TDMA Scheduling Strategies for Emerging VANET MAC Protocols: A Survey

Abubakar Bello Tambawal[ab], Rafidah Md Noor[a*], Rosli Salleh[a], Christopher Chembe[a], Mohammad Hossein Anisi[c], Oche Michael[d], Jaime Lloret[e]

[a]Faculty of Computer Science & Information Technology, University of Malaya, 50603, Kuala Lumpur, Malaysia

[b]Department of Computer Science, College of Science & Technology, Umaru Ali Shinkafi Polytechnic, Sokoto, Nigeria

[c]School of Computer Science and Electronic Engineering, University of Essex, Colchester CO4 3SQ, United Kingdom

[d]Department of Computing, Faculty of Science & Technology, Kampala International University, Kampala, Uganda

[e]Integrated Management Coastal Research Institute, Universitat Politecnica de Valencia, Valencia 46022, Spain

**corresponding author*

ABSTRACT

Vehicular Ad hoc Network (VANET) is an emerging and promising technology, which allows vehicles to communicate and share resources. These 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 literature using Time Division Multiple Access (TDMA) scheme to enhance the efficiency of MAC protocol. Nevertheless, this technique is faced with some challenges including access and merging collisions due to inefficient time slot allocation strategy and hidden terminal problem. In this paper, we relatively examined the most prominent TDMA MAC protocols proposed in the literature from the year 2010 to 2017. We classify them based on scheduling strategy and the technique they adopt. We also comparatively analysed them based on different parameters and performance metrics used. Finally, some open issues are presented for future deployment.

Keywords: Intelligent Transportation System, VANET, MAC Protocol, TDMA, Distributed Scheduling, Centralised Scheduling, Access Collision, Merging Collision.

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 component of ITS [3], were envisioned to support applications that can improve road traffic safety and provide comfort to drivers and passengers [4-6]. 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 neighbours 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 broadcast to make all nearby neighbours aware of any instant 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 defined to support vehicles communication is Dedicated Short Range Communication (DSRC) by USA Federal Communication Commission (FCC) [10]. It allows transmission range from 300m to 1000m using a data rate of 6Mb/s to 27Mb/s. The FCC allocated 75 MHz frequency band which is divided into seven channels of 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 meant for different services. Similarly, to support multichannel operations, IEEE1609.4 was defined in the wireless access in vehicular environment (WAVE) protocol stack as an extension of IEEE802.11p MAC [11] as shown in Figure 1.

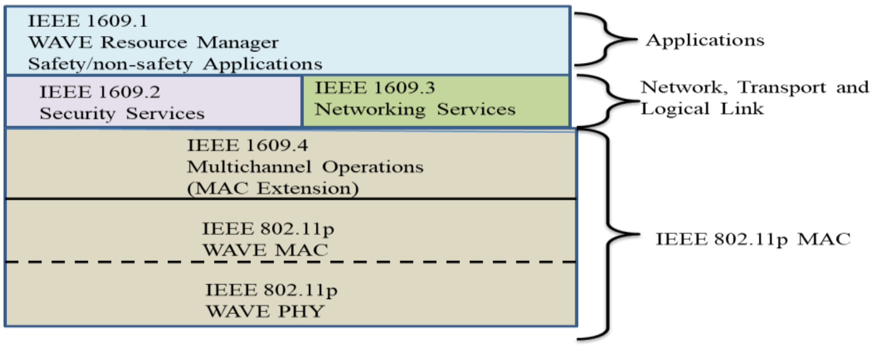


Figure 1WAVE MAC protocol stack [9]

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 result to 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 safety messages are delivered without collision by ensuring that each vehicle is allowed access to 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 Section 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. Additionally, a great deal of research efforts have been proposed in the literature to tackle the high collision rate problem experienced in the original IEEE 802.11p standard using TDMA [21-25]. The proposed solutions improve 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 analysed based on different parameters and performance metrics. Furthermore, we discuss about 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 Section 2, related work is highlighted and in Section 3, classification of VANET MAC protocols is discussed. In Section 4, challenges associated with TDMA MAC protocols are highlighted. In Section 5, some selected existing approaches are surveyed and comprehensively reviewed, focusing on the distributed and centralized channel scheduling schemes. In Section 6, we comparatively analysed these MAC protocols based on parameters including channel access method and time slot scheduling strategy as well as performance metrics used for both safety and non-safety applications. Section 7 discusses open issues and future direction and finally, in Section 8, we conclude the paper.

2. Related Work

This section gives highlight on the existing literatures that have 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 on 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. Detailed qualitative analysis was presented and the performance metrics used for evaluating these MAC protocols are compared. Authors in [30] presented a survey on TDMA MAC protocols, identify and describe 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 mechanism they use to access wireless medium [31]. The mechanisms fall into two broad categories, which include contention-based and contention-free schemes as shown in Figure2 below. A brief discussion of each category follows below.

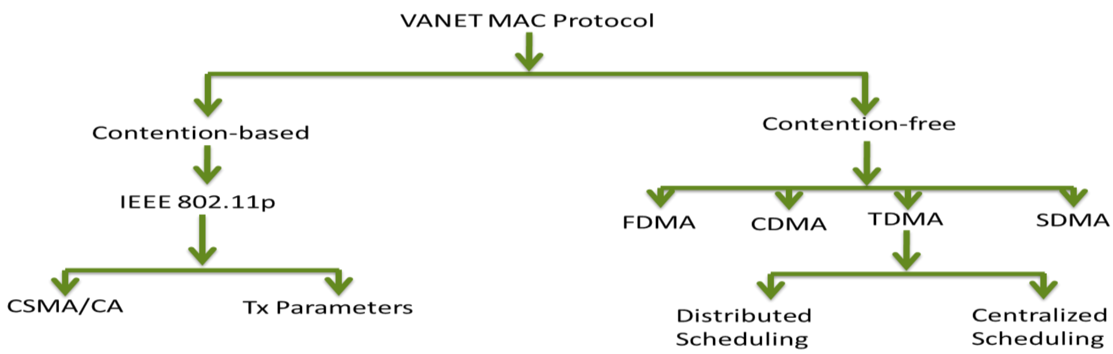


Figure 2 Classification of VANET MAC protocols.

