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Time division multiple access scheduling strategies for emerging vehicular ad hoc network medium access control protocols: a survey

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Abstract

Vehicular ad hoc network (VANET) is an emerging and promising technology, which allows vehicles while moving on the road to communicate and share resources. These resources are aimed at improving traffic safety and providing comfort to drivers and passengers. The resources use applications that have to meet high reliability and delay constraints. However, to implement these applications, VANET relies on medium access control (MAC) protocol. Many approaches have been proposed in the literature using time division multiple access (TDMA) scheme to enhance the efficiency of MAC protocol. Nevertheless, this technique has encountered some challenges including access and merging collisions due to inefficient time slot allocation strategy and hidden terminal problem. Despite several attempts to study this class of protocol, issues such as channel access and time slot scheduling strategy have not been given much attention. In this paper, we have relatively examined the most prominent TDMA MAC protocols which were proposed in the literature from 2010 to 2018. These protocols were classified based on scheduling strategy and the technique adopted. Also, we have comparatively analyzed them based on different parameters and performance metrics used. Finally, some open issues are presented for future deployment.

Keywords Vehicular ad hoc network · Medium access control protocol · TDMA · Distributed scheduling · Centralized scheduling

1 Introduction

Road traffic injuries are one of the major causes of death worldwide among all age groups [1, 2]. Vehicular ad hoc network (VANET), which is one of the vital components of Intelligent Transportation System (ITS) [3, 4], was envisioned to support applications that can improve road traffic safety and provide comfort to drivers and passengers [5, 6]. To support these applications, vehicles communicate and exchange information through vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) [7]. Vehicle automatically transmits periodic messages at regular intervals to determine their neighbors and share status information (position, speed, acceleration, and direction) in order to avoid any hazardous situation on the road such as accident before it occurs. On the other hand, emergency messages are transmitted to inform all nearby neighbors to be aware of any instantaneous situation in case of an emergency event [8, 9]. To broadcast these messages, VANET relies on IEEE802.11p Medium Access Control (MAC) architecture.

The first standard which is defined to support vehicles communication is the Dedicated Short Range Communication (DSRC) by USA Federal Communication Commission (FCC) [10]. It allows transmission range from 300 to 1000 m using a data rate of 6–27 Mb/s. The FCC allocated a 75 MHz frequency band which is divided into seven channels of

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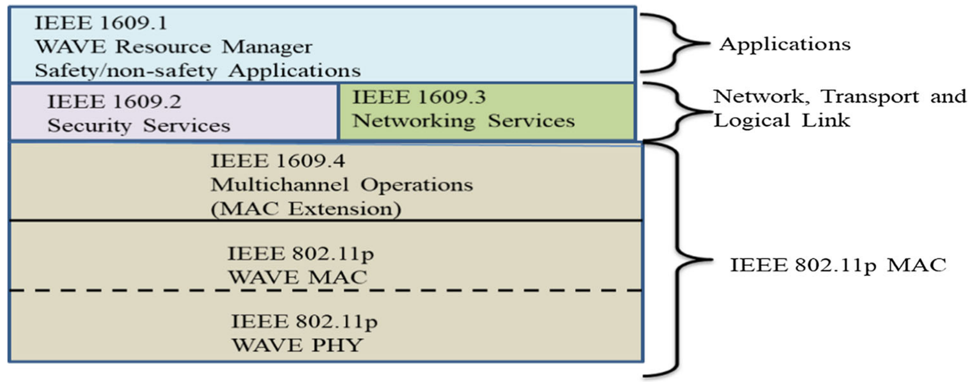


Fig. 1 WAVE MAC protocol stack [9]

10 MHz (one control channel and six service channels). The Control Channel (CCH) is mainly for transmitting high priority messages (periodic and emergency messages) and control information that determines which time slots a vehicle should access, while the six service channels (SCHs) are generally for data transmission which are used for different services. Similarly, to support multichannel operations, IEEE1609.4 was defined in the wireless access in the vehicular environment (WAVE) protocol stack as an extension of IEEE802.11p MAC [11] as shown in Fig. 1.

The conventional IEEE802.11p MAC protocol uses a carrier sense mechanism to access wireless medium called Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). Unlike in a unicast transmission, there is no ready to send/clear to send (RTS/CTS) handshake mechanism for broadcast messages. Hence, resulting in a hidden terminal problem, which happens whenever a receiver is within the range of two transmitters that do not hear each other [12]. It is known that the main aim of MAC protocol is to ensure that safety messages are delivered without collision by ensuring that each vehicle is allowed access to the medium in a bounded delay. However, research has shown that this MAC protocol does not adequately address the requirements imposed by VANET safety applications [13–15]. To improve the efficiency and reliability of conventional IEEE 802.11p MAC protocol many research efforts have been proposed [16–19]. These proposed mechanisms fall into two broad categories: contention-based and contention-free schemes [20] as discussed in Sect. 3.

Recently, TDMA based MAC protocols have received a lot of attention where numerous protocols have been proposed in the literature. This is due to the fact that a vehicle can be assigned bandwidth resources on request and time slots can be rescheduled based on access priority. Thus, TDMA is well-matched to the stringent requirements of VANET safety applications. In addition, a lot of research efforts has been proposed in the literature to tackle the high collision rate problem which has been experienced in the original IEEE 802.11p standard using TDMA [21–25]. The proposed solutions improve the reliability of the safety applications without compromising the increased throughput of the non-safety applications. There have been many research works which surveyed various MAC protocols in VANET as presented in the following section. In this paper, we review TDMA based MAC protocols and classify them based on their scheduling strategy. Moreover, they have been compared and analyzed based on different parameters and performance metrics. Furthermore, we have discussed the open issues and future directions to highlight areas where the TDMA protocol can be improved for future deployment.

The remaining part of this paper is organized as follows; in Sect. 2, related work is highlighted and in Sect. 3, classification of VANET MAC protocols is discussed. In Sect. 4, challenges associated with TDMA MAC protocols are highlighted. In Sect. 5, some selected existing approaches are surveyed and comprehensively reviewed, focusing on the distributed and centralized channel scheduling schemes. In Sect. 6, we comparatively analyzed these MAC protocols based on parameters including the channel access method and time slot scheduling strategy as well as performance metrics used for both safety and non-safety applications. Section 7 discusses the open issues and future directions and finally, in Sect. 8, we conclude the paper.

2 Related work

This section gives a highlight on the existing literature that has surveyed various VANET MAC protocol challenges and proposed solutions. Several efforts on the existing decentralized congestion control techniques and their limitations were presented in [26]. However, the paper did not extensively highlight the challenges associated with TDMA MAC protocol. Authors in [27] highlighted some benefits and challenges that need to be addressed for future enhancement of MAC protocol. Though, issues such as access and merging collision problems which can affect the reliability of TDMA based MAC protocols have not been discussed in the paper. In [28], various issues were discussed involving the design of the multichannel MAC protocols for channel allocation. Nevertheless, the paper fails to highlight the effect of scheduling strategy for TDMA based multichannel MAC protocols which can affect the performance of the protocol. In [29], the authors presented a comprehensive survey on IEEE 802.11p MAC protocols for VANETs safety applications in an integrated fashion. The detailed qualitative analysis was presented and the performance metrics used for evaluating these MAC protocols were compared. Authors in [30] presented a survey on TDMA MAC protocols, identified and described the problems associated with each topology. Nevertheless, the paper did not give any highlights on the scheduling strategy for the studied protocols, which is very significant with regard to TDMA based MAC protocol.

3 Classification of MAC protocols for VANETs

This section describes the different categories of MAC protocols for VANET, which have been classified based on the mechanisms used to access wireless medium [31]. The mechanisms fall into two broad categories, which include contention-based and contention-free schemes as shown in Fig. 2. A brief discussion of each category is given below.

3.1 Contention-based approach

Contention-based MAC protocols use Enhanced Distributed Channel Access (EDCA) based on IEEE802.11e [32]. An example of a contention-based MAC protocol proposed for VANET is IEEE802.11p. The MAC layer of IEEE 802.11p employs a carrier sense mechanism (CSMA/CA) for channel access. This is whereby vehicles can access the medium randomly without a predetermined schedule. Two or more vehicles can sense a free channel and decide to transmit simultaneously especially when traffic density is high. This technique usually relies on some parameters such as carrier sensing, transmission power control and contention window size [33]. Similarly, the hidden terminal problem due to high vehicle density affects the reliability of safety–critical scenarios [34]. Thus to ensure channel access fairness and reliable transmission of safety messages, it is very vital to minimize collision on the CCH. Safety–critical applications which have stringent QoS requirement cannot be guaranteed by the contention-based MAC such as IEEE 802.11p MAC protocol, especially in heavy traffic conditions [20].

