Possible	Possible	Possible	Possible
Mobility	N/A	N/A	N/A	N/A
Density (scalability)	Medium	High	Medium	Very low
Broadcast service	Yes	No	Yes	No
Mobility model	N/A	N/A	Simple Highway	Highway
Vehicular traffic	N/A	N/A	Unidirectional	Unidirectional
Traffic load	High load	N/A	High load	Low
Control overhead	Low	Low	High	Low
Transmission range	N/A	N/A	Medium	N/A
Multimedia applications	Yes	No	Yes	N/A
Real-Time applications	No	Yes	No	N/A
GPS System	Yes	Yes	Yes	Yes
Time Synchronization	Yes/No	Yes	Yes	Yes
Simulator	N/A	NS2 and Matlab	Matlab	NS2

D. TDMA-BASED MAC Protocols In Centralized Topology (TCT)

A MAC protocol should exploit VANET characteristics like restricted mobility, the presence of Roadside Units (RSUs), and the large transmission range of RSUs to ensure real-time and reliable delivery of messages. Centralized TDMA-based MAC protocols which exploit the existence of RSUs assign time slots and disseminate control information which can reduce channel allocation delay and scheduling overhead. The centralized slot allocation mechanism consists of two simple phases. In the first phase, each vehicle that has message ready to transfer requests the RSU for a slot on a specific channel. In the second phase, the RSU allocates a particular slot to the vehicles that are moving within its communication area. Then the RSU broadcasts the final slot allocation map to all the vehicles in its area.

TDMA problem statement in Centralized Networks

When a centralized scheduling and management of the time slots is used, some issues should be addressed in order to implement efficient and fair centralized TDMA-based MAC protocols:

1) *Inter-RSU interference*: Each RSU adaptively creates and manages the TDMA slot reservation schedule for vehicles in its coverage. Thus, the same set of time slots can be allocated to vehicles in neighboring RSU regions. However, if there is an overlap between two neighboring RSUs that use the same frequency band, the messages broadcasted in one RSU region will affect the communications in the neighboring RSU region.

2) Short stay period in an RSU region: Due to their high speed, vehicles can join/leave an RSU region in short intervals of time, which leads to breaks in communication. Thus, the centralized MAC should ensure that a vehicle can continue to communicate at all times. Moreover, at any moment, the density of vehicles in an RSU region can vary rapidly from only a few vehicles to a high number of vehicles.

TCT protocols

In recent years, some centralized TDMA-based MAC protocols have been proposed to guarantee real-time and reliable communications in VANETs while avoiding the access collision problem due to concurrent access to the same time slot. Each protocol has been proposed for a particular problem in a specific mobility scenario.

1) Adaptive Collision-Free MAC (ACFM): Guo et al. in [10] propose an Adaptive Collision-Free MAC (ACFM) protocol based on a centralized dynamic time slot reservation mechanism in Roadside Units (RSUs). Thus, by using a schedule, ACFM ensures efficient time slot utilization for the exact number of active vehicles. As shown in Figure 12, the time is divided into frames and each frame is divided into a fixed number of time slots: one RSU Slot (RS) which is used by an RSU to broadcast control messages to the vehicles within its coverage area and 36 Data Slots (DS) which can be used by the vehicles to broadcast their beacon data to their neighboring vehicles.