3.1 Contention-based approach

Contention-based MAC protocols use Enhanced Distributed Channel Access (EDCA) based on IEEE802.11e [32]. An example of 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 access the medium randomly without 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 minimizes 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, they require time synchronization among the contending nodes to provide a predictable bounded delay for safety-critical applications. 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 when the vehicles density is high. Moreover, they have the advantage of guaranteeing QoS requirements and performance is also better even when the network load is high. They enhanced channel access fairness and are more efficient than CSMA schemes [35]. A brief description of these protocols follows below.

a. Frequency Division Multiple Access MAC Protocol

In FDMA mechanism, the communicating vehicles are synchronized to the same channel frequency [36]. Though, the synchronization algorithm requires the need for a CCH frequency to be created, consequently allow exchange of control messages among the contending vehicles. However, this mechanism makes FDMA very complex, hence increases high overhead to the communication channel.

b. Code Division Multiple Access MAC Protocols

This MAC protocol scheme support simultaneous data transmission where vehicles share the same frequency channel by using a unique code sequence. Unlike FDMA mechanism, before communication begins, the two communicating vehicles must agree on the code to use so that transmission collision rate can be reduced [17]. This mechanism requires that an assignment algorithm is created in order to exchange and also to assign codes for every transmission among the contending nodes. Thus, CDMA protocols suffer significant overhead as well as increased transmission delay. In addition, CDMA protocols usually suffer from worst delay performance and low throughput due to high packet error probability and interference [37].

c. Space Division Multiple Access MAC Protocols

SDMA is a technique that involves the use of geographical space to allocate the wireless medium. This mechanism avoids the use of creating code for each transmission as in CDMA scheme, hence minimises delay and high overhead on the control channel. In SDMA, the space is divided into smaller units called cells and allows vehicles to transmit data depending on the spatial locations [38]. Road is divided into segments where each vehicle send its beacon frame according to its position in the segment to which it belongs. This scheme mainly is divided into three main parts [39]; i) Spatial discretization scheme, which divides the road into equal size areas called cells, ii) Mapping function, which distributes the time slots to the different cells and iii) Assignment rule, which assigns the particular time slot to every vehicle where it can access the channel. However, map error merging, inaccurate positioning and time synchronization can lower the performance of SDMA protocol [12].

d. Time Division Multiple Access MAC Protocols

TDMA based scheme allows many vehicles to use the same frequency channel without any interference from neighbouring 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 Figure 3. In this technique, each vehicle will have access to the channel during its allocated time slot for its messages transmission, while received only during the time slot assigned for neighbouring vehicles. All vehicles use the same frequency channel but at a different time unlike in FDMA scheme, where interference occurs [40]. TDMA provides bandwidth resource utilization by allowing the allocation of different number of time slots to several vehicles. This improves MAC protocol reliability and support implementation of VANET applications unlike other contention-free mechanisms. However, the following section presents some of the challenges affecting the existing TDMA based MAC protocols scheme.

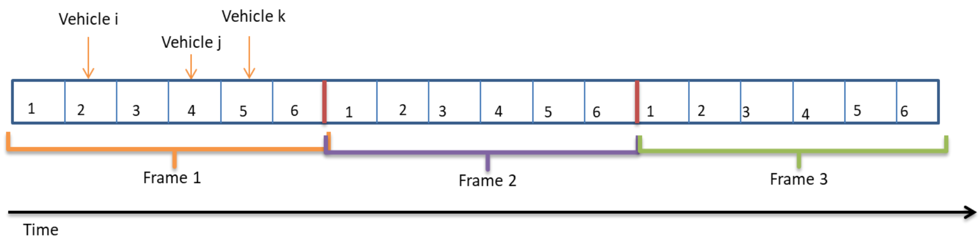


Figure 3 TDMA Frame structure.

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 hidden terminal, these MAC protocols are challenged with transmission collision, which can occur when allocating time slot to the contending vehicles [41]. The transmission collision can either be access collision or merging collision [30] as described in the following sections.

a. Access collision

This usually occur when two or more vehicles are within the range of two-hop neighbourhood set try to acquire the same available time slot as shown in Figure 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 neighbours. So, if two or more vehicles joined the network concurrently may likely choose the same free time slot sand hence results to access collision. For example, if vehicles D and E moving on the same direction received information from their neighbours that the time slot index number 5 is free. Then, trying to access this free time slot index number 5 by these vehicles would cause access collision problem.

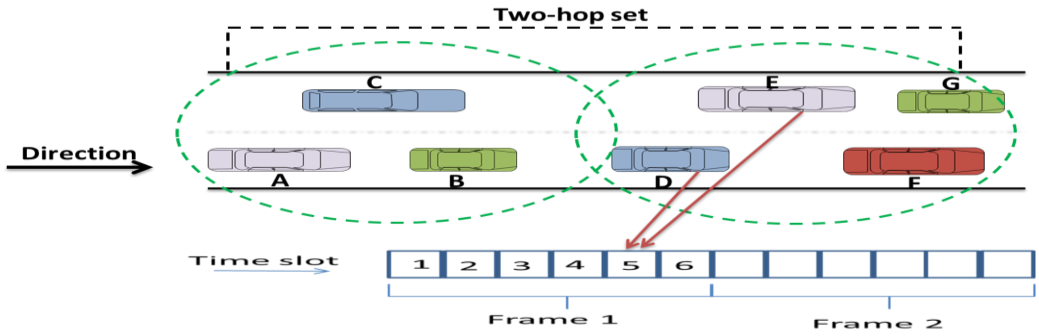


Figure 4 Access Collision

b. Merging collision

This problem occurs when two or more vehicles in a different two-hop neighbourhood 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 hidden node problem

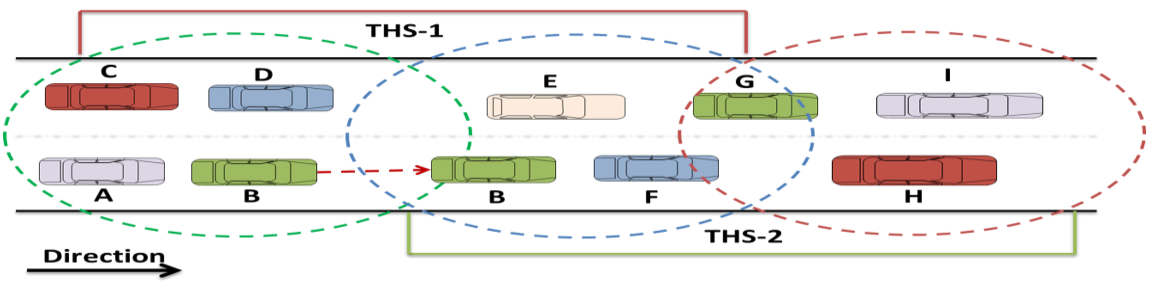


Figure 5 Merging Collision among vehicles moving in the same direction due to vehicles speed

The scenario in Figure5 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 member of THS-2 as vehicle H, then it will results in 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.