3.2 Contention-free MAC protocols

This class of MAC protocol requires a predetermined channel access scheme. Some of the contention-free MAC protocols that have been proposed in the literature include Frequency Division Multiple Access (FDMA), Code Division Multiple Access (CDMA), Space Division Multiple Access (SDMA) and TDMA [30]. These protocols improve channel access utilization and reduce transmission collision rate. However, time synchronization is required among the contending nodes to provide a predictable bounded delay for safety–critical applications. It is assumed that the synchronization is achieved by using a Global Positioning System (GPS) or a Galileo receiver [35]. Each node exchanges its current clock value periodically through transmitted periodic messages to its neighbors [36], which allow each node to obtain an accurate real-time position, speed and exact time. For fine synchronization, an additional synchronization sequence is transmitted in parallel which can enhance the synchronization accuracy. Other useful information transmitted is the node status information. Such information is called beacons. In a distributed system, an algorithm is required for timing the synchronization [37]. Consequently, this means that instead of a node to rely on sensing mechanism to determine the free wireless medium for its data transmission, in this case by synchronization and exchanging the periodic messages among the neighbor nodes, each node would be aware of the available bandwidth to use. Hence, contention-free MAC protocols mechanism helps to increase the performance of the conventional IEEE 802.11p MAC protocol by eliminating the use of sensing technique thereby reducing the channel access time bounded delay when the density of vehicles is high. Moreover, they have the advantage of guaranteeing QoS requirements, and performance is also better even when the network load is high. These techniques also enhance the channel access fairness and are more efficient than CSMA schemes [38]. A brief description of these protocols is given below.

3.2.1 Frequency division multiple access MAC protocol

FDMA is a process of dividing the bandwidth into multiple frequency bands, where each channel is assigned on demand to a different node per frequency. In FDMA mechanism, the communicating vehicles are synchronized to the same channel frequency. It is assumed that the carrier frequency and the available bandwidth are specified through the CCH [39] even though, the synchronization algorithm requires for a CCH frequency to be created. Nodes in the same communication range share the same frequency sub-channels by contending among themselves to acquire the available channel. Similarly, whenever there is a change in network topology the exchange of control messages among the contending vehicles is generated. This also generates an extensive message exchange between communicating vehicles in order of $O\left(d^2C\right)$ where d is the average number of neighbors and C is the number of sub-channels [40]. Thus, this mechanism makes FDMA very complex, hence increases the transmis-

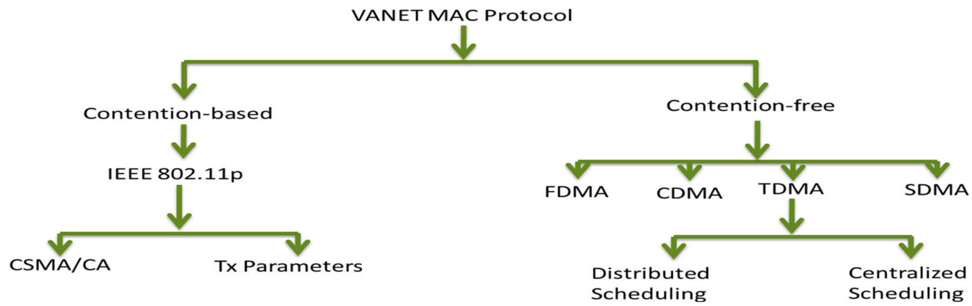


Fig. 2 Classification of VANET MAC protocols

sion delay for applications that are time-bound as well as high overhead to the communication channel. Furthermore, due to several technical problems such as frequency synchronization and presence of Doppler effects due to the high mobility of vehicles, FDMA technique is not suitable for VANET [41].

3.2.2 Code division multiple access MAC protocols

CDMA technique is a spread spectrum (SS) aimed to allow multiple communications using the same frequency channel at the same time for vehicles within the same communication range. The CDMA-based MAC protocol scheme supports simultaneous data transmission where vehicles share the same frequency channel by using a unique code sequence called Pseudo Random Noise (PN) code [42]. Unlike the FDMA mechanism, before communication begins, the two communicating vehicles must agree on the code to be used so that the transmission collision rate can be reduced [17]. It is required that in CDMA technique each vehicle should have a prior knowledge of the PN code to be used for data transmission [43]. This mechanism requires that an assignment algorithm be created in order to exchange and also to assign codes for every transmission among the contending nodes. The main challenge in this scheme is how to assign the PN codes to different nodes especially when the network density is very high. One solution proposed in [44] is by using distributed PN codes, where each node in the network would be provided with several matched filters that correspond to the available PN codes shared by all nodes. In this case, each node would attempt to select a unique PN code corresponding to the matched filter within its communication range. As the number of vehicles increases, the contention to find free available PN code also increases where the possibility of two or more vehicles could attempt to select the same PN code in the same transmission range especially when there are few available PN codes. However, this approach may result in a hidden terminal problem which increases the delay in accessing the wireless medium. Similarly, the requirement of a matched filter for each PN code based on the location of a vehicle makes its implementation very complex and not suitable in a realistic traffic scenario where highly reliable transmissions are required between nodes [45, 46]. Thus, CDMA protocols suffer significant overhead and also generate low throughput due to high packet error probability and interference [47].

3.2.3 Space division multiple access MAC protocols

SDMA is a technique that involves the use of geographical space to allocate the wireless medium to vehicles moving on the road. For example, a single channel could be used simultaneously if the vehicles are spaced far enough from one another. This mechanism avoids the use of creating a code for each transmission as in CDMA scheme, which minimizes delay and high overhead on the control channel. In SDMA, space is divided into smaller units called cells which allows vehicles to transmit data depending on the spatial locations [48]. It is assumed that the precise location of each vehicle is known by using Global Positioning System (GPS) or any other geo-localization system. A road is partitioned into segments where each vehicle can send its beacon frame according to its position in the segment to which it belongs. SDMA technique is mainly divided into three main parts [49];

- Spatial discretization scheme: This divides the road segment into equal size areas called cells.
- Mapping function: Defined as a function that allocates time slots to each of these cells, where no two cells are mapped to the same time slot within a predefined range of each other.
- Assignment rule: This assigns a particular time slot to every vehicle where it can access the channel based on vehicles current position.

Consequently, this could allow each vehicle to determine its position at any given time and also which channel to use while moving on the road [50]. Let us assume that the geographical space X is divided into n areas ($X_1, X_2, X_3, \ldots X_n$) where each cell holds at most one vehicle. Furthermore, the channel bandwidth represented by the time slot T, which is required to access the medium is divided into n slices (T_1, $T_2, T_3, \ldots T_n$). Thus, the SDMA is represented as a one-to-one mapping function assigning a unique channel bandwidth division to every cell [51] as follows:

$$F : X \to T \tag{1}$$

Due to the dynamic nature of network topology in VANET, the location of vehicle v at time t may not be the same as a location at time t' such that:

$$X_v(t) \neq X_v(t') \tag{2}$$

Hence, the access time of vehicle v varies as it moves to a new location. These binding changes need to be periodically updated and hence, the delay bound is necessary. Some of the benefits of SDMA based MAC protocols are low communication overhead and increased channel reusability. However, map error merging, inaccurate positioning and time synchronization can lower the performance of the SDMA protocol [12, 52]. For example, considering vehicles i and j located in space division X_i and X_j, the positioning error of vehicle i may cause it to assume that it is located in space division of X_j causing a transmission collision. Similarly, a situation may arise in a less dense network where a particular portion of the road segment is not occupied and the time slot associated with that space will not be in use, hence resulting to bandwidth wastage.