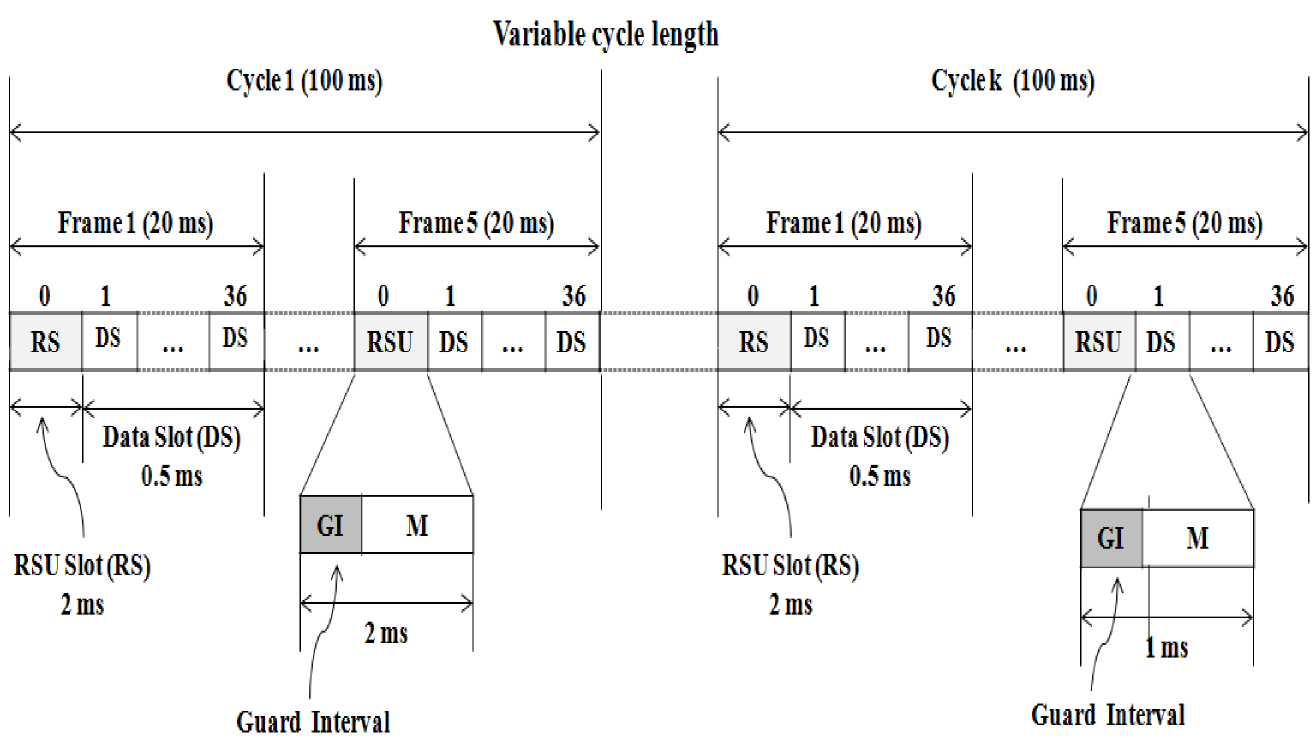

Figure 12 TDMA frame structure of the ACFM protocol

The control message that is periodically diffused by an RSU contains the DS assignment schedule for vehicles under its coverage and time synchronization information. Therefore, each RSU independently and dynamically maintains a slot schedule cycle of a maximum time equal to 100 ms for vehicles in its coverage.

The cycle consists of N frames, where N varies from 1 to 5 according to vehicle density in the coverage area of the RSU. However, to avoid interference between adjacent segments, the authors have proved that two orthogonal frequencies are needed to ensure the same frequency is not used for a distance of two hops (see Figure 13). Moreover, the vehicles in the intersection of two segments must select and tune to one of the two frequencies to send messages based on the RSSI (Received Signal Strength Indication).

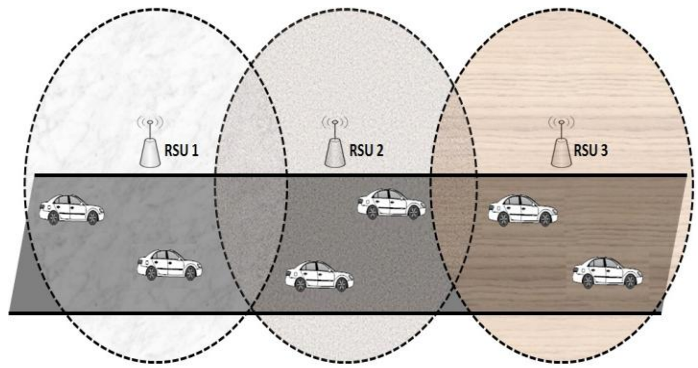

Figure 13 shows the frequency assignment to subnet

A cycle length expansion and shrinking mechanism has been added to ACFM to ensure the fairness of the channel access protocol. When vehicle density is low in a particular subnet, the corresponding RSU coordinator will shrink the slot assignment cycle frame by frame to avoid the appearance of free slots. In contrast, if vehicle density is high, the RSU will expand the assignment cycle frame by frame (at most five frames), where 36 additional free DS slots are added. Although the simulation results show the interest of ACFM in terms of average access delay and packet loss ratio compared with the IEEE 802.11p standard and the pure 3G transfer protocol, it also has some drawbacks: the protocol uses a single channel and does not exploit the seven available WAVE channels as well as being limited only to periodic messages and does not support QoS for non-safety applications. The protocol does not handle communications between vehicles belonging to two different subnets. Moreover, due to high node mobility, the interval of time in which the vehicle stays in an RSU region is very short, which can lead to breaks in communication.