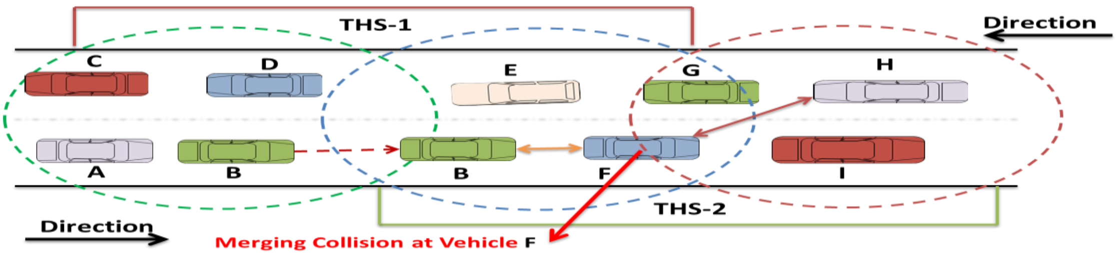


Figure 6 Merging Collision due to vehicles moving in opposite directions

Similarly, merging collision could be caused by hidden node problem as shown in Figure 7. It happens when vehicles that are not within transmission range of each other but 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 transmission range of each other. But vehicle C is within transmission range of both vehicles B and D, thus a merging collision will occur at vehicle C because both will transmit simultaneously.

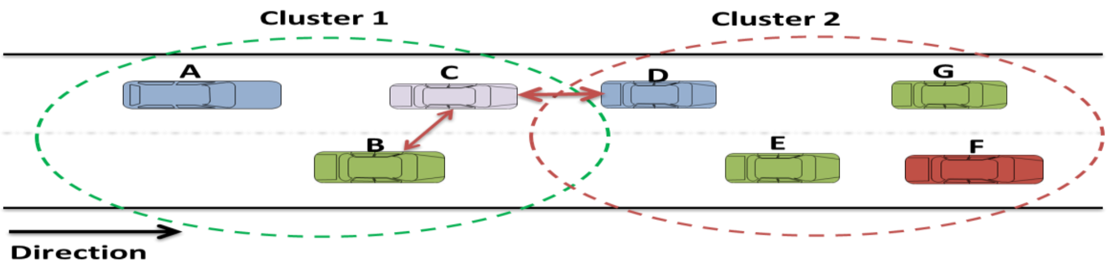


Figure 7 Merging Collision due to hidden node problem.

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.

5. Review of the existing TDMA based MAC Protocols

This section comprehensively explores and reviews the most prominent MAC protocols based on 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 details.

5.1 Distributed TDMA based MAC Protocols

In a distributed TDMA based MAC protocols, each vehicle communicates with its neighbours within one-hop range to access the channel using the technique they adopt. In this technique, vehicles do not require 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 [42], dedicated multichannel MAC protocol (DMMAC) was proposed. The main aim was to minimize collision and improve 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 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 to by the proposed mechanism.

A novel Distributed Asynchronous Multichannel MAC Scheme (AMCMAC-D) was proposed in [43]. The paper focuses on the inefficient utilization of wireless medium and transmission collision due to hidden terminals problem. The distributive nature of channel access reduces the overhead 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 [44] was proposed to address the issue of channel access fairness. In this scheme, 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 high overhead on the CCH and improve channel access fairness. However, no validation was carried out to confirm their claim.

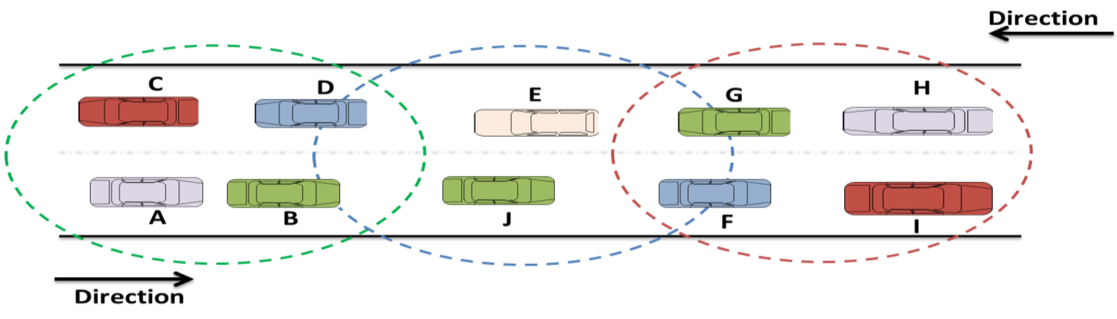


Figure 8 Distributed TDMA based topology.

Authors in [45] presented a multichannel TDMA MAC protocol called VeMAC. It is achieved by allocating disjoint set of time slots to vehicles moving in opposite directions. The paper employs fixed time slot allocation strategy to vehicles and RSU. Additionally, each node announces its time slot periodically to all nearby neighbours 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 time slot. As a consequence, the rate of both access and merging collision increases. Similarly, reserving any available time slot by vehicles associated with any direction may trigger both access and merging collision. Authors in [46], 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 [47]. The approach extends frame information of VeMAC to include vehicle's speed and direction. This is achieved by dividing each time slots 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 needs to be further investigated.

A hybrid approach using both CSMA and TDMA was presented in [48]. In this mechanism, the synchronization interval on the CCH is divided into reservation period (RP) and contention-based period CP). The number of 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 increases high overhead to the CCH. As the vehicles density increases, the RP increases which conversely decreases the length of CP for the successful number of time slot for the SCHs (SerSlot) for non-safety applications. Simulation result shows that when a density increases, it takes longer time to finish the EmgSlot reservations, which result in packets dropped. In [49], 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 fixed contention window size may lead to access collision when two or more vehicles back-off their counters to zero simultaneously. The paper also did not evaluate the rate of merging collision.

A fully distributed TDMA MAC protocol (DTMAC) was proposed in [50]. 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 access the wireless medium. However, there is a possibility of merging collision due to fixed allocation strategy of time slots. Furthermore, the proposal was evaluated only using analytical analysis. Recently, authors in [51],proposed distributed TDMA MAC protocols (D-TDMA). Two state Markov chain model was employed to estimate the channel state when 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 high speed of the vehicles. Table 1 below gives the summary of the distributed TDMA based MAC protocols under review.

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 [42]	Multiple	Dynamic	Highway	Unidirectional	Not Addressed	Addressed	Not Addressed	PDR
2012 AMCMAC-D [43]	Multiple	Fixed	Highway	Unidirectional	Addressed	Addressed	Not Addressed	Throughput PDR
2013 VeMAC [45]	Multiple	Fixed	Highway/City	Bidirectional	Addressed	Addressed	Addressed	RMC, RAC, Tx Throughput, Rx Throughput
2013 ATSA [46]	Single	Dynamic	Highway	Bidirectional	Addressed	Addressed	Addressed	Delay, RAC
2014 TDMA-CCA [44]	Single	Dynamic	City	Bidirectional	Addressed	Addressed	Not Addressed	RAC, Fairness
2014 HER-MAC [48]	Multiple	Dynamic	Highway	Unidirectional	Addressed	Not Addressed	Not Addressed	Throughput, PDR
2014 CS-TDMA [49]	Multiple	Dynamic	Highway	Unidirectional	Addressed	Not Addressed	Not Addressed	Throughput, PDR, Loss
2014 CFR-MAC [47]	Single	Fixed	Highway	Bidirectional	Addressed	Addressed	Not Addressed	TCR
2015 DTMAC [50]	Single	Fixed	Highway	Bidirectional	Addressed	Addressed	Not Addressed	None
2017 D-TDMA [51]	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