3.2.4 Time division multiple access MAC protocols

TDMA based MAC protocol is an emerging area in VANET, which allows many vehicles to use the same frequency channel without any interference from neighboring vehicles on the network. It is achieved by allotting bandwidth resources to all vehicles within the network. Time is divided into several frames and each frame is divided into a number of time slots as shown in Fig. 3. Furthermore, it is also required that each vehicle is equipped with a positioning system GPS (Global Positioning System) and the one-Pulse-Per-Second (IPPS) signal for real-time synchronization of the communicating vehicles. This would provide accurate real-time three-dimensional positions (latitude, longitude, and altitude), direction and velocity of each vehicle. In this technique, each vehicle is allocated a unique time slot to access a wireless medium for its data transmission while it would be in listening mode for its neighbors during their own time slot [53]. All vehicles use the same frequency channel but at a different time unlike in FDMA scheme, where interference occurs [41]. The main idea of TDMA scheduling scheme is to assign time slots to the competing nodes in the network in order to avoid a collision when transmitting data packets. For TDMA MAC protocols to operate efficiently, each vehicle must be aware of the status of its neighbors through hello messages broadcasted periodically. Generally, TDMA can either be distributed or centralized scheduling scheme [30]. In a distributed TDMA based schedule, each node in the network manages its own time slot without any central coordination. Similarly, to acquire and maintain a time slot in this technique, each node needs to communicate with its one-hop neighbor by broadcasting its frame information which contains the time slot status [54]. For example, when a vehicle joins a network, it will first listen to its neighbors by receiving beacon (periodic) messages. The message received contains information about the neighbor's node status information and the reserved time slot for all the vehicles within the one-hop neighbor communication range. This allows the new vehicle to determine all the available free slots within which it can select and reserve its own time slot for an onward broadcast of its beacon message to the neighborhood. By reserving a time slot successfully, it means the node can have access to the wireless medium especially the CCH for transmitting both periodic and other safety messages [55]. Each vehicle can only broadcast during its reserved time slot while it would be in listening mode for its neighbors during their own time slot.

On the other hand, in a centralized scheme, it involves a central coordinator who is responsible for controlling and maintaining the time slots schedule within the network. The coordinator needs to have the status information of all the vehicles within the communication range and make a schedule decision based on some desired criteria. In the TDMA scheme, the bandwidth resource utilization is guaranteed by allowing the allocation of different number of time slots to several vehicles. This improves the MAC protocol reliability and support implementation of VANET applications, unlike other contention-free mechanisms. Both distributed and centralized TDMA scheduling scheme for VANET MAC protocols have been thoroughly investigated in Sect. 5. However, the following section presents some of the challenges affecting the existing TDMA-based MAC protocols scheme.

4 Challenges associated with TDMA based MAC protocols

This section highlights some of the challenging issues associated with the existing TDMA MAC protocols. In VANETs, vehicles move at a very high speed so the topology changes frequently. However, due to this high mobility and problems of a hidden terminal, these MAC protocols are challenged with transmission collision, which can occur when allocating a time slot to the contending vehicles [56]. The transmission collision can either be access collision or merging collision [30] as described in the following sections.

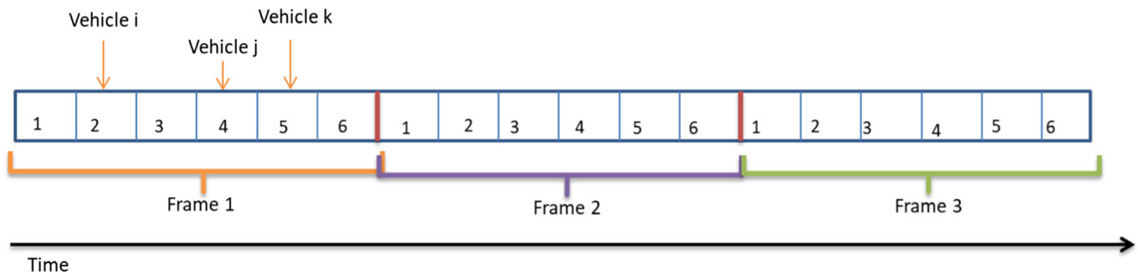
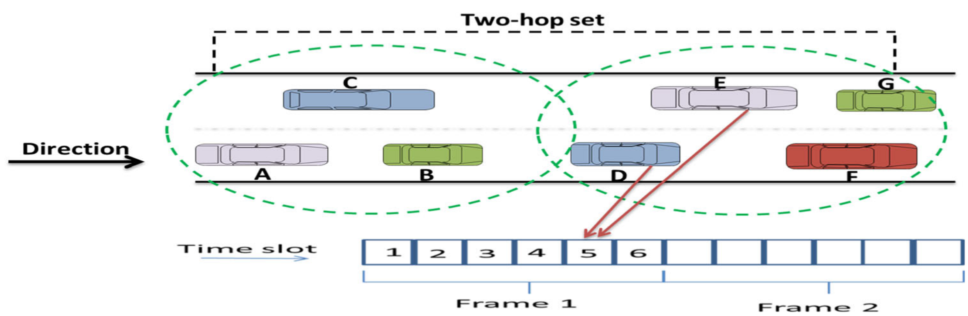


Fig. 3 TDMA frame structure

Fig. 4 Access collision



4.1 Access collision

This usually occurs when two or more vehicles are within the range of two-hop neighborhood set try to acquire the same available time slot as shown in Fig. 4. In most cases, this happens in a distributed scheduling technique where vehicles acquire their time slots randomly based on the information received from their neighbors. So, if two or more vehicles joined the network concurrently it may likely choose the same free time slots and hence results to access collision. For example, if vehicles D and E moving on the same direction received information from their neighbors that the time slot index number 5 is free. Then, trying to access this free time slot index number 5 by these vehicles would lead to an access collision problem.

4.2 Merging collision

This problem occurs when two or more vehicles in a different two-hop neighborhood set using the same time slot becomes members of the same two-hop set due to changes in their position (i.e. vehicles moving in opposite directions or moving at different speeds). Specifically, it can happen in one of the following scenarios.

- Merging collision can happen among vehicles moving in the same direction with variant vehicles speed.
- Can happen among vehicles moving in opposite directions (approaching each other).
- Can happen due to a hidden node problem.

The scenario in Fig. 5 shows that vehicle B in two-hop set1 (THS-1) is moving in the same direction with vehicle F in two-hop set2 (THS-2) and these vehicles are using the same time slot. If vehicle B due to its high speed becomes a member of THS-2 as vehicle H, then it will result to a merging collision problem.

Figure 6 below shows the merging collision caused by vehicles moving in opposite directions. Vehicle B in the first two-hop set moving in opposite directions to vehicle H in the second two-hop set is using the same time slot as vehicle H. Since vehicles B and H become members of the same two hop set, a merging collision occurs at vehicle F.

Similarly, merging collision could be caused by a hidden node problem as shown in Fig. 7. It happens when vehicles that are not within the transmission range of each other but is in communication range with another node. For example, when vehicle B in cluster 1 and vehicle D in cluster 2 are using the same time slot and these two vehicles are not within the transmission range of each other. But vehicle C is within the transmission range of both vehicles B and D, thus a merging collision will occur at vehicle C because both will transmit simultaneously.

Consequently, scheduling mechanism should consider traffic density and mobility of vehicles in order to minimize transmission collision, reduce channel access delay and packet loss. In the following section, some of the prominent TDMA based MAC protocols are considered and reviewed based on the scheduling technique in solving the existing challenges.

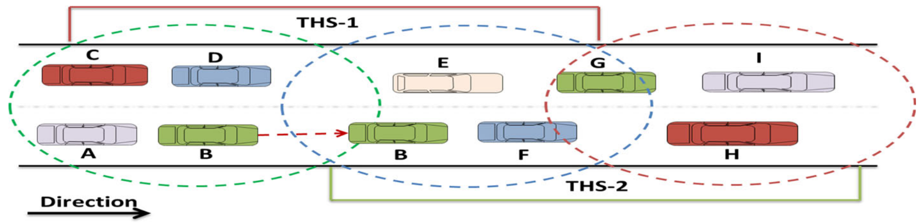


Fig. 5 Merging collision among vehicles moving in the same direction due to vehicles speed

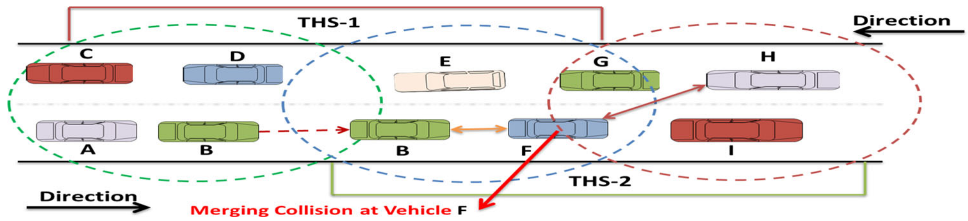


Fig. 6 Merging collision due to vehicles moving in opposite directions

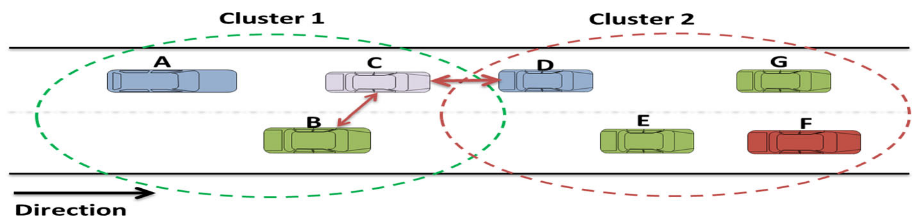


Fig. 7 Merging collision due to hidden node problem

5 Review of the existing TDMA based MAC protocols

This section comprehensively explores and reviews the most prominent MAC protocols based on the TDMA scheme. This class of MAC protocols can either be distributed or centralized based on the scheduling strategy adopted. The following subsections describe these two approaches in detail.

