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TDMA based contention-free MAC protocols for vehicular ad hoc networks: A survey

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ABSTRACT

Vehicular ad hoc network as an intelligent transportation system supports traffic management to facilitate navigation, safety, and services to end-users. Delivery of safety messages is prioritized to avoid hazards in the system. In this regard, this paper discusses the existing TDMA MAC protocols in vehicular ad hoc networks that efficiently coordinate and communicate with the vehicles and minimize the message collision. Vehicular movement and traffic density lead to link failures, collisions, and load imbalance in the network. MAC protocols with dynamic time slot synchronization, message priority, bandwidth, and frequency management techniques ensure safe message delivery, hazard prevention, and low message collision rates in VANETs. This article provides the classification of TDMA MAC protocols for distributed, centralized and hybrid protocols. Various types of collisions, two-way traffic load, multi-channel utilization, and access challenges are discussed in detail. Further, the working mechanism and performance attributes of TDMA MAC protocols are explained.

1. Introduction

Vehicular Ad hoc Network (VANET) [1] is a distinct instance case of MANETs, that consider vehicles as mobile nodes. For vehicular communication, two types of nodes are responsible i.e. OBU and RSU. On-Board unit (OBU) embedded on the vehicle is responsible for the generation and communication of messages. Application unit (AU) is a wired or wireless device connected to the OBU within the vehicle for accessing safety and non-safety applications. Roadside unit (RSU), a fixed unit acts as the coordinator for the communication between the nodes. The network range [2] of VANETs is from 100 to 300 m. Vehicle communication is classified as a) V2V: Vehicle-to-vehicle communication [3] provides the exchange of control and data messages among the vehicles, b) V2I: Vehicle-to-infrastructure communication [3] provides communication among the vehicles and the roadside infrastructures such as traffic signals, traffic lights, RFID readers etc., c) V2B: Vehicle-to-broadband cloud communication [4] uses wireless broadband services for vehicle communication, d) V2R: Vehicle-to-roadside communication [5] provides communication among the vehicles and RSU, and e) V2X: Vehicle-to-everything communication [5] where the vehicles communicate with infrastructure, network, pedestrian, device and other vehicles. Vehicle interaction [1,6] is categorized as cooperation, assistance and warning. Information exchanged between vehicles consists of traffic density, congestion, accident, failure and detour. The exchanged information decides the next action based on predictions such as the position of the vehicle and probability of occurrence of the accidents. The author in [7] has categorized safety-related messages as: i) driver assistance messages, ii) alert messages and iii) warning messages. Vehicular communication factors include the randomly changing velocity of the vehicles [8], dynamically configured links, hurdles in the path, intermediate node failure, and high congestion. Local factors that affect the communication in VANETs are driving pattern of vehicles (slow/fast), types of road (urban area, highway) and drivers response time in adverse conditions [9]. Due to the above factors, congestion arises in the network. Therefore, the MAC layer determines the available channel for message transmission. In high-density traffic conditions, IEEE 802.11p (CSMA/CA) protocol suffers from message collisions that further lead to a decrease in throughput rate [10,11]. When accidents occur traffic density increases [12] and further the alert messages cannot be transmitted successfully using CSMA/CA protocol. To resolve the issue of CSMA/CA based MAC protocol, researchers have proposed MAC protocols based upon CDMA, SDMA, TDMA that resolves the issue of IEEE 802.11p. In CDMA approach [13] vehicles generate the code and get them to register on the RSU. Generation and maintenance of these codes increase the computational overhead of the vehicles. In the SDMA approach [14] frequency, PN codes, channels and time slots are distributed among the OBUs. Resource reusabil-

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ity is more in highway paths as compared to denser paths in urban areas. Many authors have proposed multiple variations of TDMA and are most commonly used. TDMA approach proves to be better in terms of collision minimization as different time slots are provided to vehicles for communication. Since OBUs obtain the different time slots, the issue of the hidden terminal is also resolved by TDMA MAC protocols. In the TDMA approach, the total available time is divided into slots that are randomly assigned to the vehicles. To avoid channel collision vehicles use the required channel during the allocated time slots. After successful message transmission, the slots are released by the vehicles. In TDMA based MAC, the hidden terminal problem occurs when vehicles are two-hop distance apart and contend for the same time slot. Fig. 1 represents the randomly assigned time slots for the different directions of vehicles movement. Here the vehicles $A, B, C, D, \ldots, U$ are allocated time slots t_A, t_B, t_C, t_D,..., t_U respectively. If all the time slots are allocated, then the incoming vehicles will wait for the available time slot.

Types of collision

During the transmission of messages from one node to another, different types of collision occur and are given as follows:

- Hidden Terminal [15]: When two nodes are not within the direct communication range and contend to reserve the same time slot it leads to hidden terminal problem.
- Exposed Terminal [16]: When two sender nodes V_{x_1} and V_{x_2} are in the communication range of each other but, their expected receivers V_{y_1} and V_{y_2} are far away from each other such that V_{x_1} and V_{x_2} can transmit the message concurrently, using the same time slot, without any conflict. But V_{x_1} and V_{x_2} are not allowed to reserve the same time slot leading to inefficient reusability. This problem is known as the exposed terminal problem.
- Merging Collision [17]: When two mobile nodes, having reserved the same time slot, come in the direct communication range of each other, then the conflict of using of same time slot leads to merging collision.
- Encounter Collision [18]: Encounter collision is a special case of the merging collision. When two moving nodes having reserved the same time slot encounters, then the conflict due to reservation of the same time slot leads to encounter collision.
- Access Collision [19]: Two nodes within the direct communication range and contend to reserve the same time slot cause the access collision.
- Reservation Collision [20]: If the vehicles reserve the same time slot without the occurrence of access collision, then reservation collision occurs.
- Transmission Collision [19]: Transmission collision is a combination of access and merging collision and can be resolved by allocating the dynamic frame based on varying traffic density.
- Cooperation Collision [21]: Cooperation collision occurs when the nodes, which are acting as the cooperating nodes for relaying the lost messages, try to reserve the allocated time slot.