5.2 Centralized TDMA based MAC Protocols

Centralized TDMA based MAC protocols adopt 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.

a. Cluster based approach

Clustering is the process whereby a group of nodes is organized to form a sub-network on the road based on some predefined metrics, which include vehicles density, velocity and geographical locations. Nodes are classified into cluster head (CH) and cluster members (CM) as shown in Figure 9. This technique provides efficient and fair channel access utilization as vehicles density increases. It also minimizes access collision and enhances MAC scalability. A cluster head is elected for each group, which will be responsible for allocating time slots to other group members and intra-cluster transmission arrangement etc. However, the main challenges in this technique are electing the cluster head, inter-cluster interference, intra-cluster communication and time slot reservation due to vehicles high mobility and dynamic topology changes.

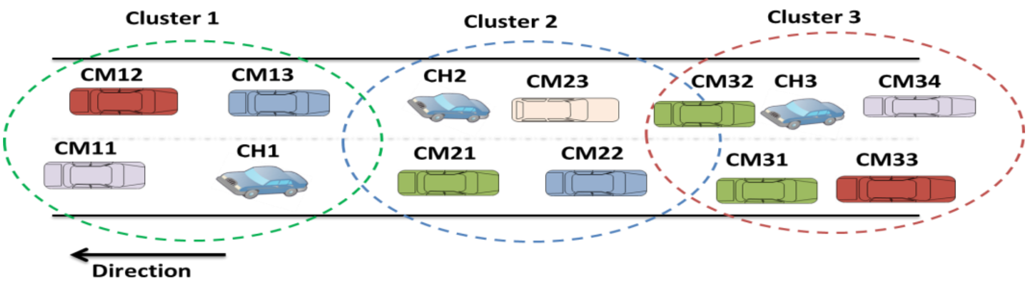


Figure 9 Centralized TDMA MAC using Cluster-based topology.

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 collision rate, a cluster based TDMA (CBT) was proposed in [52]. The authors used 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 to unstable cluster which can degrade the reliability of the CBT MAC protocol. Similarly, the rate of access and merging collisions were not evaluated. In [53], 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 [54] and further modified in [55]. The authors address 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 [56] 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 guarantee that no two vehicles can have the same ordered pair of time slots. However, TC-MAC considers only intra-cluster communication leaving inter-cluster interference problem which may cause merging collision. Similarly, high transmission rate for non-safety applications on the SCHs may impair the reliability of safety applications. Similarly, authors in [57] came up with another modification of TC-MAC called enhanced TDMA cluster-based MAC protocol (ETCM). This mechanism uses only 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 [58], a Cooperative ADHOC MAC (CAH MAC) was presented. This mechanism allows a neighbouring 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 to problem of access collision with vehicles attempting to reserve the available time slots. The authors in [59] address the problem of channel access fairness by allocation of time slots according to each vehicle's required bit rate. The paper use 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 [60], 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 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 [42]. 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 bidirectional approach.

Authors in [61] proposed TM MAC protocol using variable interval multichannel scheduling strategy. 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 [62]. 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 [63], 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 MAC protocols are given in Table 2 below.

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 [54, 55]	Multiple	Fixed	Unidirectional	Highway	Addressed	Addressed	Not addressed	TCR Pkt loss
2013 CAH-MAC [58]	Single	Fixed	Unidirectional	Highway	Not addressed	Addressed	Not addressed	Throughput
2014 CBT [52]	Single	Not mentioned	Unidirectional	Highway	Not addressed	Addressed	Addressed	Delay
2014 HC-MAC [53]	Single	Not mentioned	Unidirectional	Highway	Addressed	Addressed	Not addressed	Throughput Transmission delay
2014 ASAS [60]	Single	Dynamic	Bidirectional	Highway	Addressed	Addressed	Addressed	RMC RAC ICC
2014 TCA [59]	Multiple	Fixed	Unidirectional	Highway	Not addressed	Addressed	Not addressed	BU Fairness
2016 ETCM [57]	Multiple	Dynamic	Unidirectional	Highway	Not addressed	Addressed	Not addressed	PDR, E2E Delay, Throughput
2016 TM-MAC [61]	Multiple	Dynamic	Bidirectional	City	Not addressed	Addressed	Not addressed	RAC PDR Throughput
2016 WCS-MAC [62]	Single	Fixed	Unidirectional	Highway	Not addressed	Addressed	Not addressed	None
2017 ABM-MAC [63]	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

b. RSU-based approach

This technique employs the use of RSU, which act 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 neighbouring RSUs due to vehicles high mobility. The simple architecture of RSU based approach is shown in Figure10.

Numerous approaches have been proposed in the literature to tackle and minimize the challenging issues in RSU based topology. Authors in [64] proposed a cluster-based RSU centric channel access (CBRC) MAC protocol. The information about the assigned time slots and available channel information within the coverage area is maintained by 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, fixed number of slots allocation degrades the performance of CBRC especially when the density is very high. Authors in [65] 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 single channel and does not support non-safety application. To improve ACFM, authors in [66] 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.

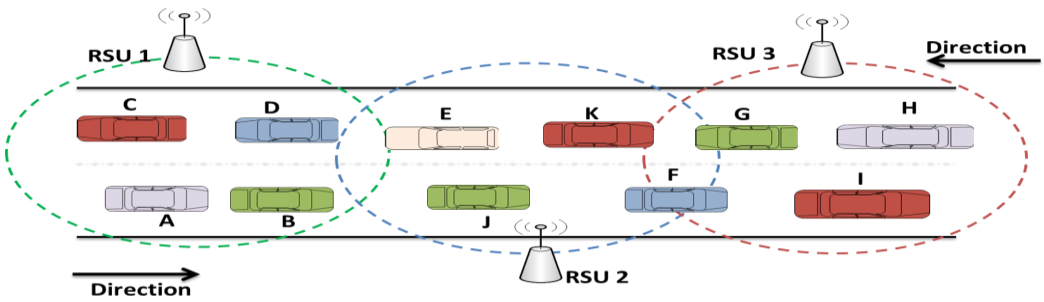


Figure 10 Centralized TDMA MAC using RSU.

In [67], unified TDMA-based scheduling protocol (UTSP) was proposed. Time slot is allocated based on 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 [68]. In this scheme, the RSU calculates the scheduling weight factor of each communication link. 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 road side causing interference.