2) *Risk-Aware Dynamic MAC (R-MAC):* Guo et al. in [44] propose an extension scheme of ACFM, named Risk-Aware Dynamic MAC Protocol for Vehicular Cooperative Collision Avoidance System. The goal of the research is to design a risk-aware dynamic medium-access control (R-MAC) protocol tailored to Cooperative Collision Avoidance CCA applications. One key element of CCA systems is the real-time and reliable delivery of warning messages as well as beacons between vehicles. As for the ACFM protocol, each frame is divided into an RSU segment and a vehicle segment. The RSU segment is reserved for RSUs to disseminate control messages. However, in contrast to the ACFM protocol, the vehicle segment is divided into two segments: a CSMA segment which is a contention-based segment, responsible for transmitting warning messages in emergency situations, and a TDMA segment which is a contention-free segment and used for delivering beacon messages. The CSMA segment size in a frame is determined by the average total number of potential collisions. For this, the authors have proposed a stochastic collision prediction model to compute the average total number of potential collisions within a platoon. However, R-MAC is a single channel protocol and has been proposed for a simple highway with one lane in which all the vehicles are moving in the same direction. Moreover, like the ACFM protocol, R-MAC cannot support QoS for non-safety applications and it is limited only to safety applications.
3) *Cluster Based RSU Centric Channel Access (CBRC):* The RSU assisted frequency and TDMA allocation protocol has been proposed and evaluated by Tomar et al. in [45], [46]. The goal of the work is to develop a contention-free MAC approach with centralized control in Roadside Units (RSUs), which minimizes channel allocation time and management overhead.

CBRC works by dividing the frequency spectrum into a number of frequency bands separated by guard bands and each frequency band is shared between vehicles via a TDMA scheme in which the access time is divided into eight fixed time slots of equal size separated by guard times. CBRC operates both on the RSUs and the vehicles. Each RSU divides the road into static clusters and the RSU can be the cluster head for all the clusters. It can broadcast beacon messages containing its identity and location to all the vehicles in its communication area. When a vehicle enters the communication coverage of an RSU and receives its beacon message, it will attempt to get the attention of the RSU by sending it a registration request. In order to support service differentiation and give safety messages a higher access priority than data messages, each RSU maintains two different queues of channel requests: one for safety applications and one for non-safety applications and, higher priority access is given to the safety application requests. When a registered vehicle has a message ready to transfer, it uses the control channel to request a channel by sending the RSU a channel request containing the application type. Moreover, the protocol is able to solve hidden and exposed node problems by using a channel allocation matrix which keeps information about the currently free and assigned channels. When a vehicle sends a channel request to an RSU to transmit data or a safety message to a neighboring vehicle which is already in communication with another vehicle, the RSU uses the channel allocation matrix, and refuses to allocate the channel. On the other hand, when an exposed node sends a channel request to RSU it will be assigned a different frequency channel that will not conflict with its neighboring vehicle already in communication. However, the approach proposed by Tomar et al. has some serious drawbacks. Although this protocol has been evaluated in scenarios where there are junctions, the authors do not detail inter-cluster communication at junctions where vehicles are moving in different directions. CBRC has a fixed number of slots which may degrade its performance when vehicle density is very high. Moreover, due to its high speed and frequent changes in velocity, a vehicle can join/leave an RSU region very quickly, which can lead to a break in communication. The authors do not describe multi-hop communication between vehicles and RSUs and how a new vehicle that is joining an RSU area can change from one slot to another while remaining in communication.