The primary focus of our paper is to analyze how different algorithms are designed to divide the time slots and allocate them to the vehicles so that different types of collisions are minimized. We focus on analyzing the fixed-size, variable-size and disjoint sets of time frames for distributed, centralized and hybrid TDMA MAC protocols. In this paper, we have emphasized the allocation of time slots efficiently. This paper also discusses different types of collisions along with their solutions. It is categorized under different sections. Section 2 briefs the related approaches proposed by the

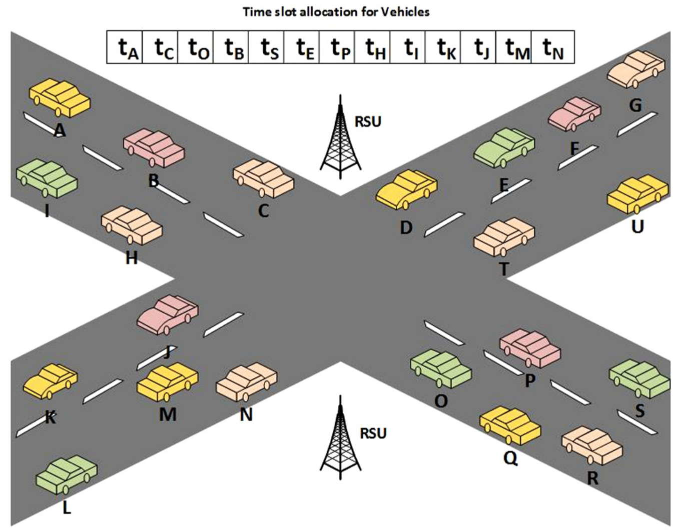

Fig. 1. Time slot assigned to vehicles in VANET.

researchers for TDMA MAC protocols. Section 3 gives the classification of MAC protocols for vehicular networks. Section 4 discusses the classification of contention-free TDMA MAC and section 5 discusses the collision resolution in TDMA MAC. Challenges of TDMA based MAC are discussed in section 6. Conclusion of TDMA MAC protocols is provided in Section 7.

2. Related work

The survey papers [22] and [23] explain the mechanism for scheduling of time slots for different approaches. MAC protocols [22,23] for VANETs are categorized as: contention-based, contention-free and hybrid protocols. IEEE 802.11p [24] is a contention-based protocol based on CSMA/CA approach. AMAC [25] is an enhancement of IEEE 802.11p and detects the congestion in the network to provide adaptive switching between control and service channels. Contention-free protocols are further classified as SDMA, TDMA, FDMA, CDMA, OFDMA. TDMA MAC protocols are classified as distributed, centralized and hybrid. Distributed TDMA based MAC protocols are implemented using different approaches such as VeSOMAC [26] and STDMA [27]. DMMAC [28] and AMCMAC-D [29] are a multichannel adaptive MAC protocol. VeMAC [30] protocol resolves the issue of the hidden terminal, access, and merging collision for multihop multichannel by allocating a disjoint set of time slots to the vehicles moving in different directions. Adaptive TDMA (ATSA) [31] is an extension of VeMAC [30] with a variable time frame based on the vehicle density for collision reduction and improved channel utilization. In [32] the number of slots for control and service channel is adaptively adjusted for multichannel MAC based on the traffic density. Author [33] has classified and compared the adaptive multichannel protocols based on their transmission periods. TDMA-CCA [34] divides time slots into disjoint sets for vehicles moving in a different direction. CFR-MAC [35] is based upon VeMAC and randomly reserves a time slot. HER-MAC [36] uses CSMA along with TDMA. Centralized MAC protocol considers either RSU or cluster head (CH) as a central coordinator. Ad hoc MAC [37] considers CH for time slot allocation and is based upon RR-Aloha. CBMCS [38], CBMMAC [39], ETCM [40] are the cluster-based MAC protocol for multichannel multihop network. TC-MAC [41], CAH-MAC [42], CBT [43], ASAS [44], TCA [45] forms a cluster of vehicles with a CH responsible for time slot allocation. In ACFM [46], CBRC [47], RC-MAC [48], CTMAC [49] RSU is responsible for the dynamic allocation of the time slot to the vehicles. CCFM-MAC protocol [50] forms clusters of the nodes based on the lifetime of the neighboring links. R-MAC [51] is based upon a prediction of the cooperation collision. In UTSP [52] RSU uses weight factor scheduler. In CBT [43] time slot is allocated randomly, in CAH-MAC [42] nodes cooperate for the time slot reservation, whereas in CBMAC [53], A-Adhoc MAC [54] and ASAS [44] time slot is reserved adaptively. In HC-MAC [55] CH node is selected based on node mobility whereas in WCS-MAC [56] CH node is selected based on energy. In ABM-MAC [57] CH is selected based upon the speed and distance of the members of the cluster. Hybrid MAC protocols such as SOFT MAC [58] is based on space and orthogonal frequencies in which the roads are divided into cells and assigned frequencies, DTMAC [59] uses OFDM and CDMA mechanisms for the allocation of the time slot. Multichannel transmission using SCH for multicast service messages and CCH for periodic control messages is essential in IoV [60]. So the congestion control is required at the MAC layer in IoV. The Internet of vehicles [61] has multiple nodes (vehicles, RSU, infrastructure components) contending for the same channel that increases delay and results in a collision. It reduces throughput leading to in-efficient channel utilization that can be improved by using an optimized back-off algorithm. A massive amount of real-time data is transmitted over the IoV that requires an efficient message delivery. The security-related issues of the MAC layer in IoV are discussed in [62]. In [22], the author's primary focus is to identify the usage of collision-free MAC protocols. TDMA-based MAC protocols are classified based on their topology. The author in [63] has discussed the dynamic interval MAC protocols based on their operations, advantages, and disadvantages. Survey article [64] discusses the delivery performance of the safety and non-safety message in hybrid MAC for VANETs. The primary focus of our paper is to analyze various TDMA MAC Protocols, designed to minimize the different types of collisions by dividing the time slots and allocating them to the vehicles. Further, the fixed-size, variable-size, and disjoint sets of timeframes for distributed, centralized, and hybrid TDMA MAC protocols are analyzed. Emphasis is given to the efficient allocation of time slots. The paper also discusses the solutions to different types of collisions.