Similarly, authors in [69] proposed RCMAC where all vehicles within the coverage area receive control information. Each node maintains one-hop neighbour list (ONL). Once it receives packet transmitted on the CCH it updates its ONL. However, choosing random time slots by neighbour nodes may cause access collision. In [70], 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 time slot that will decrease interference and rate of access collision. However, no any mechanism was provided to avoid merging collision. Moreover, 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 are given in Table 3.

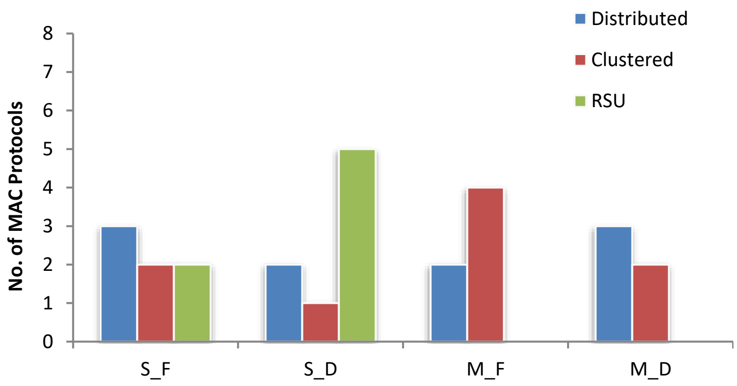
Table 3 Summary of RSU based TDMA MAC Protocols

Year (Ref)	Channel Access	Time Slot Allocation	Vehicular Traffic	Mobility scenario	Inter-RSU interference	Metrics
2010 CBRC [64]	Single	Fixed	bidirectional	Highway	Addressed	PRR
2012 ACFM [65]	Single	Dynamic	Unidirectional	Highway	Addressed	Delay, Packet loss ratio
2013 RMAC [66]	Single	Dynamic	Unidirectional	Highway	Not addressed	PDR, Delay, Fairness
2013 UTSP [67]	Single	Dynamic	Unidirectional	Highway	Not addressed	Throughput, Delay
2015 CTDMA [68]	Single	Dynamic	Bidirectional	Highway	Not addressed	Throughput, Fairness, Delay
2016 RC-MAC [69]	Single	Fixed	Bidirectional	Highway	Not addressed	RAC
2016 CTMAC [70]	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 1-3. Consequently, comparisons are made using some parameters as shown in Figures 11-14. 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.



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

Figure 11 Channel Access Allocation Strategies.

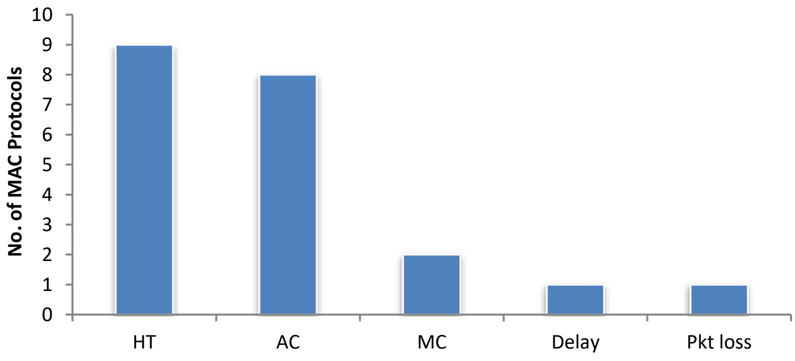
Channel access and time slot allocation strategies are very crucial for efficient implementation of TDMA based MAC protocol. Figure 11 shows the distribution of the techniques used in the existing literature under review. Single channel access uses only CCH for safety and non-safety messages, while multichannel access implement the full DSRC channel (one CCH and six SCHs). It is observed that all the proposal using RSU based approach utilised 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 allocated time slot while dynamic allocation scheme supports different vehicles density.

6.1 Distributed TDMA based MAC protocols

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

From Figure 12, we can deduce that more than 90% of the existing approaches tackled the issue of hidden terminal problem, which generally minimises the problem of access collision for about 80%. 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, multichannel access scheme separate control data and application data, hence improve 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 and 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 Figure 12. It is also observed that authors in [44, 46] proposed dynamic scheduling in a bidirectional traffic utilizing single channel access. Likewise, approaches in [43-46] minimise 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 fixed frame length can lead to inefficient channel utilization, which result to packet delay and thus degrade performance of MAC protocol especially at high density scenario. Furthermore, merging collision is also a challenge for almost all the proposed approaches cause by inefficient slot allocation strategy to the contending nodes.



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

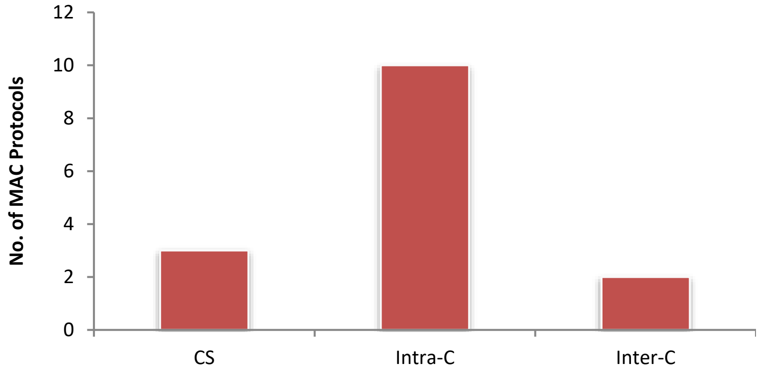
Figure 12 Challenging Issues Tackled by Distributed TDMA based MAC Protocols.

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 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 was used to plot Figure 13.

Figure 13 shows that less than 30% of the proposed approaches tried to address the issue of cluster stability with some little improvements. 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 [55, 57, 59, 60, 63] support the implementation of both safety and non-safety messages, but performance decreases due inter-cluster interference when the density of vehicles increases. Similarly, vehicles that are moving in a different directions are considered in [60, 61], but this may cause 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. Hence, 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 minimise the effect of access collision. However, less than 20% attempted to solve the issue of inter-cluster interference and therefore 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.



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

Figure 13 Challenging Issues Tackled by Cluster based TDMA MAC Protocols

6.3 RSU based TDMA MAC protocols

Several research efforts in the literature with reference to Table 3 in section 5.2b 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 Figure 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 improves delivery of delay sensitive applications, decrease channel access delay and packet loss. It has also been shown that only about 40% consider evaluating the delivery of non-safety applications and 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 merging collision problem. It is known that, both access and merging collision degrade the reliability of MAC protocol; however, authors in [64, 67, 68] proposed some approaches to reduce the effect of access collision, while merging collision is still an issue to be addressed. Using the bidirectional traffic scenario in [67-70]also reduce 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.