5.1 Distributed TDMA based MAC protocols

In a distributed TDMA based MAC protocols, each vehicle communicates with its neighbors within one-hop range to access the channel using the technique they have adopted. In this technique, vehicles do not require a central coordinator to control the time slot allocation among the contending nodes. The approach is faced with challenging issues such as inefficient utilization of wireless medium, fairness, hidden terminal problem and transmission collision (both access and merging collision). Figure 8 shows the distributed TDMA based MAC protocol topology.

There are numerous research contributions in the literature to improve distributed TDMA based MAC protocols. In [57], a dedicated multichannel MAC protocol (DMMAC) was proposed. The main aim was to minimize collision and improve the transmission of delay sensitive applications. The authors used a hybrid approach combining TDMA and CSMA/CA channel access mechanism. The Control Channel Interval (CCHI) was divided into an adaptive broadcast frame (ABF) and contention-based reservation period (CRP). The ABF consists of time slots which are dynamically reserved by an active vehicle as its basic channel (BCH) for transmitting high priority messages. On the other hand, vehicles reserve resources for SCHs operations using CRP. However, when the network density increases, the time for the CCHI increases, which relatively decreases the CRP for the non-safety applications hence, reduces the MAC scalability. Similarly, the transmission collision and delay metrics which are specified as the main aim of the paper were not evaluated by the proposed mechanism.

A novel Distributed Asynchronous Multichannel MAC Scheme (AMCMAC-D) was proposed in [58]. The paper focuses on the inefficient utilization of wireless medium and transmission collision due to the problem of hidden terminals. The distributive nature of channel access reduces the overhead that is associated with channel allocation between the contending nodes. Nonetheless, the probability of both access and merging collision is very high when the density of vehicles increases. Similarly, performance metrics such as delay and packet loss were not evaluated. The TDMA-based CCH access MAC (TDMA-CCA) in [59] was proposed to address the issue of channel access fairness. In this scheme, the available time slot is acquired by a vehicle considering its position and direction. Equally, the frame length is adjusted dynamically based on the vehicles density, which may reduce the high overhead on the CCH and improve channel access fairness. However, no validation was carried out to confirm their claim.

Authors in [60] presented a multichannel TDMA MAC protocol called VeMAC. It is achieved by allocating a disjoint

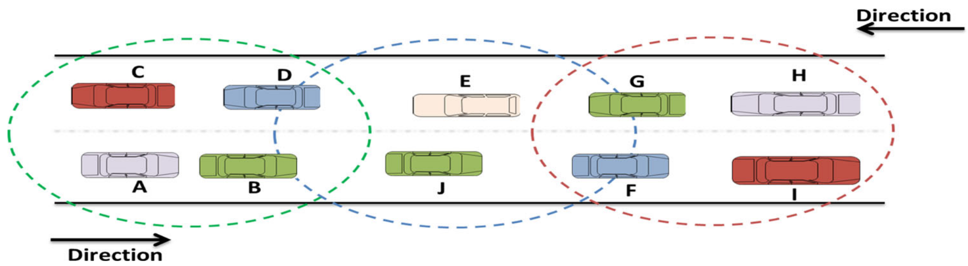


Fig. 8 Distributed TDMA based topology

set of time slots to vehicles moving in opposite directions. The paper employs a fixed time slot allocation strategy to vehicles and RSU. Additionally, each node announces its time slot periodically to all nearby neighbors within one-hop range. However, fixed time slot allocation may limit the number of vehicles that could be accommodated especially when the number of vehicles is greater than the number of the time slot. As a consequence, the rate of both access and merging collision increases. Similarly, reserving an available time slot by vehicles associated with any direction may trigger both access and merging collision. Authors in [61], proposed an adaptive TDMA slot assignment (ATSA) protocol. In this approach, the frame length is dynamically adjusted to decrease the probability of transmission collision using binary tree algorithm. However, a single channel approach limits the performance of this proposal and simulation was not carried out to validate the theoretical analysis. A near collision free reservation MAC protocol (CFR-MAC) was proposed in [62]. The approach extends the frame information of VeMAC to include the vehicle's speed and direction. This is achieved by dividing each time slot set of the two directions (L and R) into three subsets associated with speed intervals; high, medium and low as well as traffic flow of the vehicles. However, both VeMAC and CFR-MAC used two scenarios with split up parameter values which need to be further investigated.

A hybrid approach using both CSMA and TDMA was presented in [63]. In this mechanism, the synchronization interval on the CCH is divided into reservation period (RP) and contention-based period CP). The number of the time slot in the RP is dynamically adjusted according to the vehicles density within the two-hop range. The CP is used to reserve time slot (EmgSlot) during the ABF period or to exchange control messages for 3-way WSA/RFS (wave service announcement/request for service) handshake. Regardless, broadcasting safety messages twice may consume bandwidth and increase high overhead to the CCH. As the density of vehicles increases, the RP increases which conversely decreases the length of CP for the successful number of the time slot for the SCHs (SerSlot) for non-safety applications. Simulation result shows that when a density increases, it takes a longer time to finish the EmgSlot reservations, which result in packets drop. In [64], Carrier Sense Multiple Access and Self Organizing TDMA MAC (CS-TDMA) protocol was presented to provide channel access and switching simultaneously. Dynamically, the switching between CCH and SCH is adjusted based on the traffic density. However, a fixed contention window size may lead to access collision when two or more vehicles back-off their counters to zero simultaneously. Also, the paper did not evaluate the rate of merging collision.

A fully distributed TDMA MAC protocol (DTMAC) was proposed in [65]. The main goal of this scheme was to minimize access collision and provide high throughput under various traffic conditions. DTMAC uses vehicular location information to allow vehicles to access the wireless medium. However, there is a possibility of merging collision due to the fixed allocation strategy of time slots. Furthermore, the proposal was evaluated only using analytical analysis. Recently, authors in [66], proposed distributed TDMA MAC protocols (D-TDMA). Two state Markov chain model was employed to estimate the channel state when a transmission failure occurs. In this case, a node releases its time slot and acquires a new one when the transmission failure is estimated solely due to transmission collision. This improves the performance of D-TDMA protocols by allowing nodes to release their time slots only when needed. However, this approach did not consider merging collision problem which can happen due to the high speed of the vehicles. Table 1 below gives the summary of the distributed TDMA based MAC protocols under review.

5.2 Centralized TDMA based MAC protocols

Centralized TDMA based MAC protocols adopted a technique that requires central coordination for time slot allocation to the contending vehicles. This technique is categorized into two, including cluster based and RSU based approach as discussed below.