3. MAC protocols in VANETs

MAC protocols for vehicular networks are classified as:

- Contention-based MAC: In these protocols, vehicles sense the channel continuously at random intervals. These protocols have an issue of the hidden terminal as RTS/CTS mechanism is not supported. Here, the messages are not acknowledged and further, the random channel access leads to an increase in delay and number of broadcast messages. The message priority is not considered and critical safety messages are also delayed in case of the busy channel state. Collision probability is high in case of high traffic density. Multiple node contention and increased contention window size lead to increased delay. The contention-based CSMA/CA mechanism used in the IEEE 802.11p protocol senses the channel randomly for allocating the available time slot. Simultaneous random channel access by multiple vehicles increases the issue of transmission collision in the case of a highly dense network. Fixed-size of the contention window in CSMA/CA affects IEEE 802.11p in terms of channel access, collision, and delay in allocating resources [65]. Based on vehicle density, the contention-window size must be optimized [66] for increased efficiency.
- Contention-free MAC: In contention-free MAC protocol, each vehicle has a dedicated resource for its usage. FDMA, CDMA, SDMA and TDMA are examples of contention-free MAC protocols. Periodic message exchange for free channel reservation used in contention-free MAC protocols reduces the transmission collision problem for high traffic density. FDMA protocol divides frequency into multiple channels, and communicating vehicles are synchronized to the same frequency channel. Control messages are exchanged by the communicating vehicles during CCH to synchronize at the same frequency. For every communicating pair, the synchronization at the same frequency channel increases complexity. In the case of a highly dense network exchange, a large number of control messages increase network overhead. To access the same frequency channel for communication with multiple vehicles leads to transmission collision or hidden terminal issues. OFDMA [67], an extension to FDMA is proposed to resolve the issue of the hidden terminal and increase efficiency; however, OFDMA is more successful in the infrastructure based network as compared to VANETs. In the case of CDMA, the same frequency is used by all the vehicles with different codes [68]. Communicating vehicles exchange the codes before communication that reduces the issue of the transmission collision. The generation of different codes for each pair of communicating vehicles increases overhead and leads to transmission delay. The overhead of CDMA is reduced by assigning a pre-defined set of codes to the vehicles as they enter the network. The selection of a matching code by the communicating vehicles increases the possibility of a hidden terminal issue. In SDMA protocol [69,70], the same frequency can be used simultaneously by the different pairs of communicating vehicles that are spatially away from each other. The road is divided logically into cells, and vehicles are allocated to each cell based on their GPS position. Due to the dynamic nature of vehicular topology, the vehicle position is changed frequently, leading to the issue of merging collision. Hence a periodic update of the spatial location and the allocated resources is required leading to an increase in the overhead and transmission delay. In TDMA based contention-free MAC protocols [46–48], the same frequency is used by all the vehicles at different time slots in a rotational manner. Total time is divided into slots allocated to the vehicles to access the same channel at different periods. The allocation of different time slots to the vehicles reduces transmission collision as vehicles access the channel only during the allocated time slot. The same time slot can be re-used by several vehicles leads to proper utilization of channels. Since the time slot is re-used after a specified number of hops, so the issue of the hidden terminal is reduced. In TDMA-based contention free MAC protocol [30,31,34,35] the allocation of the time slots from disjoint sets for vehicles moving in different directions reduces merging collision. Due to the efficient utilization of channel resources and reduced possibility of the hidden terminal and transmission collisions, TDMA proves to be better than the other contention-free protocols and contention-based IEEE 802.11p.
- Hybrid MAC: The features of contention-based and contention-free MAC approaches are integrated in hybrid MAC protocols.