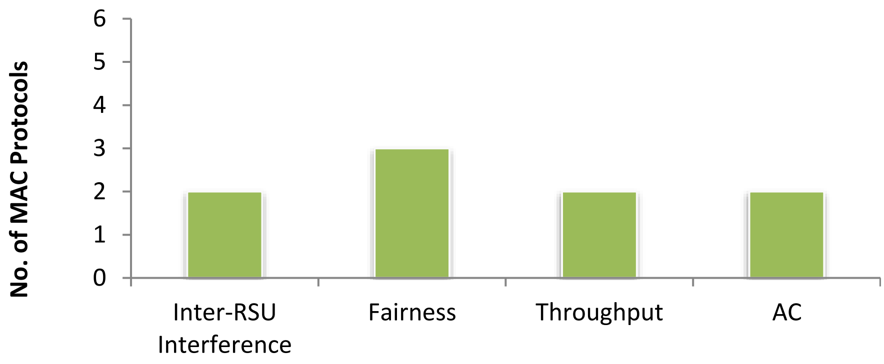


Figure 14 Challenging Issues Tackled by RSU based TDMA MAC Protocols

6.4 Summary of the comparative analysis

It is observed that in a distributed scheduling as shown from Figures 11& 12, there is an improvement in solving hidden terminal problem which is the main cause of 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 merging collision problem due to inefficient slot allocation strategy. Furthermore, there is a relatively channel access fairness which improves utilization of wireless medium and increase 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 Figure 13, most of the proposed approaches addressed the issue of intra-cluster interference, and this reduce 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 high mobility of vehicles is a serious challenge regardless of 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 vehicles movement at different directions and at high speed.

Similarly, majority of the proposed RSU mechanisms implement 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 Figure 10. Unlike using the full DSRC channels, single channel could lead to high overhead to the CCH and result in 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 emergence technologies that have some salient characteristics due to 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.

a. Merging collision Problems

The literature reviewed on TDMA MAC protocols especially centralized TDMA scheme minimize access collision problem while merging collision due to inefficient slots allocation strategy is still a serious issue. Hence, this problem has a great effect on the efficiency of this class of MAC protocol and needs to be looked into for future deployment. Effective mechanism involving slot assignment strategy to allow vehicles access their time slot need to be developed. Thus, a future work on both distributed and centralized TDMA MAC protocols schemes should put more emphasis on this challenge in order to minimize the effects it may cause.

b. Cluster stability

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 fairly distribution of time slots to vehicles in a TDMA based MAC protocols. Stable cluster reduces overhead of re-clustering, where the CH would take longer time before it moves out of the cluster. However, existing cluster-based TDMA MAC approaches show that maintaining stability of the cluster due to high mobility of vehicles is a serious issue, which affect the reliability of TDMA MAC protocol. Therefore, it is suggested that a new technique should be propose 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, hence reduce the overhead of executing clustering algorithm and improve the performance of the TDMA MAC protocol.

c. 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, most of the inter-cluster communication is only when the adjacent CHs are within transmission range of each other. However, there are situations, when the adjacent CMs are within 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 occur on the road. Hence, a new mechanism should be provided for inter-cluster communication among the adjacent CMs.

d. Inter-RSU interference

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

8. Conclusion

This paper has explored the most interesting and promising TDMA scheduling strategies for emerging VANET MAC protocols. We 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 were 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, majority of the proposed schemes suffer from inter-cluster interference and cluster stability due to inefficient slot assignment strategy. Hence results in 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 short stay period of vehicles within a coverage area of RSUs.

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

References

[1] C. Antoniou and K. Kostovasilis, "How may external information affect traffic risk perception?," *Journal of Transportation Safety & Security*, vol. 9, pp. 347-368, 2017.

[2] W. H. O. Violence, I. Prevention, and W. H. Organization, *Global status report on road safety 2013: supporting a decade of action*: World Health Organization, 2013.

[3] K. N. Qureshi and A. H. Abdullah, "A survey on intelligent transportation systems," *Middle-East Journal of Scientific Research*, vol. 15, pp. 629-642, 2013.

[4] I. Ahmad, R. M. Noor, I. Ali, M. Imran, and A. Vasilakos, "Characterizing the role of vehicular cloud computing in road traffic management," *International Journal of Distributed Sensor Networks*, vol. 13, p. 1550147717708728, 2017.

[5] M. H. Anisi and A. H. Abdullah, "Efficient data reporting in intelligent transportation systems," *Networks and Spatial Economics*, vol. 16, pp. 623-642, 2016.

[6] X. Ma, J. Zhang, X. Yin, and K. S. Trivedi, "Design and analysis of a robust broadcast scheme for VANET safety-related services," *IEEE Transactions on Vehicular Technology*, vol. 61, pp. 46-61, 2012.

[7] G. Yan and D. B. Rawat, "Vehicle-to-vehicle connectivity analysis for vehicular ad-hoc networks," *Ad Hoc Networks*, vol. 58, pp. 25-35, 2017.

[8] S. S. Anjum, R. M. Noor, and M. H. Anisi, "Review on MANET based communication for search and rescue operations," *Wireless Personal Communications*, vol. 94, pp. 31-52, 2017.

[9] K. Tanuja, T. Sushma, M. Bharathi, and K. Arun, "A survey on VANET technologies," *International Journal of Computer Applications*, vol. 121, 2015.

[10] J. B. Kenney, "Dedicated short-range communications (DSRC) standards in the United States," *Proceedings of the IEEE*, vol. 99, pp. 1162-1182, 2011.

[11] I. W. Group, "IEEE Standard for Information technology-Telecommunications and information exchange between systems-Local and metropolitan area networks-Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," *IEEE Std*, vol. 802, 2010.

[12] S. A. Gillani, P. A. Shah, A. Qayyum, and H. B. Hasbullah, "Mac layer challenges and proposed protocols for vehicular ad-hoc networks," in *Vehicular Ad-hoc Networks for Smart Cities*, ed: Springer, 2015, pp. 3-13.

[13] H. J. Qiu, I. W.-H. Ho, K. T. Chi, and Y. Xie, "A methodology for studying 802.11 p vanet broadcasting performance with practical vehicle distribution," *IEEE Transactions on Vehicular Technology*, vol. 64, pp. 4756-4769, 2015.

[14] R. Stanica, E. Chaput, and A.-L. Beylot, "Reverse back-off mechanism for safety vehicular ad hoc networks," *Ad Hoc Networks*, vol. 16, pp. 210-224, 2014.

[15] Y. Yao, L. Rao, and X. Liu, "Performance and reliability analysis of IEEE 802.11 p safety communication in a highway environment," *IEEE transactions on vehicular technology*, vol. 62, pp. 4198-4212, 2013.

[16] J. Sahoo, E. H.-K. Wu, P. K. Sahu, and M. Gerla, "Congestion-controlled-coordinator-based MAC for safety-critical message transmission in VANETs," *IEEE transactions on intelligent transportation systems*, vol. 14, pp. 1423-1437, 2013.