5.2.1 Cluster-based approach

In a cluster-based scheme, vehicles moving on the road are groups based on some predefined parameters such as vehicles density, speed, position and road ID [67]. Each vehicle identifies its neighbor by sharing their mobility information through hello messages. Based on the clustering algorithm

Table 1 Summary of distributed TDMA based MAC protocols

Year (Ref)	Channel access	Time slot allocation	Mobility scenario	Vehicular traffic	Hidden terminal	Access collision	Merging collision	Metrics
2010 DMMAC [57]	Multiple	Dynamic	Highway	Unidirectional	Not addressed	Addressed	Not addressed	PDR
2012 AMCMAC-D [58]	Multiple	Fixed	Highway	Unidirectional	Addressed	Addressed	Not addressed	Throughput PDR
2013 VeMAC [60]	Multiple	Fixed	Highway/City	Bidirectional	Addressed	Addressed	Addressed	RMC, RAC, Tx Throughput, Rx Throughput
2013 ATSA [61]	Single	Dynamic	Highway	Bidirectional	Addressed	Addressed	Addressed	Delay, RAC
2014 TDMA-CCA [59]	Single	Dynamic	City	Bidirectional	Addressed	Addressed	Not addressed	RAC, Fairness
2014 HER-MAC [63]	Multiple	Dynamic	Highway	Unidirectional	Addressed	Not addressed	Not addressed	Throughput, PDR
2014 CS-TDMA [64]	Multiple	Dynamic	Highway	Unidirectional	Addressed	Not Addressed	Not Addressed	Throughput, PDR, Loss
2014 CFR-MAC [62]	Single	Fixed	Highway	Bidirectional	Addressed	Addressed	Not addressed	TCR
2015 DTMAC [65]	Single	Fixed	Highway	Bidirectional	Addressed	Addressed	Not addressed	None
2017 D-TDMA [66]	Single	Fixed	Highway	Unidirectional	Addressed	Addressed	Not addressed	TCR

RMC rate of merging collision, *RAC* rate of access collision, *TRC* transmission collision rate, *ACP* access collision probability

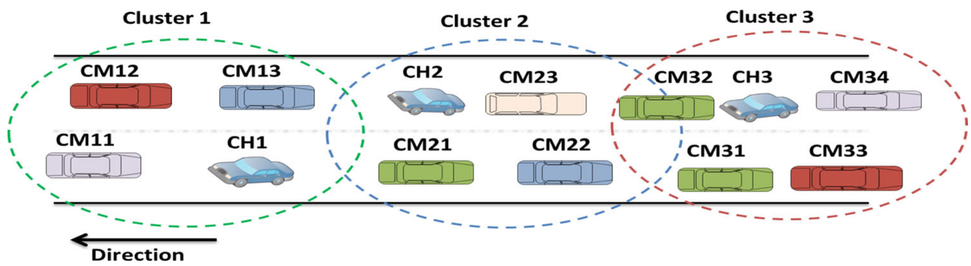


Fig. 9 Centralized TDMA MAC using cluster-based topology

implemented, a cluster head (CH) is elected for each group while the remaining ones become cluster members (CMs). Once CH is elected it bears the responsibility of controlling the cluster and also coordinates the time slot scheduling for the CMs. Clustering technique for a TDMA MAC protocol involves five phases which include cluster formation, cluster head election, inter-cluster communication, cluster maintenance, and time slot allocation. In a cluster-based TDMA MAC protocol, efficient time slot allocation is required to avoid inter-cluster interference for vehicles that are adjacent to each other and within communication range, which will result in merging collision problem. However, the main challenges in this technique are electing the cluster head, inter-cluster interference, intra-cluster communication and time slot reservation due to the vehicles high mobility and dynamic topology changes. The cluster-based architecture is shown in Fig. 9.

Many research efforts have been proposed in the literature to improve the performance of TDMA MAC protocols in a cluster-based scheduling approach. In an effort to improve scalability and reduce the collision rate, a cluster based TDMA (CBT) was proposed in [68]. The authors used a transmit-and-listen mechanism to randomly elect a CH. In CBT, the first frame is for cluster nodes to compete for CH while the remaining slots from 1 to $n - 1$ are used for data transmission. However, electing a CH randomly may result in an unstable cluster which can degrade the reliability of the CBT MAC protocol. Similarly, the rate of access and merging collisions were not evaluated. In [69], a hybrid clustering based MAC protocol (HCMAC) was proposed. CHs are selected using mobility factors. Though the proposed approach did not give any information about how the time slot is allocated to CMs.

A TDMA cluster based MAC protocol (TC-MAC) has been proposed in [70] and further modified in [71]. The authors addressed three issues which include cluster formation, time slot reservation and intra-cluster communication. Unlike IEEE 1609.4 standard architecture, in TC-MAC each vehicle tuned to either CCH or SCHs when needed during the SI. Traffic flow algorithm in [72] was adopted for CH formation. In TC-MAC, the frame length is based on the number of vehicles in the cluster. Each node in a cluster will be allocated a local ID by the CH from 0 to $N - 1$ where N is the number of vehicles. The CH keeps a list of all the current active vehicles and broadcasts to all members in the cluster. The integer division theorem used for slot reservation guarantees that no two vehicles can have the same ordered pair of time slots. However, TC-MAC only considers intra-cluster communication leaving the inter-cluster interference problem which may cause a merging collision. Similarly, the high transmission rate for non-safety applications on the SCHs may impair the reliability of safety applications. Similarly, authors in [73] came up with another modification of TC-MAC called enhanced TDMA cluster-based MAC protocol (ETCM). This mechanism uses only a single radio interface that can switch between CCH and SCHs. In contrast to TC-MAC, each vehicle gets two mini-slots in two consecutive CCH slots for channel negotiation among CMs. It also improves SCHs utilization by reallocation of unused slots dynamically to some vehicles that need more than one SCH slots. However, this scheme failed to consider any challenge related to inter-cluster communications, which may cause interference and high rate of collision.

In [74], a Cooperative ADHOC MAC (CAH MAC) was presented. This mechanism allows a neighboring node (helper) to cooperate for retransmission of a packet which failed to reach the target receiver by utilizing unreserved time slots. Nonetheless, using this unreserved time slots can result in a problem of access collision with vehicles attempting to reserve the available time slots. The authors in [75] address the problem of channel access fairness by allocating the time slots according to each vehicle's required bit rate. The paper uses Jain's index mechanism to measure the channel access fairness. However, some active vehicles that do not use all their possible transmission token, results in decreased bandwidth utilization. In [76], an adaptive TDMA slot assignment strategy (ASAS) was also proposed. The authors use Euclidean distance to divide the vehicles into clusters and vehicle's position and direction for CH election process. The assignment of the time slot to vehicles is based on the request from their hello messages. This is achieved using a hybrid approach by dividing each logical frame into ABS and CRP period as used in [57]. However, the paper fails to consider what will happen when the density of vehicles increase where many vehicles try to reserve a time slot since it is using CRP for time slot reservation. It is also difficult to maintain cluster stability using a bidirectional approach.

Authors in [77] proposed TM MAC protocol using variable interval multichannel scheduling strategy. The time slot is divided into four sets including RSU, left, right, and leader slot. Each vehicle in the cluster sends its leadership quality indicator (LQI) along with its periodic messages for it to be elected as a leader. In this approach, merging collision affects only one vehicle that joined the cluster whereby it will release its current time slot. Similarly, to reduce the effect of access collision in both directions, free slots are calculated based on the vehicles arrival rate by the leader. However, maintaining cluster stability for vehicles moving in both left and right directions is impractical. Weight clustering based TDMA MAC scheme (WCS-MAC) has also been proposed in [78]. In this approach, in a cluster, each vehicle is allowed to borrow the time slot that is assigned to other vehicles at an access probability. However, the authors did not consider the inter-cluster communication which if implemented, can improve the efficiency of the proposed scheme. In [79], Adaptive Beaconing in Mobility Aware Clustering based MAC (ABM-MAC) protocol was proposed where CCH/SCHs are partitioned into two frames of equal duration and the same number of slots. Each CM is allocated a different time slot based on the message priority. However, this approach can cause merging collision problem within the adjacent CMs because the time slot allocation of adjacent CMs is not taken care of. Similarly, no any mechanism for inter-cluster communication was proposed. The summary of these Cluster based TDMA MAC protocols is given in Table 2 below.

5.2.2 RSU-based approach

This technique employs the use of RSU, which acts as a central coordinator for time slot allocation and it is placed on the roadside, unlike a cluster-based approach. However, it is challenged with some issues such as interference within the neighboring RSUs due to the high mobility of vehicles. The simple architecture of the RSU-based approach is shown in Fig. 10.