TDMA approach resolves the issues of IEEE 802.11p, FDMA, CDMA and SDMA. Fig. 2 illustrates the classification of TDMA based contention-free MAC protocols for VANETs. Fig. 3 illustrates time slot division for fixed size frames. The time T is split into n number of frames that are further split into i number of time slots and are given as follows:

$$T = \sum_{f=1}^{n} \sum_{s=1}^{i} t_{f,s} \tag{1}$$

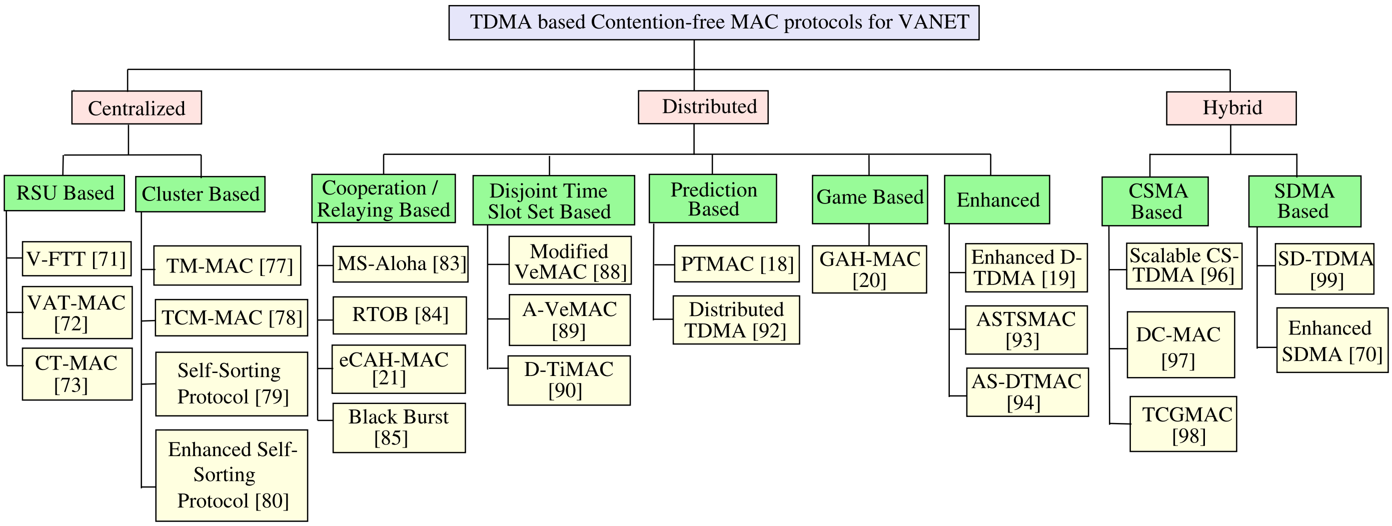

Fig. 2. Classification of TDMA based contention-free MAC protocols for VANETs.

Fig. 3. Time slot division for fixed size frames.

Fig. 4. Time slot division for variable size frames.

Fig. 4 illustrates time slot division for variable size frames. Here, the time T divided into n frames of variable size x time slots is as follows:

$$T = \sum_{s_1=1}^{i} t_{s_1} + \sum_{s_2=1}^{j} t_{s_2} + \sum_{s_3=1}^{k} t_{s_3} + \ldots + \sum_{s_n=1}^{x} t_{s_n} \tag{2}$$

4. Contention-free TDMA-MAC protocols for vehicular networks: A survey

In time division based contention-free MAC protocols, each node is assigned a dedicated t_i. Node V_x sends the message to receiver node V_y during t_i. Contention-free MAC protocols are categorized as centralized and distributed.

1. Centralized TDMA MAC

In centralized MAC protocols, the central coordinator (RSU/cluster head (CH)) allocates and controls the message forwarding in the network. Central coordinator allocates a dedicated t_i to each vehicle in the network. V_x sends the message to V_y using the allocated time slot t_i.

1.1. RSU based

RSU collects the vehicle information within its range and decides the schedule based on vehicle information and channel quality and further allocates the time slots. For high traffic conditions such as urban area, large number of RSUs are used.

1.1.1. V-FTT [71]: Flexible time-triggered protocol considers multiple spatial masters and multiple slaves in TDMA. The RSU acts as the master and nodes act as the slaves. This protocol provides data privacy, road safety and reduced time delay for data transmission in high-density traffic. The area around the RSU coverage range is known as a safety zone. Whenever a vehicle V_x enters the safety zone it registers itself with the RSU. Further, RSU allocates the time slot T_i to V_x for message transmission and send its scheduling information to the OBU of V_x. Information of allocated T_i and schedule of V_x is sent to other RSUs in a distributed manner. OBUs listen to the RSU and transmit the information such as acceleration, average speed, and current location of V_x to the RSU during reserved T_i. RSU will validate and modify the received information. The modified information is broadcast or multicast to the nearby vehicles. This information is also received by the OBUs that are not registered with the RSU. OBUs register themselves and contend for their turn to transmit the message further. Fig. 5 illustrates the process of vehicle registration and scheduling information exchange among different RSU for V-FTT. The limitation of this protocol is the complexity of message transmission among the vehicles registered to different RSUs and increasing traffic density.