[17] X. Shen, X. Cheng, R. Zhang, B. Jiao, and Y. Yang, "Distributed congestion control approaches for the IEEE 802.11 p vehicular networks," *IEEE intelligent transportation systems magazine*, vol. 5, pp. 50-61, 2013.

[18] A. A. S. Syed, A. Ejaz, J. P. C. R. Joel, A. Ihsan, and M. N. Rafidah, "Shapely Value Perspective on Adapting Transmit Power for Periodic Vehicular Communications," *IEEE Transactions on Intelligent Transportation Systems*, vol. PP, pp. 1-10, 28-01-2018 2018.

[19] N. Taherkhani and S. Pierre, "Improving dynamic and distributed congestion control in vehicular ad hoc networks," *Ad Hoc Networks*, vol. 33, pp. 112-125, 2015.

[20] M. J. Booysen, S. Zeadally, and G.-J. Van Rooyen, "Performance comparison of media access control protocols for vehicular ad hoc networks," *IET networks*, vol. 1, pp. 10-19, 2012.

[21] X. Jiang and D. H. Du, "PTMAC: A Prediction-Based TDMA MAC Protocol for Reducing Packet Collisions in VANET," *IEEE Transactions on Vehicular Technology*, vol. 65, pp. 9209-9223, 2016.

[22] W. Ke, Y. Weidong, L. Pan, and Z. Hongsong, "A decentralized adaptive tdma scheduling strategy for vanet," in *Wireless Communications and Networking Conference Workshops (WCNCW)*, 2013, pp. 216-221.

[23] J.-K. Lee, H.-J. Noh, and J. Lim, "TDMA-based cooperative MAC protocol for multi-hop relaying networks," *IEEE Communications Letters*, vol. 18, pp. 435-438, 2014.

[24] G. Ren, T. Long, and H. Wen, "A Dynamic Time-slot Assignment for Ground Wireless Sensor Network," *International Journal of Future Generation Communication and Networking*, vol. 9, pp. 239-256, 2016.

[25] Z. Zhang and X. Zhang, "A Qos-based dynamic slot assignment algorithm with adaptive frame," in *Communications and Networking in China (CHINACOM), 2013 8th International ICST Conference on*, 2013, pp. 143-148.

[26] H. Song and S. L. Hwang, "A survey on how to solve a decentralized congestion control problem for periodic beacon broadcast in vehicular safety communications.. IEEE, 2013.," in *15th International Conference on Advanced Communication Technology (ICACT),*, 2013, pp. 649-654.

[27] M. J. Booysen, S. Zeadally, and G.-J. Van Rooyen, "Survey of media access control protocols for vehicular ad hoc networks," *IET communications*, vol. 5, pp. 1619-1631, 2011.

[28] J. Kakarla and S. S. Sathya, "A survey and qualitative analysis of multi-channel MAC protocols for VANET," *International Journal of Computer Applications*, vol. 38, pp. 38-42, 2012.

[29] N. Gupta, Prakash, A., & Tripathi, R., "Medium access control protocols for safety applications in Vehicular Ad-Hoc Network: A classification and comprehensive survey," *Vehicular Communications*, vol. 2, pp. 223-237, 2015.

[30] M. Hadded, P. Muhlethaler, A. Laouiti, R. Zagrouba, and L. A. Saidane, "TDMA-based MAC protocols for vehicular ad hoc networks: a survey, qualitative analysis, and open research issues," *IEEE Communications Surveys & Tutorials*, vol. 17, pp. 2461-2492, 2015.

[31] L. Miao, K. Djouani, B. J. van Wyk, and Y. Hamam, "Evaluation and enhancement of IEEE 802.11 p standard: A survey," *Mobile Computing*, vol. 1, pp. 15-30, 2012.

[32] J. R. Gallardo, D. Makrakis, and H. T. Mouftah, "Performance analysis of the EDCA medium access mechanism over the control channel of an IEEE 802.11 p WAVE vehicular network," in *Communications, 2009. ICC'09. IEEE International Conference on*, 2009, pp. 1-6.

[33] R. Reinders, M. van Eenennaam, G. Karagiannis, and G. Heijenk, "Contention window analysis for beaconing in VANETs," in *Wireless Communications and Mobile Computing Conference (IWCMC), 2011 7th International*, 2011, pp. 1481-1487.

[34] S. Bastani and B. Landfeldt, "The Effect of Hidden Terminal Interference on Safety-Critical Traffic in Vehicular Ad Hoc Networks," in *Proceedings of the 6th ACM Symposium on Development and Analysis of Intelligent Vehicular Networks and Applications*, 2016, pp. 75-82.

[35] I. F. M. Zain, A. Awang, and A. Laouiti, "Hybrid MAC protocols in VANET: a survey," in *Vehicular Ad-Hoc Networks for Smart Cities*, ed: Springer, 2017, pp. 3-14.

[36] H. S. Ferdous and M. Murshed, "Ad hoc operations of enhanced IEEE 802.11 with multiuser dynamic OFDMA under saturation load," in *Wireless Communications and Networking Conference (WCNC), 2011 IEEE*, 2011, pp. 309-314.

[37] I.-S. Liu, F. Takawira, and H.-J. Xu, "A hybrid token-CDMA MAC protocol for wireless ad hoc networks," *IEEE Transactions on Mobile Computing*, vol. 7, pp. 557-569, 2008.

[38] Z. Doukha and S. Moussaoui, "An sdma-based mechanism for accurate and efficient neighborhood-discovery link-layer service," *IEEE Transactions on Vehicular Technology*, vol. 65, pp. 603-613, 2016.

[39] R. W. Surabhi, & Mohinder, K., "A Survey on MAC Protocol for Vehicular Adhoc Networks," *International Journal of Advanced Research in Computer Science and Software Engineering*, vol. 6, 2016.

[40] A. Bazzi, A. Zanella, and B. M. Masini, "An OFDMA-Based MAC Protocol for Next-Generation VANETs," *IEEE Transactions on Vehicular Technology*, vol. 64, pp. 4088-4100, 2015.

[41] T. Zhang and Q. Zhu, "A TDMA Based Cooperative Communication MAC Protocol for Vehicular Ad Hoc Networks," in *Vehicular Technology Conference (VTC Spring), 2016 IEEE 83rd*, 2016, pp. 1-6.

[42] N. Lu, Y. Ji, F. Liu, and X. Wang, "A dedicated multi-channel MAC protocol design for VANET with adaptive broadcasting," in *Wireless Communications and Networking Conference (WCNC), 2010 IEEE*, 2010, pp. 1-6.

[43] C. Han, M. Dianati, R. Tafazolli, X. Liu, and X. Shen, "A novel distributed asynchronous multichannel MAC scheme for large-scale vehicular ad hoc networks," *IEEE Transactions on Vehicular Technology*, vol. 61, pp. 3125-3138, 2012.