4) *Unified TDMA-based Scheduling Protocol for V2I communications (UTSP):* Zhang et al. have proposed in [47] and [48] a Unified TDMA-based Scheduling Protocol (UTSP) for V2I communications. The goal of the work is to optimize the throughput for non-safety applications in VANETs. In the proposed TDMA scheduling strategy, the RSU collects the necessary information including channel state information, the speed, and the Access Category AC characteristic of the vehicles within its communication range and then it assigns the time slots to the vehicles based on the weight function which consists of three factors, i.e. channel-quality weight factor, speed weight factor and AC weight factor. The first factor is used to maximize the network throughput; the second one is used to ensure fairness between vehicles that are moving at different speeds, while the last one distinguishes the access priorities of different slot reservation requests. The vehicle which has the maximum weight value will be served first by the RSU in the current TDMA frame. The simulation results prove that UTSP has good performance in terms of throughput and fairness compared with the traditional standard IEEE 802.11. However, UTSP was designed to support only VANET applications that are throughput-sensitive. In addition, the authors do not describe the mobility scenarios used to evaluate the performance of UTSP. Since the protocol was evaluated only for one RSU, an interference problem can occur between vehicles in the overlapping regions where several RSUs are used to coordinate access to the channel. As a result, UTSP cannot satisfy the requirements of VANET applications because they are mainly oriented to road safety issues.

Summary of TCT protocols

Four TDMA-based MAC protocols in centralized network topologies have been presented. Table 4 compares the performance and features of these protocols. As shown in this table, we note that all the protocols consider the medium as a single shared channel for their safety or/and data transmissions. Although these protocols have been proposed recently, we found that most of them do not exploit the seven channels provided by the DSRC technology, which confirms that they were developed for a specific class of applications. Unlike CBRC and UTSP, ACFM and R-MAC do not support throughput-sensitive applications and are limited only to delay-sensitive applications which make ACFM and R-MAC unsuitable for VANETs. R-MAC only addresses the need to create a protocol to efficiently deliver beacon and warning messages, while ACFM only addresses the need to develop a protocol to efficiently send beacon messages.

TABLE 4: Qualitative comparison of TDMA-based MAC protocols in centralized network topology

	ACFM	R-MAC	CBRC	UTSP
References	[10]	[44]	[45] [46]	[47]
Published	2012	2013	2013	2013
Channel	Single	Single	Single	Multiple
Pure TDMA	No	No	No	Yes
Inter-RSU interference	Solved	Solved	Solved	Possible
Access collision	Solved	Solved	Solved	Solved
Mobility	High	High	High	Medium
Density (scalability)	High	High	Low	Low
Broadcast service	Yes	Yes	Yes	No
Mobility model	Highway	Highway	Highway + Junctions	Highway
Vehicular traffic	N/A	Unidirectional	Unidirectional	Bidirectional
Traffic load	High load	High load	High load	High load
Control overhead	Low	Low	Low	Medium
Transmission range	N/A	Low	Low	Medium
Multimedia applications	No	No	Yes	Yes
Real-Time applications	Yes	Yes	Yes	No
Positioning System GPS	Yes	Yes	Yes	Yes
Time Synchronization	Yes	No	No	Yes
Simulator	NS2	NS2	NCTUns 5.0	N/A

VI. ANALYSIS OF THE TDMA-BASED MAC PROTOCOLS BASED ON THE MAC QOS METRICS

The QoS metric-based comparison is shown in Table 5. This table helps us to draw several important conclusions. Figure 14 presents the number of TDMA-based MAC protocols which support each metric. All the existing protocols have been developed to provide less access delay for safety applications at the expense of other MAC QoS metrics such as throughput, stability, fairness and packet loss. Figure 15 illustrates the number of times each of the TDMA-based MAC design issues was addressed by the protocols presented in this survey. Having no central coordination and supporting an efficient broadcast ser-vice on the CCH appear to be the most popular MAC issues in VANETs. However, mobility scenarios (both highway and urban), scalability, different QoS requirements have not been taken into account for many protocols. Thus, these issues need to be considered and addressed efficiently in future TDMA-based MAC protocols.