1.1.2. VAT-MAC [72]: VAT-MAC protocol dynamically optimizes the length of the time frame for improving system scalability and throughput. RSU determines the length of time frame based on the number of vehicles. At the end of time frame, RSU identifies the number of vehicles contending for the time slots. The length of time frames is dynamically optimized to provide efficient utilization of available time. Total time is divided into frames that are further divided into three categories: management, transmission and contention. During the management period, RSU broadcasts the time duration of the transmission and contention period to the vehicles. During the contention period, vehicles contend for

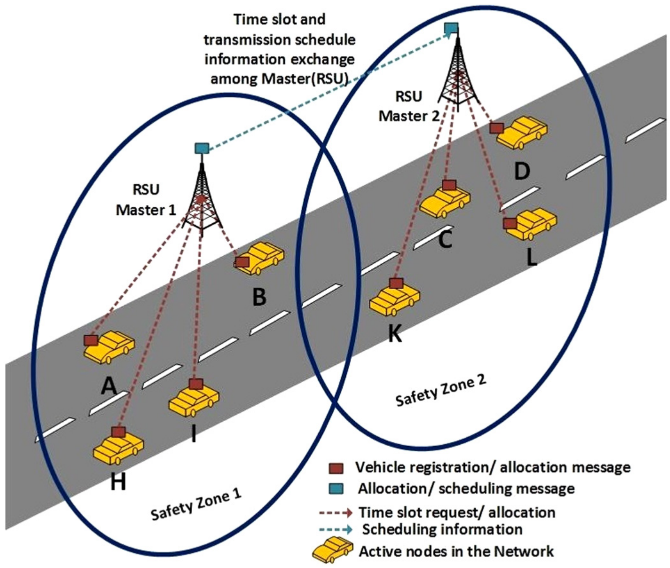

Fig. 5. Vehicle registration and scheduling information exchange in V-FTT MAC.

allocation of the transmission time slot. During the transmission period, nodes transmit the message using the allocated time slot. The vehicle that enters the communication range of the RSU after transmission of the management frame cannot obtain the details of the transmission and contention period. Due to lack of the information vehicle have to reserve the time slot randomly leading to the collision.

1.1.3. CT-MAC [73]: TDMA based capture-aware MAC protocol improves channel utilization with an optimized length of the time frame. CT-MAC provides efficient transmission of the safety messages. Based on the number of contending nodes, RSU determines the length of the time frames. Total available time is divided into time frames that are further segmented as broadcast period, allocation period and contention period. During the broadcast period, RSU broadcast the details of the allocation period and contention period to the vehicles. During the allocation period, the vehicles with the reserved time slot transmit the message. Vehicles request for the reservation of a time slot during the contention period. The vehicles that enter the RSU range during the allocation period can randomly select any time slot for their transmission. Capture effect is used to resolve the issue of transmission collision. Two vehicles can reserve the same time slot without conflict due to the capture effect. In case two or more vehicles contend for the same time slot, then the RSU allots the time slot to the requesting vehicle with a higher power. The limitation of this protocol is that vehicles with low transmission power wait for the contention period until the next frame.

1.2. Cluster based

In cluster based MAC protocols, vehicles in a specified range (100 m to 300 m) form a cluster with CH node. It is responsible for the time slot allocation, scheduling for transmission and communication among the vehicles within the cluster. In this approach, RSU act as an intermediate for inter-cluster communication. Time slots of the frames are separated into four disjoint sets: a) RSU, b) Left moving vehicles, c) Right moving vehicles and d) cluster head. Time slot partitioning for cluster based approaches is illustrated in Fig. 6. Network size determines the variable number of time slots required for the allocation to the RSU.

Time T for disjoint partitioning of the time frame for cluster based approach is represented as:

$$T=\sum_{f=1}^{n}(\overbrace{\sum_{s_l=1}^{i} t_{f,s_l}}^{Left}+\overbrace{\sum_{s_r=1}^{j} t_{f,s_r}}^{right}+\overbrace{\sum_{S_{rsu}=1}^{k} t_{f,s_{rsu}}}^{RSU}+\overbrace{\sum_{s_{ch}=1}^{l} t_{f,s_{ch}}}^{CH}) \qquad (3)$$

The fixed-size frame is used for evenly distributed traffic. The vehicles moving in left direction are comparatively equal to the vehicles moving in right direction i.e. $i=j$ so the above equation is modified as:

$$T=\sum_{f=1}^{n}(\sum_{s_l=1}^{2i} t_{f,s_l}+\sum_{s_{rsu}=1}^{k} t_{f,s_{rsu}}+\sum_{s_{ch}=1}^{l} t_{f,s_{ch}}) \qquad (4)$$

1.2.1. TM-MAC [77]: TM-MAC combines TDMA with the variable-length multichannel scheduling technique and provides reliable services for a lossy network. TM-MAC resolves the issue of transmission collision, provides high throughput and maximum channel utilization. Vehicles that are within one-hop range form the cluster. One vehicle V_L is elected as a CH, that allocates an available time slot for transmission of the messages to the vehicles. Selection of V_L is based on two parameters: a) vehicle that was elected a maximum number of times as a CH in the past and b) vehicle with least mobility. V_L is responsible for the scheduling of slots, maintenance, compaction, allocation of channel and message transmission. Disjoint set of the time slot is assigned to adjacent clusters that resolve the issue of the hidden terminal. TM-MAC is scalable as the number of allocated time slots are comparable to the vehicles entering the cluster per ms. For memory management, V_L provides compaction of empty time slots. It reallocates the new time slots to vehicles and combines the scattered empty time slots. Messages are categorized as a) reservation message: transmitted by all the vehicles for reservation of the time slot and b) leader message: transmitted by a V_L in the cluster. During merging collision, V_L allocates available time slot T_j to the new vehicle V_x entering the cluster, whereas in existing protocols both the contending vehicles release the allocated time slot and request for the new time slot. The limitation of TM-MAC is the higher time taken to reserve t_i by V_x, and less throughput rate in dense traffic conditions. Here, the performance is analyzed using the packet delivery ratio (PDR) and throughput. Due to message loss in the network, PDR alone is not efficient, hence scheduling and vulnerability is also analyzed. Scheduling evaluates the speed and time of V_x to acquire t_i. Vulnerability evaluates the possibility of V_x to release the reserved t_i during the occurrence of merging collision.