Numerous approaches have been proposed in the literature to tackle and minimize the challenging issues in the RSU-based topology. Authors in [80] proposed a cluster-based RSU centric channel access (CBRC) MAC protocol. The information regarding the assigned time slots and available channel information within the coverage area is maintained by the RSU. Similarly, the RSU always uses channel allocation matrix to refuse channel allocation to a requesting vehicle that is already in communication range with another vehicle, and hence, minimizes access collision problem. However, the fixed number of slots allocation degrades the performance of CBRC especially when the density is very high. Authors in [81] proposed an adaptive collision free MAC protocol (ACFM). In this scheme, each frame is divided into two segments; RSU segment and vehicle segment. RSU slot is used to broadcast control messages and 36 data slots for vehicles to broadcast their periodic messages. To ensure fairness in accessing channel by the vehicles, the RSU dynamically adjust the slot assignment cycle frame based on the traffic density. However, ACFM uses a single channel and does not support a non-safety application. To improve ACFM, authors in [82] proposed R-MAC. They employ CSMA/TDMA mechanism. The CSMA scheme is responsible for transmitting emergency messages, while TDMA scheme for transmitting periodic messages. However, using the CSMA mode for transmission of emergency messages may affect the reliability of this protocol. Similarly, simulation results show that it cannot operate well under heavy traffic situations.

In [83], a unified TDMA-based scheduling protocol (UTSP) was proposed. The time slot is allocated based on the weight-factor scheduler using some parameters. This technique improves throughput and channel access fairness. However, inter-RSU interference may occur, which can cause transmission collision. A novel centralized TDMA based scheduling protocol was also proposed in [84]. In this scheme, the RSU calculates the scheduling weight factor of each communication link and broadcast the scheduling decisions to all vehicles to allow individual data transmissions during the allocated time slots. Similarly, the authors employ a resource-reuse if the distance between the vehicles exceeds a predefined interference interval. However, using only one RSU to evaluate their proposal, limits the efficiency of this approach especially when two or more RSU's are placed on the roadside causing interference.

Similarly, authors in [85] proposed RCMAC where all vehicles within the coverage area receive control information. Each node maintains a one-hop neighbor list (ONL). Once it receives a packet transmitted on the CCH it updates its ONL. However, choosing random time slots by neighbor nodes may cause an access collision. In [86], CTMAC protocol was proposed in order to avoid RSU interference without any complex spectrum mechanism such as CDMA. Each frame in this scheme is divided into two sets of time slots *S1* and *S2* which are associated with vehicles moving in adjacent RSU areas. This provides the two adjacent RSU to access disjoint sets of a time slot that will decrease interference and rate of access collision. However, no any mechanism was provided to avoid merging collision. Moreover, a short stay interval within the RSU coverage area may affect the performance of this protocol especially safety applications, which are time bounded. The summary of these protocols is given in Table 3.

Table 2 Summary of cluster based TDMA MAC protocols

Year (Ref)	Channel access	Time slot allocation	Vehicular traffic	Mobility scenario	Cluster stability	Intra-cluster interference	Inter-cluster interference	Metrics
2012, 2013 TC-MAC [70, 71]	Multiple	Fixed	Unidirectional	Highway	Addressed	Addressed	Not addressed	TCR Pkt loss
2013 CAH-MAC [74]	Single	Fixed	Unidirectional	Highway	Not addressed	Addressed	Not addressed	Throughput
2014 CBT [68]	Single	Not mentioned	Unidirectional	Highway	Not addressed	Addressed	Addressed	Delay
2014 HC-MAC [69]	Single	Not mentioned	Unidirectional	Highway	Addressed	Addressed	Not addressed	Throughput Transmission delay
2014 ASAS [76]	Single	Dynamic	Bidirectional	Highway	Addressed	Addressed	Addressed	RMC RAC ICC
2014 TCA [75]	Multiple	Fixed	Unidirectional	Highway	Not addressed	Addressed	Not addressed	BU Fairness
2016 ETCM [73]	Multiple	Dynamic	Unidirectional	Highway	Not addressed	Addressed	Not addressed	PDR, E2E Delay, Throughput
2016 TM-MAC [77]	Multiple	Dynamic	Bidirectional	City	Not addressed	Addressed	Not addressed	RAC PDR Throughput
2016 WCS-MAC [78]	Single	Fixed	Unidirectional	Highway	Not addressed	Addressed	Not addressed	None
2017 ABM-MAC [79]	Multiple	Fixed	Unidirectional	Highway	Addressed	Addressed	Not addressed	Throughput, PDR, Packet loss, E2E Delay

RMC rate of merging collision, *RAC* rate of access collision, *TRC* transmission collision rate, *BU* bandwidth utilization, *ICC* inter-cluster collision

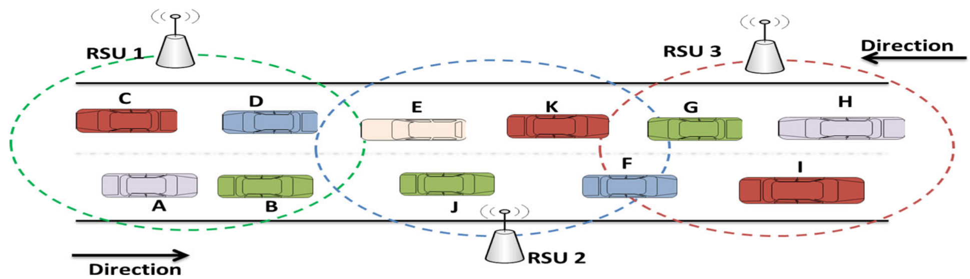


Fig. 10 Centralized TDMA MAC using RSU

Table 3 Summary of RSU based TDMA MAC protocols

Year (Ref)	Channel access	Time slot allocation	Vehicular traffic	Mobility scenario	Inter-RSU interference	Metrics
2010 CBRC [80]	Single	Fixed	Bidirectional	Highway	Addressed	PRR
2012 ACFM [81]	Single	Dynamic	Unidirectional	Highway	Addressed	Delay, Packet loss ratio
2013 RMAC [82]	Single	Dynamic	Unidirectional	Highway	Not addressed	PDR, Delay, Fairness
2013 UTSP [83]	Single	Dynamic	Unidirectional	Highway	Not addressed	Throughput, Delay
2015 CTDMA [84]	Single	Dynamic	Bidirectional	Highway	Not addressed	Throughput, Fairness, Delay
2016 RC-MAC [85]	Single	Fixed	Bidirectional	Highway	Not addressed	RAC
2016 CTMAC [86]	Single	Dynamic	Bidirectional	Highway	Addressed	RAC, RMC

PRR packet reception ratio, *RAC* rate of access collision

6 Comparative analysis of existing TDMA based MAC protocols

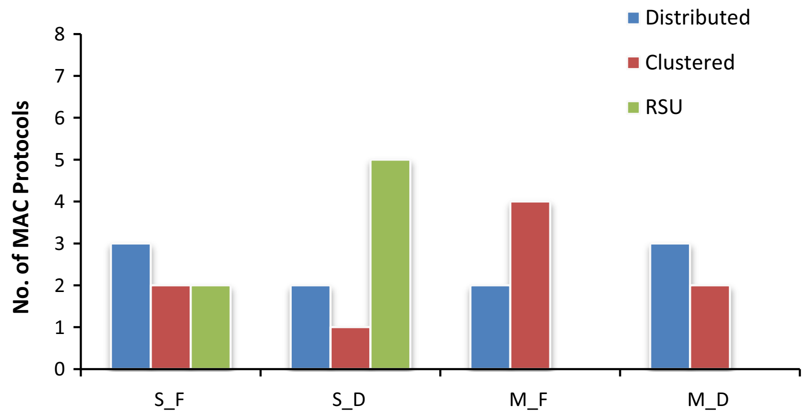
To determine the strength and weaknesses of the proposed TDMA based MAC protocols with respect to scheduling strategy, challenging issues discussed in the literature are considered. Hence, the performance results in each class are derived from the corresponding references specified in Tables 1, 2 and 3. Consequently, comparisons are made using some parameters as shown in Figs. 11, 12, 13 and 14. This comparison is intended to give researchers some highlight on which area is lacking with the aim of improving the efficiency and reliability of the MAC protocol for both safety and non-safety applications.

Channel access and time slot allocation strategies are very crucial for the efficient implementation of TDMA based MAC protocol. Figure 11 shows the distribution of the techniques used in the existing literature under review. Single channel access uses only CCH for safety and non-safety messages, while multichannel access implements the full DSRC channel (one CCH and six SCHs). It is observed that all the proposal using RSU based approach utilized only CCH for data transmission which has an effect on the delivery of non-safety applications. It also shows the time slot allocation scheme used by each category of TDMA MAC protocol. Fixed time slot allocation, confines the number of vehicles to acquire time slot when the number of vehicles is greater than the allocated time slot while a dynamic allocation scheme supports the different vehicles density.