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TABLE 5: Classification and analysis of existing TDMA-based MAC protocols for VANET

Protocols		Metrics					
		Access Delay	*Throughput*	*Packet Loss*	*Fairness*	*Stability*	*Services differentiation*
TDV Protocols	VeSoMAC	✔	✔				Multi-channel
	STDMA	✔		✔	✔	✔	Access priority
	SOFTMAC	✔	✔				Access priority
	DMMAC	✔	✔			✔	Multi-channel
	VeMAC	✔	✔		✔	✔	Multi-channel
	ATSA	✔					None
	CS-TDMA	✔	✔	✔			Multi-channel and access priority
	CFR MAC	✔		✔	✔	✔	None
	HER-MAC	✔	✔				Multi-channel and access priority
TCBT Protocols	ADHOCMAC	✔					Access priority
	A-ADHOC	✔			✔	✔	None
	CBT	✔					None
	CAH-MAC	✔	✔				None
TCT Protocols	ACFM	✔		✔	✔	✔	None
	R-MAC	✔	✔	✔	✔		Access priority
	CBRC	✔	✔				Access priority
	UTSP	✔	✔		✔		Multi-channel and access priority

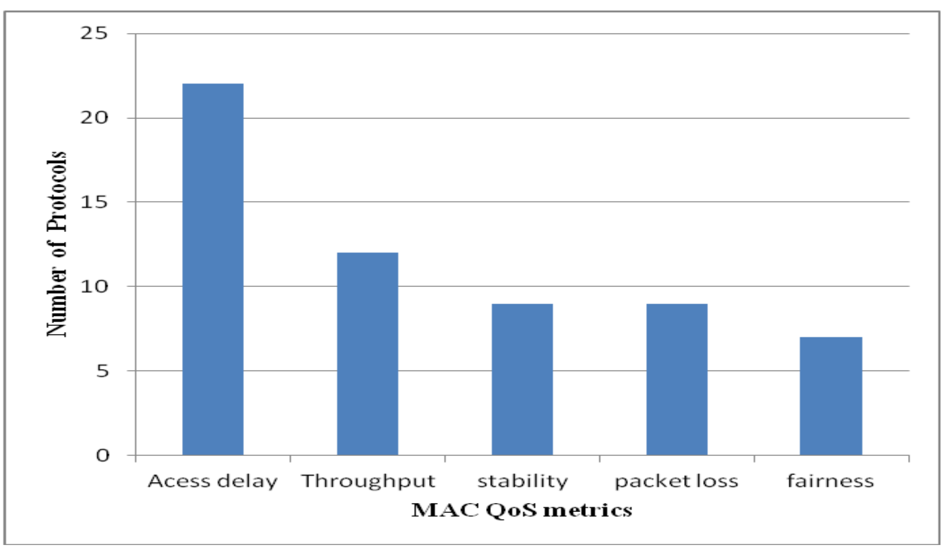

Fig14. Number of protocols versus MAC QoS metrics supported

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Figure 16 gives the percentage of protocols in our three classes (TDV, TCBT, and TCT) which address a given QoS metric. It is clear from the figure that the centralized TCT protocols are the most suitable for VANETs with respect to the QoS performance metrics. Moreover, we note that the TCBT protocols are the second best, except for the throughput metric where the TDV protocols are the second best.