1.2.2. TCM-MAC [78]: Triggered CCHI multi-channel MAC protocol uses cluster-based technology to switch between control channel (CCH) and service channel (SCH) for efficient transmission of sensitive messages. TCM-MAC dynamically adjust the CCH interval length to reduce the consumption of resources and delay involved. TCM-MAC resolves the issue of the hidden terminal in multi-channel, improves message delivery ratio and throughput, and reduces message loss rate. Unlike other protocols, V_L provides variable-length CCH and SCH for TCM-MAC. Cluster member V_x sends a CMR (cluster member request) message to V_L before transmission of data. If CCH is idle, V_x acquires it to transmit CMR. On receiving the CMR, V_L determines the current channel status. V_L broadcasts the SR (silence request) and increase the length of CCH. V_x transmit safety messages to V_L using increased CCH. V_L broadcasts the received safety message to other cluster members and neighborhood CHs. If the SCH is idle, V_x transmit CMR to V_L over SCH interval. V_L switch to the CCH and continues as mentioned above for control channel. This process repeats for all the safety messages in the queue. The control and service channel are used interchangeably and their length is adjusted dynamically. The problem of resource utilization and time

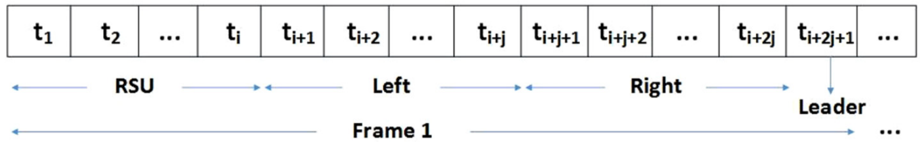

Fig. 6. Time slot division for cluster based approaches.

Table 1(A)
Comparisons of contention-free centralized TDMA protocols in VANET.

	V-FTT [71]	**VAT-MAC [72]**	**CT-MAC [73]**
Approach	Master-slave	Prediction Based	Capture-effect
Communication	Multicast, Broadcast	Broadcast	Broadcast
Channel	Single	Single	Single
Coordinator	RSU	RSU	RSU
Hop Count	Multi-hop	One Hop	Two Hop
Type of Road	Highway	Highway	Highway
Number of Lanes	Four	Five	Four
Movement Direction	Two way	One way	Two way
Node Distribution	Realistic	Krauss-car-following model	Free flow
Propagation Model	Protocol interference model, physical interference model	Nakagami RF Model	Nakagami-m
Data Structure	Binary Matrix	-	-
Type of Message	OBU message, CAM (cooperative awareness message)	Safety Messages	Safety Messages
Transceiver	Single Transceiver per vehicle	Single Transceiver per vehicle	Single Transceiver per vehicle
Communication Mode	Synchronous	Synchronous	Synchronous
Collision Resolution	Transmission Collision	-	Transmission Collision
Performance Parameters	data privacy, road safety, time delay	Scalability, Throughput	Channel Utilization, Frame Length Optimization
Better Than	-	ACFM, VeMAC, ATSA	VeMAC, VAT-MAC
Simulator Used	MATLAB [74]	NS-2 [75], SUMO [76]	MATLAB [74]
Limitations	Transmission of message among RSUs.	Random time slot allocation in absence of management frame	Increased waiting time for vehicles with low transmission power

delay during the allocation of the CCH and SCH are improved. Control packets (i.e., $CMRs$) resolve the issue of the hidden terminal. The limitation of TCM-MAC is the delay involved for frequent switching from the SCH to CCH. The performance of TCM-MAC is based on PDR, delay, throughput and ratio of packet loss.

1.2.3. Self-sorting protocol [79,80]: The self-sorting protocol [79] is based on collision-tolerance for efficient service message delivery in the highly-dense traffic conditions. TDMA based channel access mechanism is used according to the vehicle position in the queue, maintained during self-sorting. Vehicles communicate using three steps: self-sorting, reservation of channel, and transmission of messages. During the self-sorting phase, vehicle V_x, contends to join the existing queue. If the queue doesn't exist, then the vehicle V_x acts as a temporary queue-head (QH1) and creates a new queue. If any other QH2 is detected, then V_x registers itself to the existing QH2. After reaching the queue threshold value, the channel is allocated to the vehicles for communication. During the channel reservation phase, TDMA based MAC is used to minimize the hidden terminal problem. Only the service messages are transmitted during the data transmission phase. This protocol allows access to the channel in an organized manner. It proves to be efficient than the other slotted MAC protocols that allow continuous message transmission. In [80], an enhanced self-sorting protocol is proposed to manage the transmission of the control messages. It allows an efficient message delivery of safety and service messages. A queue formed during the self-sorting reduces access collision in case of highly dense traffic conditions.

1.3. Summary of centralized TDMA MAC

In these protocols, the central coordinator (CH/RSU/QH) is responsible for the assignment of time slot and communication among the vehicles. RSU act as a coordinator in centralized TDMA. Since a large number of RSUs are required to accommodate high traffic, this approach is not suitable for the highway roads. These protocols are analyzed based on different parameters, and their comparison is given in Table 1(A). Cluster-based approaches choose a vehicle as a CH or QH dynamically. The challenges in cluster-based centralized TDMA protocols are cluster formation, selection of the cluster head, and cluster instability. Comparison of cluster-based approaches is discussed in Table 1(B).