6.1 Distributed TDMA based MAC protocols

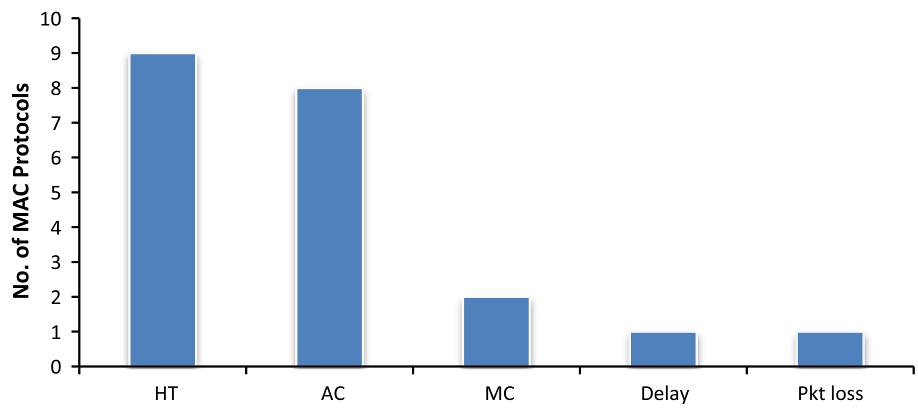
Distributed TDMA based MAC approaches mostly focused on challenging issues such as inefficient utilization of wireless medium, channel access fairness, and transmission collision. Also included is a hidden terminal problem at a high-density network. In a distributed scheduling technique, vehicles access channel without central coordination, hence, minimizes the overhead associated with channel allocation on the CCH.

From Fig. 12, we can deduce that more than 90% of the existing approaches tackled the issue of the hidden terminal problem, which generally minimizes about 80% of the problem of access collision. However, the probability of transmission collision increases in a single channel access scheme because all the contending nodes share the same wireless medium for transmission of both safety and non-safety applications. Conversely, the multichannel access



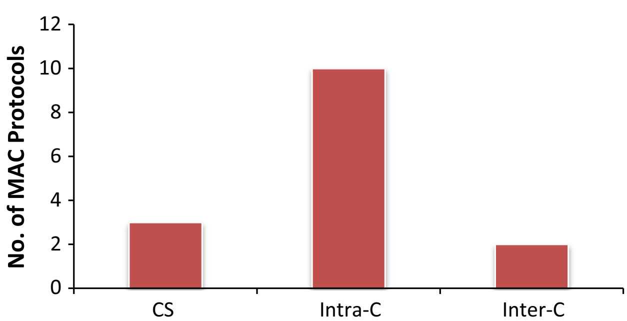
S_F: Single channel access/Fixed time slot allocation; S_D: Single channel/Dynamic time slot; M_F: Multiple channel access/Fixed time slot; M_D: Multiple channel access/Dynamic time slot

Fig. 11 Channel access allocation strategies



HT: Hidden Terminal; AC: Access Collision; MC: Merging Collision

Fig. 12 Challenging issues tackled by distributed TDMA based MAC protocols



CS: Cluster Stability; Intra-C: Intra-Cluster Interference; Inter-C: Inter-Cluster Interference

Fig. 13 Challenging issues tackled by cluster based TDMA MAC protocols

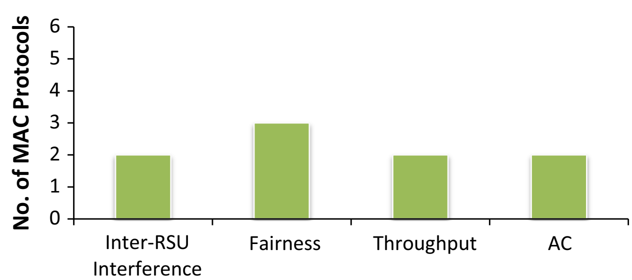


Fig. 14 Challenging issues tackled by RSU-based TDMA MAC protocols

scheme separates the control data and application data, thus improving the reliability of safety messages and high throughput of non-safety applications.

Fixed time slot allocation results in delay and high probability of access and merging collision. However, the dynamic time slot allocation strategy can operate well under variable traffic density and support delay bounded transmission for safety applications as well as reduces transmission collision. Metrics such as packet delay and loss which can affect the reliability of safety messages were not evaluated by most of these papers as shown in Fig. 12. It is also observed that authors in [59, 61] proposed dynamic scheduling in a bidirectional traffic utilizing single channel access. Likewise, approaches in [58–61] minimized the effect of merging collision problem by allocating time slots to vehicles moving in opposite directions but did not eliminate this problem completely when the traffic density increases. In conclusion, it is observed that a fixed frame length can lead to inefficient channel utilization, which could results in packet delay, and thus degrades the performance of MAC protocol, especially in a high-density scenario. Furthermore, merging collision is also a challenge for almost all the proposed approaches caused by the inefficient slot allocation strategy to the contending nodes.

6.2 Cluster-based TDMA MAC protocols

In an effort to improve channel access fairness and minimize transmission delay, cluster-based techniques experience some challenges such as maintaining cluster stability by increasing the cluster lifetime. Others include intra-cluster and inter-cluster interference as well as time slot allocation strategy. Thus, the reliability of safety messages is affected by the high probability of transmission collision rate, which may cause delay or packet loss. The references for these claims can be found in Table 2, which were used to plot Fig. 13.

Figure 13 shows that less than 30% of the proposed approaches addressed the issue of cluster stability but with little improvement. However, when the traffic density is very high, none of the proposed schemes give a reliable mechanism especially when a CH leaves the network. Consequently, this may result in channel access delay and can also cause packet delivery delay or loss. The mechanisms provided by [71, 73, 75, 76, 79] support the implementation of both safety and non-safety messages, but performance decreases due to inter-cluster interference when the density of vehicles increases. Similarly, vehicles that are moving in different directions are considered in [76, 77], but this may cause an unstable cluster. This is because vehicles are moving away from each other, and the CH may lose connectivity from its members thereby causing a new CH to be elected within a short time. Consequently, reduce the efficiency and reliability of the MAC protocol.

Furthermore, more than 80% of the existing literature tackled the issue of intra-cluster interference hence minimizing the effect of access collision. However, less than 20% attempted to solve the issue of inter-cluster interference which remains a challenge. This problem can result to a merging collision problem, which may degrade the reliability of TDMA MAC protocol in supporting the delay bounded applications.

6.3 RSU-based TDMA MAC protocols

Several research efforts in the literature with reference to Table 3 in Sect. 5.2.2 proposed the use of RSU to implement TDMA mechanism in order to improve channel access fairness and reduce scheduling overhead among the contending nodes. It is observed that from Fig. 14, more than 60% of the proposed approaches tackled the issue of channel access fairness by employing a dynamic time slot allocation strategy, where the time slot assignment is adjusted based on the traffic density. This not only improves delivery of delay-sensitive applications, but also decreases channel access delay and packet loss. It has also been shown that about 40% consider evaluating the delivery of non-safety applications and the rate of access collision within the coverage area.

Similarly, less than 40% of the authors addressed the issue of inter-RSU interference which can cause a merging collision problem. It is known that both access and merging collision can degrade the reliability of MAC protocol. However, authors in [80, 83, 84] proposed some approaches to reduce the effect of an access collision, whereas merging collision is still an issue to be addressed. Using the bidirectional traffic scenario in [83–86] also reduces the effect of access collision problem. Moreover, VANET is envisaged to support both safety and non-safety applications. However, majority of the mechanisms proposed in this class of protocols do not support non-safety applications which limit the efficiency of the MAC protocol.

6.4 Summary of the comparative analysis

It is observed that in a distributed scheduling as shown from Figs. 11 and 12, there is an improvement in solving the hidden terminal problem which is the main cause of an access collision. However, the issue of merging collision is still not well addressed. This is because most of the approaches proposed in a distributed TDMA did not address the merging collision problem due to inefficient slot allocation strategy. Furthermore, there is a significant channel access fairness which improves the utilization of wireless medium, and increases the efficiency of the proposed MAC protocol to support both safety and non-safety applications. Likewise, some important performance metrics such as packet delay and loss were not evaluated by most of the authors.

In a cluster-based scheduling scheme as shown in Fig. 13, most of the proposed approaches addressed the issue of intra-cluster interference, and thus reduced the effect of access collision. On the other hand, inter-cluster interference which can cause merging collision problem is still a challenge. Similarly, maintaining the stability of the cluster due to the high mobility of vehicles is a serious challenge regardless of the few mechanisms proposed to address the issue. It was also observed that bidirectional traffic scenario is not suitable for cluster-based scheduling technique. This is because maintaining a stable cluster head for a long period of time is impractical due to the movement of vehicles at different directions and at high speed.