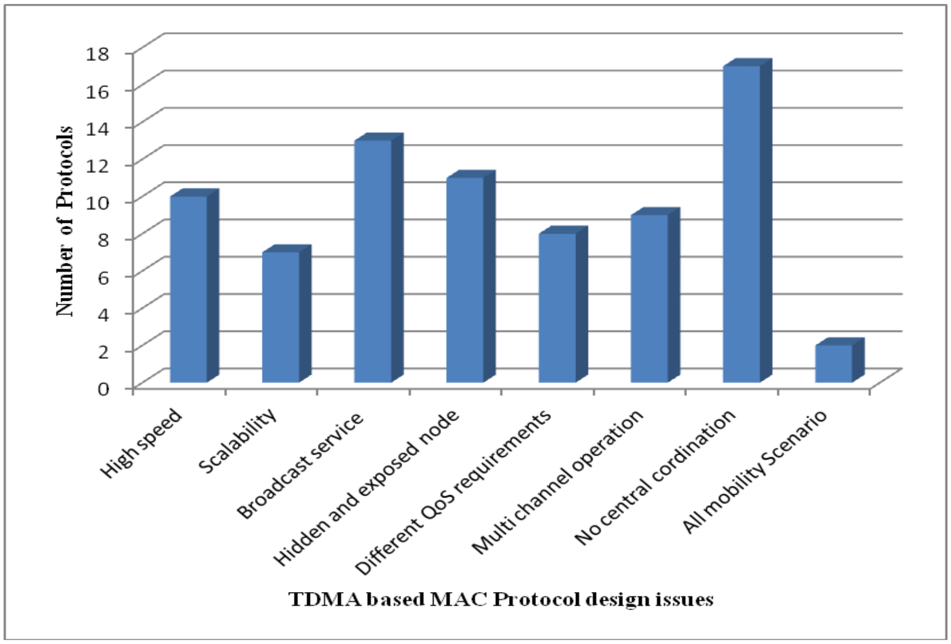

Fig15. Number of protocols versus MAC protocol design issues

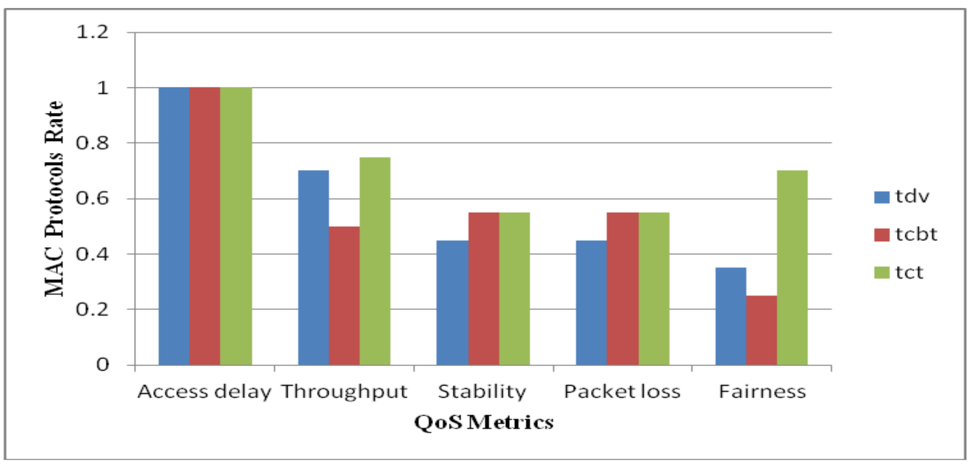

Fig16. Percentage of TDMA based MAC Protocols (each class) addressing a given MAC QoS metrics.

VII. COMPARISON AND SUMMARY

It is no simple task to establish a fair comparison between TDMA-based MAC protocols as each of them has been developed with a different architecture and for a specific class of applications. The nodes in VANETs are characterized by their high mobility, so the network topology can change quickly and frequently. Therefore, an efficient MAC protocol in VANETs must assume as general a topology as possible. In this section, we summarize the benefits and drawbacks of the different classes of protocols and the effect a particular topology has on the network's performance. TDMA-based MAC protocols in a fully distributed VANET assume that each vehicle needs only to communicate with its direct neighbour in order to acquire a time slot. Thus these protocols are referred to as single hop protocols. VeMAC, ATSA, STDMA, DMMAC, HER-MAC, CFR MAC, VeSOMAC and SOFTMAC are all examples of this category. Since each vehicle has a local view of the network, the access delay increases exponentially and the throughput decreases continuously in the network as vehicle density and traffic load increase.

DMMAC and ATSA provide a dynamic and adaptive frame length according to vehicle density in order to add scalability and adaptability to this class of topology. SOFTMAC differentiates between services by attributing access priority in order to provide fair channel access and make better use of the common channel. VeSOMAC, DMMAC, HER-MAC and VeMAC provide multiple channels to achieve a high throughput and less transmission delay under different network conditions. VeMAC offers a novel TDMA slot assignment strategy to reduce transmission collisions caused by node mobility. Although these protocols support efficient slot reservation techniques, they produce a significant communication overhead in highly dense networks. For instance, in order to ensure that a vehicle's established reservation will not conflict with another reservation within its two-hop neighborhood, the vehicle must periodically broad-cast frame information including the slot ID and their states to all its one-hop neighbors, which is likely to lead to a high communication overhead, specially in a dense scenario thus reduce the overall bandwidth. Even if collision-free transmission is ensured, the high mobility of nodes increases the communication overhead, which may be avoided in a hierarchy or centralized topology in which the TDMA slot reservation schedule is managed by central node in each sub-network. In contrast to fully-distributed VANET protocols, cluster-based TDMA has attracted more attention over recent years, in order to provide fair channel access without access collisions due to concurrent access to the same available time slot. In a clustered or hier-archical topology, one vehicle among a group of vehicles is elected to act as the cluster head to create and manage the TDMA slot reservation schedule for its cluster members.