2. Distributed MAC

In distributed MAC protocols, the nodes communicate with each other by using cooperation or relaying mechanism. Vehicles communicate with each other based on one-hop distance towards the destination. The time slot is randomly reserved for each vehicle in the network. The message is broadcast from source node V_x to the one-hop neighborhood nodes which in turn relay this message to destination node V_y. All the nodes register themselves with the RSU. During message transmission, V_x sends the message to relaying nodes or RSU, which in turn sends it to V_y. If V_x is registered to RSU_x and V_y is registered to RSU_y, then the message is forwarded to the RSU_y with the help of RSU_x. RSU_y then relay the message further to V_y. In [82], a real-time testbed for distributed TDMA is proposed for the evaluation of the network capabilities and mobility challenges of VANETs.

2.1. Cooperation/relaying based MAC

In cooperation based MAC protocols, cooperating nodes relay the messages that are multi-hop distant from the source.

2.1.1. MS-ALOHA [83]: Mobile slotted aloha is a distributed slotted protocol for MAC that provides solutions for scalability and mobility. During the reserved time slot, each vehicle broadcasts a message to the one-hop neighboring vehicles. On receiving the

Table 1(B)
Comparisons of contention-free centralized TDMA protocols in VANET.

	TM-MAC [77]	TCM-MAC [78]	Self-sorting protocol [79]	Enhanced self-sorting protocol [80]
Approach	Cluster-based	Cluster-based	Cluster-based	Cluster-based
Communication	Broadcast	Broadcast	Broadcast	Broadcast
Channel	Multichannel	Multichannel	Single Channel	Multichannel
Coordinator	Cluster head	Cluster head	Queue Head (QH)	Queue Head (QH)
Hop Count	One	Multi-hop	Two	Two
Type of Road	City	Urban	City, Junction, Highway	-
Number of Lanes	One	Two	One	-
Movement Direction	Two way	Two way	One way	-
Node Distribution	Poisson Distribution	Realistic	Approximate	Poisson Distribution
Propagation Model	Stationary discrete time Markov chain model, PALM	Nakagami model	Markov Chain and Queueing Model	Markov Chain and Queueing Model
Data Structure	Transition probability matrix	-	Queue	Queue
Type of Message	Periodic Message, Event Driven Message	Safety, non-safety messages	Control and Data Message	Control, Safety and Service Messages
Transceiver	Single Transceiver per vehicle	Single Transceiver per vehicle	Two Transceiver	half-duplex transceiver
Communication Mode	Synchronous	Synchronous	Asynchronous	Asynchronous
Collision Resolution	Transmission Collision	Hidden terminal	Hidden Terminal	Hidden Terminal
Performance Parameters	Channel utilization, Scheduling, Vulnerability	Resource wastage, Message delivery rate, Throughput, Delay, Message loss	Packet loss, Delay, PDR	PDR, Throughput
Better Than	VeMAC	CAVI-MAC, IEEE 802.11p	Hassan's model, DMMAC, VeMAC	Self-sorting protocol, DC-MAC, IEEE 1609.4
Simulator Used	OMNET ++ [81]	NS2 [75], SUMO [76]	-	-
Limitations	Higher slot reservation time and less throughput for high-density traffic	Delay during frequent switching between CCH and SCH	Only service message transmission during Data transmission phase	Only for Safety messages

message vehicles determine the time slot status as free, busy or collision and append its determined details in the frame information message (FI_i). This frame information message is propagated over the network to the other nodes which are three hop distance apart. If a vehicle receives a FI_i message in the t_i time slot with busy status as 1 and collision status as 0 then it determines that the current time slot t_i is used by the vehicle which is one hop distance away. But, if a vehicle receives a FI_i message in t_j time slot, then it determines that the t_j is reserved by the vehicle either two or three hop distance apart. If the vehicle receives the FI_i message with busy status 1 and collision as 1 then it determines that there is a collision, and then the vehicle will forward a FI_i with busy as 0 and collision as 0 so that the vehicles in four hop distance can reserve this time slot hence resolves access collision. If the vehicle receives multiple frame information at the same time, then the vehicle with least hop count is allocated the time slot. The limitation of MS-Aloha is the restricted reusability of the time slot during high-density traffic. The performance of MS-Aloha is based on PDR (packet delivery ratio) that considers the message transmission for all the nodes and the message reception for only the nodes in the defined area. QoS evaluation of MS-Aloha is based on channel access delay and the probability of packet reception.