Similarly, the majority of the proposed RSU mechanisms implement a dynamic time slot scheduling strategy and this improves the efficiency of this class of protocols. Generally, all the reviewed TDMA based MAC protocols using RSU technique are utilizing single channel for channel access as shown in Fig. 10. Unlike using the full DSRC channels, the single channel could lead to high overhead to the CCH resulting to channel access delay. Furthermore, most of these proposed schemes using RSU do not support non-safety applications and consider only very few performance metrics to evaluate their approaches. Figure 14 shows that Inter-RSU interference has not been investigated by most of the authors; consequently, this can affect the reliability of the MAC protocol by causing a merging collision problem.

7 Open research issues and future direction

This section highlights some of the open research issues for the implementation of an efficient TDMA based MAC protocol. It is known that VANET technology is one of the emerging technologies that have some salient characteristics due to the high mobility of vehicles and frequent change in topology. Therefore, the realization of the envisioned applications is dependent on the reliability of the MAC protocol. Some of the issues concerning the design of an efficient TDMA MAC protocol are highlighted below. These challenges need to be addressed for future deployment in order to support VANETs applications.

7.1 Merging collision problems

The transmission collision in VANET is broadly categorized into two; access collision and merging collision. Considering our literature survey, we found that the rate of access collision has been minimized significantly especially in a centralized TDMA scheme. On the other hand, merging collision is still a serious issue. This problem generally happens due to inefficient time slots allocation strategy. It has a great effect on the efficiency of TDMA MAC protocols especially for broadcasting safety–critical messages, which are delay bounded. Therefore, an effective slot assignment strategy should be developed in order to allow vehicles to use their time slot without collision. Furthermore, a future works on both distributed and centralized TDMA MAC protocols schemes should put more emphasis on this challenge for the successful deployment of VANET safety applications in order to minimize the effects it may cause.

7.2 Cluster stability

A cluster-based approach is a technique that allows one of the vehicles to be chosen as a leader in order to act as a coordinator for broadcasting control information and fair distribution of time slots to vehicles in a TDMA based MAC protocols. A stable cluster reduces an overhead of re-clustering, where the CH would take a longer time before it moves out of the cluster. However, existing cluster-based TDMA MAC approaches show that maintaining the stability of a cluster due to the high mobility of vehicles is a serious issue, which can affect the reliability of TDMA MAC protocol. This is because the CH can either leave or merge with another CH. It has been observed that most of the proposed clustering algorithms did not provide proper mechanism to deal with a situation when the elected CH moves out of a cluster. Moreover, this CH is responsible for coordinating all CMs within the cluster, if it moves out of the cluster for any reason the clustering architecture has to be reconfigured. This operation can also lead to loss of channel access schedule and may lead to transmission collision or delay delivery of safety messages. Therefore, it is suggested that a new technique should be proposed to further improve the cluster stability for future development of this class of protocols. This could be achieved by assigning one vehicle as a backup to CH. The backup CH can replace the primary CH whenever it moves out of the cluster; so that the overhead of executing a clustering algorithm could be reduced thereby improving the performance of the TDMA MAC protocol.

7.3 Inter-cluster communication

Various efforts in the literature are made to improve the MAC protocol using TDMA based scheme in a cluster-based topology. Nevertheless, most of the authors did not focus on the inter-cluster communication within the adjacent cluster members. It has been observed that in the existing literature for inter-cluster communication to be employed, the two adjacent CHs are required to exchange some information. However, there are situations, when the adjacent CMs are within the transmission range but CHs are not. And to support VANET safety applications these CMs need to communicate and exchange messages to avoid any unwanted situations to occur on the road. Hence, a new mechanism should be provided for inter-cluster communication among the adjacent CMs.

7.4 Inter-RSU interference

A number of TDMA MAC protocols adopted the use of RSUs which acts as a central coordinator for the allocation of time slot and channel access control to the vehicles within its coverage area. However, this approach is challenged with interference within the neighboring RSUs (inter-RSU interference) due to the high mobility of vehicles. An effective mechanism to deal with interference within the overlapping areas i.e. the adjacent RSUs should be developed in order to minimize this interference especially when a vehicle is leaving an existing RSU coverage area and joining a new one.

7.5 Edge-assisted content delivery through vehicle-to-vehicle communication

In ITS, Edge computing has become a promising solution to address the limitations of cloud computing in order to provide timely and intelligent services to autonomous vehicles. The content sharing considers the strict delay constraints of services and utilizes the broadcast nature of vehicular networks to significantly improve the quality of automated driving services. To initiate the content sharing, any vehicle that has any service to offer or want request for a service can inform its neighbors by exchanging broadcast message [87]. However, to realize the benefits of edge computing in VANET, there are still some challenging issues that need to be addressed. One of these issues is how to distribute and manage efficiently the data resources for more scalable services among the neighboring vehicles [88] as well as minimizes end-to-end delay for the cloud-based resources. Most of the existing solutions are based on the CSMA/CA scheme causing the broadcast messages to suffer from a severe hidden terminal problem, which causes a potential collision. Therefore, a TDMA based MAC protocol is needed using full DSRC channels so that collision could be minimized among the neighboring nodes. To maximize the total amount of data transmitted through vehicular networks, an efficient slot allocation should also be carefully designed. In this case, each vehicle can be allocated its own time slot for transmitting safety messages and other control information on the CCH. This could reduce the high overhead on the CCH and improve maximization of the DSRC channels.

7.6 Efficient MAC protocol for IoV

One area where the application of IoT is envisaged to create a big impact is the ITS, which is also known as the Internet of Vehicles (IoV). IoV is used to describe the combination of vehicles equipped with sensors, roadside units (RSU), cellular infrastructure and anything that facilitates vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communication in the VANET environment. The IoV is an infrastructure that allows vehicles to collect a different kind of data from the environment using sensors and share this data with other vehicles or to the internet through V2I. Information such as congestion on the road, road works, accidents, etc. are shared in real-time, hence, vehicles become self-aware of the environment through the contextual data provided by the sensor and eventually can become autonomous [89–91]. The autonomous vehicles will facilitate the smooth flow of traffic both in urban and highway thereby reducing accidents and low emission of CO_2 [91]. The IoV architecture was built on the VANET infrastructure; hence the research problems currently being faced by VANET are also extended to IoV. Therefore, there is a need to come up with solutions that will solve the problems. Some of the challenges to overcome before the deployment of IoV have been presented in [89, 91]. Furthermore, the unique characteristics of VANET, which include dynamic topology change due to the vehicles' high mobility, variation in vehicle density either in highway or urban environment and limited bandwidth due to constrained wireless channels pose more challenges in congestion control. Another factor which contributes to the congestion of MAC in VANET is the broadcasting nature of the beacon messages. Vehicles exchange local status messages periodically to provide current status on speed and position to other neighbors in a network. It is important to note that while there are some existing MAC approaches that have been proposed to solve congestion in VANET; IoV adds more challenges as there will be more objects which will require the same wireless medium as the vehicles, for example, sensors within the vehicle and on the roads. Therefore, there is a need to come up with an efficient TDMA MAC solution that will mitigate the congestion control in IoV.

8 Conclusion

This paper has explored the most interesting and promising TDMA scheduling strategies for emerging VANET MAC protocols. We have classified TDMA MAC protocols into three basic categories based on time slot scheduling techniques. For each category, some inherent challenging issues were identified and highlighted. Additionally, a fair comparison was made using some parameters including channel access method and time slot scheduling strategies for these protocols. This comparison provides the researchers some highlights on which area is lacking in order to improve the efficiency and reliability of the TDMA MAC protocols support VANET applications. Furthermore, we noted that, in a distributed scheduling strategy, the issue of merging collision is not well addressed which resulted in a high delay and packet loss. Similarly, in a cluster-based approach, the inter-cluster interference and cluster stability are some of the major challenges faced due to inefficient slot assignment strategy. Hence, result in the high overhead on the CCH and transmission delay, which can affect the reliability of safety applications. Furthermore, it was observed that the inter-RSU interference problem is still a challenge due to the short stay period of vehicles within the coverage area of RSUs.

Finally, we have highlighted some of the challenges that are associated with the TDMA based MAC protocols for further improvement. Some open research questions for consideration by the research community are also highlighted.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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