[44] W. Yang, W. Liu, P. Li, and L. Sun, "TDMA-based control channel access for IEEE 802.11 p in VANETs," *International Journal of Distributed Sensor Networks*, 2014.

[45] H. A. Omar, W. Zhuang, and L. Li, "VeMAC: A TDMA-based MAC protocol for reliable broadcast in VANETs," *IEEE Transactions on Mobile Computing*, vol. 12, pp. 1724-1736, 2013.

[46] W.-d. YANG, L. Pan, and H.-s. ZHU, "Adaptive TDMA slot assignment protocol for vehicular ad-hoc networks," *The Journal of China Universities of Posts and Telecommunications*, vol. 20, pp. 1125-18, 2013.

[47] R. Zou, Z. Liu, L. Zhang, and M. Kamil, "A near collision free reservation based MAC protocol for VANETs," in *Wireless Communications and Networking Conference (WCNC), 2014 IEEE*, 2014, pp. 1538-1543.

[48] D. N. M. Dang, H. N. Dang, V. Nguyen, Z. Htike, and C. S. Hong, "HER-MAC: A hybrid efficient and reliable MAC for vehicular ad hoc networks," in *Advanced Information Networking and Applications (AINA), 2014 IEEE 28th International Conference on*, 2014, pp. 186-193.

[49] L. Zhang, Z. Liu, R. Zou, J. Guo, and Y. Liu, "A scalable CSMA and self-organizing TDMA MAC for IEEE 802.11 p/1609. x in VANETs," *Wireless Personal Communications*, vol. 74, pp. 1197-1212, 2014.

[50] M. Hadded, A. Laouiti, R. Zagrouba, P. Muhlethaler, and L. A. Saidane, "A fully distributed TDMA based MAC protocol for vehicular ad hoc networks," Inria Paris Rocquencourt, 2015.
[51] S. Bharati, H. A. Omar, and W. Zhuang, "Enhancing Transmission Collision Detection for Distributed TDMA in Vehicular Networks," *ACM Transactions on Multimedia Computing, Communications, and Applications (TOMM)*, vol. 13, p. 37, 2017.
[52] T.-L. Sheu and Y.-H. Lin, "A Cluster-based TDMA System for Inter-Vehicle Communications," *J. Inf. Sci. Eng.*, vol. 30, pp. 213-231, 2014.
[53] N. Gao, L. Tang, S. Li, and Q. Chen, "A hybrid clustering-based MAC protocol for vehicular ad hoc networks," in *High Mobility Wireless Communications (HMWC), 2014 International Workshop on*, 2014, pp. 183-187.
[54] M. S. Almalag, S. Olariu, and M. C. Weigle, "Tdma cluster-based mac for vanets (tc-mac)," in *World of Wireless, Mobile and Multimedia Networks (WoWMoM), 2012 IEEE International Symposium on a*, 2012, pp. 1-6.
[55] M. S. Almalag, S. El-Tawab, S. Olariu, and M. C. Weigle, "A modified TC-MAC protocol for multi-hop cluster communications in VANETs," in *Connected Vehicles and Expo (ICCVE), 2013 International Conference on*, 2013, pp. 832-837.
[56] S. A. Mohammad and C. W. Michele, "Using traffic flow for cluster formation in vehicular ad-hoc networks," in *Local Computer Networks (LCN), 2010 IEEE 35th Conference on*, 2010, pp. 631-636.
[57] N. Shahin and Y.-T. Kim, "An enhanced TDMA Cluster-based MAC (ETCM) for multichannel vehicular networks," in *Selected Topics in Mobile & Wireless Networking (MoWNeT), 2016 International Conference on*, 2016, pp. 1-8.
[58] S. Bharati and W. Zhuang, "CAH-MAC: cooperative ADHOC MAC for vehicular networks," *IEEE Journal on Selected Areas in Communications*, vol. 31, pp. 470-479, 2013.
[59] N. Torabi and B. S. Ghahfarokhi, "A TDMA-based channel access scheme for achieving fairness in inter-vehicle communications," in *Computer and Knowledge Engineering (ICCKE), 2014 4th International eConference on*, 2014, pp. 747-752.
[60] M. Hadded, R. Zagrouba, A. Laouiti, P. Muhlethaler, and L. A. Saidane, "An AdaptiveTDMA Slot Assignment Strategy in Vehicular Ad Hoc Networks," *Journal of Machine to Machine Communications*, vol. 1, pp. 175-194, 2014.
[61] S. Babu, M. Patra, and C. S. R. Murthy, "An efficient TDMA-based variable interval multichannel MAC protocol for vehicular networks," *Wireless Networks*, vol. 22, pp. 1365-1380, 2016.
[62] J. Xie and C. Li, "Weight Clustering Based TDMA-MAC Scheme in VANET," *automatika*, vol. 57, pp. 252-260, 2016.
[63] N. Gupta, A. Prakash, and R. Tripathi, "Adaptive Beaconing in Mobility Aware Clustering Based MAC Protocol for Safety Message Dissemination in VANET," *Wireless Communications and Mobile Computing*, vol. 2017, 2017.
[64] R. S. Tomar and S. Verma, "RSU centric channel allocation in Vehicular Ad-hoc Networks," in *Wireless Communication and Sensor Networks (WCSN), 2010 Sixth International Conference on*, 2010, pp. 1-6.
[65] W. Guo, L. Huang, L. Chen, H. Xu, and J. Xie, "An adaptive collision-free MAC protocol based on TDMA for inter-vehicular communication," in *Wireless Communications & Signal Processing (WCSP), 2012 International Conference on*, 2012, pp. 1-6.
[66] W. Guo, L. Huang, L. Chen, H. Xu, and C. Miao, "R-mac: Risk-aware dynamic mac protocol for vehicular cooperative collision avoidance system," *International Journal of Distributed Sensor Networks*, 2013.
[67] R. Zhang, J. Lee, X. Shen, X. Cheng, L. Yang, and B. Jiao, "A unified TDMA-based scheduling protocol for vehicle-to-infrastructure communications," in *Wireless Communications & Signal Processing (WCSP), 2013 International Conference on*, 2013, pp. 1-6.
[68] R. Zhang, X. Cheng, L. Yang, X. Shen, and B. Jiao, "A novel centralized TDMA-based scheduling protocol for vehicular networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 16, pp. 411-416, 2015.
[69] V. Nguyen, O. T. T. Kim, T. N. Dang, and C. S. Hong, "Improving time slot acquisition through RSU's coordination for TDMA-based MAC protocol in VANETs," in *Information Networking (ICOIN), 2016 International Conference on*, 2016, pp. 406-411.
[70] M. Hadded, P. Muhlethaler, A. Laouiti, and L. A. Saidane, "A centralized TDMA based scheduling algorithm for real-time communications in vehicular ad hoc networks," in *Software, Telecommunications and Computer Networks (SoftCOM), 2016 24th International Conference on*, 2016, pp. 1-6.