The clustered topology protocols attempt to reduce the overhead in a one-hop neighbor-hood by centralizing the slot allocation function at the cluster head. CBT, ADHOC MAC, A-ADHOC and CAH-MAC are all examples of clustered topology protocols. However the main challenges in a cluster-based TDMA is the communication overhead in terms of exchanging messages needed to elect a cluster head and to maintain the cluster members in a highly dynamic topology, as well as inter-cluster interference when two or more clusters are approaching each other. Moreover, clustered topology protocols are not suitable for high density networks, as the cluster stability decreases when the density of vehicles increases. CBT uses a simple transmit-and-listen scheme to reduce the overhead of cluster head election and to quickly resolve inter-cluster collisions when two or more clusters are approaching each other by re-allocating time slots in one of the clusters. In a clustered or hierarchical topology, one vehicle among a group of vehicles is elected to act as the cluster head to create and manage the TDMA slot reservation schedule for its cluster members R-MAC, ACFM, CBRC and UTSP are examples of centralized topology protocols. All these protocols require the presence of RSUs to coordinate channel access, in which the RSUs maintain slot assignment frames for the vehicles in their coverage areas. Hence, the presence of the RSUs can minimize the communication overhead and provide fairness to channel access. However, as with clustered topology protocols, when RSUs are used to manage the slot assignment schedule, an interference problem can occur between vehicles in the overlapping regions. Thus messages transmitted in one region may affect communications in another region. Only ACFM allows two neighboring RSUs to communicate without affecting communication within an RSU's region by using different orthogonal frequencies. Based on the different priorities between messages in CBRC, R-MAC and UTSP, the RSU allocates time slots to the vehicles in its communication area, which ensures the timely delivery of safety messages. Although fully distributed MAC protocols support complex channel access mechanisms and produce a considerable control overhead, they are more generic proto-cols and assume as general a topology as possible, unlike centralized and clustered protocols which assume the presence of cluster heads and base stations, respectively. Moreover, free-contention multi-channel MAC protocols provide less delay for safety applications under different traffic conditions, and can achieve high throughput for non-safety applications.

VIII. CONCLUSION

Improving road safety in VANETs requires efficient and reliable MAC protocols. These MAC protocols can be based on TDMA schemes. This paper, which presents an extensive overview of research related to TDMA-based protocols for VANETs, shows how well these protocols can satisfy the stringent requirements of safety and user-oriented applications. To describing and giving the strengths and weaknesses of each protocol, we have proposed a novel topology-based classification of these MAC protocols. Producing an efficient TDMA-based MAC protocol is a challenging task in the context of VANETs due to their special characteristics such as high node speed, frequently changing network topologies, the hidden and exposed node problems, different QoS requirements, etc. All these issues have been identified and discussed in this paper. The paper has also highlighted the TDMA problem statement for each topology caused by the nodes mobility. Furthermore, we have surveyed the existing TDMA-based MAC protocols. A comparison of the protocols has been provided based on their performance metrics. Additionally, we have given a comparison between the three classes of MAC protocols. This comparison was made in order to help readers better understand the difference between the various protocols. We note that cluster-based TDMA MAC protocols have reached the QoS level required, due to the significant research effort made on this topic.

Centralized TDMA-based MAC protocols for VANETs have also received considerable attention over recent years. However, many distributed TDMA protocols which assume the topology to be as flat as possible, do not address the TDMA problem statement in a fully distributed VANET caused by the high levels of speed and the movement in opposite directions.

To reduce interference between overlapping areas, some protocols made use of other access techniques such as CDMA and FDMA which make them more complex and expensive. Resolving these problems requires more efforts in the future. Moreover, the topological features of VANETs in highway and urban environments can be used as part of the MAC design guideline in future work. Finally, we have specified certain MAC research challenges and open questions which may be future research directions to enable VANETs to efficiently support both safety and non-safety applications. Despite the research efforts to improve the performance of TDMA-based MAC protocols in VANETs, there is no ideal solution that can meet the QoS requirements at the MAC layer and resolve all the problems caused by the special characteristics of VANETs.

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