2.1.2. RTOB [84]: Reliable TDMA protocol that is based on one-hop broadcast (RTOB) is a distributed slotted MAC protocol that extends MS-aloha, provides reliable one-hop communication and efficient time slot reusability. For time slot allocation, the vehicle reserves the t_i that is not allocated by any vehicle within its three-hop distance or the t_i allocated by the vehicle that is four hop distance apart. t_i which is reserved by a vehicle is represented by busy status and collision status as 0. In case of a message collision, the vehicle broadcasts the busy status as 0 and collision as 1 to one-hop nodes. On receiving the FI_i of the message, vehicles aggregate its own FI_i and broadcast the modified FI_i during the next t_i. The allocation of the t_i is decided based on the received FI_i from the neighborhood vehicles. New FI_i is generated by using the frame information of the previous frame received. Since FI_i received from multiple vehicles is considered for the allocation of t_i the probability of occurrence of access collision is reduced. Since every vehicle has a single transceiver, two vehicles V_x and V_y using the same ti for transmission cannot notify to each other. Otherwise it leads to reservation collision. To resolve reservation collision, vehicle V_z acts as the cooperating node and broadcast a collision notification to V_x and V_y. In the evaluation process, RTOB considers cover ration (CR) that is an improvement of PDR. CR is the ratio of vehicle time in a safe state to vehicle time in the reserved time slot. CR outperforms PDR because CR considers the lost packets during congestion. The limitation of this protocol is low-density traffic conditions.

2.1.3. eCAH-MAC [21]: eCAH-MAC is an enhancement of CAH-MAC [42] based on point-to-point communication that resolves the issue of cooperation collision. Vehicles within two-hop range, listen to the channel for n consecutive time slots to reserve t_i and avoid access collision. The message is categorized into three types: a) reservation message, b) data message and c) cooperation message. Vehicles broadcast a message to nearby nodes using its reserved t_i. Lost messages are sent to the destination node with reduced payload size during cooperation relay. After receiving the message from V_x, the lost message is relayed by the helper node V_z to the destination V_y. Relaying node V_z reserves a time slot t_r randomly for transmission of the relay messages. In case of multiple helper nodes, the first node v_z announces the relay of the messages that will be selected as the helper node.

Cooperation collision may occur between the helper V_z and contending node V_x. Destination node V_y notifies the nodes about the cooperation collision using ACK. V_y sends ACK to V_z for the relay of the lost message. The hidden terminal problem occurs if V_x and V_y are a two-hop distance apart. V_x has reserved t_i for message transmission and V_y (two-hop distance apart) try to reserve t_i for ACK, leads to a problem of the hidden terminal. To resolve the issue of hidden terminal, V_x sends black burst B_i of t duration to V_y and V_z. If V_x and V_y are one-hop distance apart then V_y will suspend the ACK till B_i duration. If V_y is a two-hop distance apart then it will not suspend the ACK that leads to collision of ACK and B_i at the helper node. To resolve this collision helper node suspends the transmission of the relay packet. If two or more contending nodes contend for the same unreserved t_i for transmission of the B_i and message, then access collision occurs. Due to these collisions, eCAH-MAC does not work efficiently

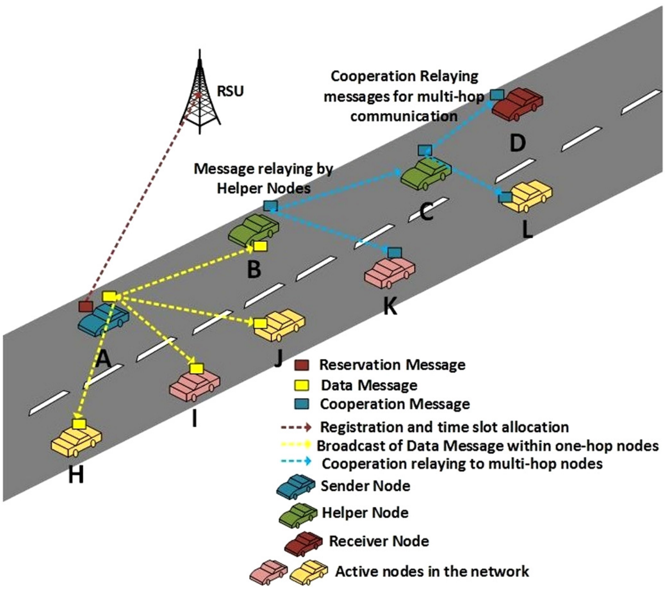

Fig. 7. Cooperative relaying in eCAH-MAC.

for the broadcast of safety messages. Fig. 7 illustrates cooperative relaying in eCAH-MAC. Performance of eCAH-MAC is based on the efficient utilization of the t_i for cooperation relay.

2.1.4. Black Burst [85]: Black burst TDMA is based on a random jamming signal known as a Black bust B_i that avoids access collision within two-hop range for multi-channel MAC protocol. Vehicles broadcast B_i after a random amount of time T_r to all the two-hop neighbors and notify their reserved t_i. Relaying nodes in one-hop distance transmits the black burst B_i to the neighboring nodes in two-hop distance. Length of B_i is modified to avoid the relaying of the B_i to multi-hop nodes. The performance is based on throughput and the successful message transmitted per time slot. This protocol is less efficient for low-density traffic as compared to high-density traffic.

2.1.5. Summary of cooperation based distributed TDMA MAC

In these protocols, nodes act as cooperating nodes and relay the message from the V_x (source node) to V_y (destination node). If the message is lost at the cooperating node V_z, then V_z directly transmits the message to the V_y. Time delay for retransmission of the message and channel busy time is reduced in these protocols. In this subsection, we have compared four cooperation based protocols and summarized the comparisons in Table 2(A). Cooperation based protocols are applied in high-density traffic as compared to low-density traffic.

2.2. Disjoint time slot set based vehicular MAC

In these protocols, the time frames are split into a disjoint set of time slots based on vehicle direction. The disjoint sets resolve the issue of merging collision. Total time T is split into n frames, that are further split into two disjoint time slot sets. These time slots sets can be fixed size or variable size based on the traffic density. If the number of moving vehicles in both directions (left/right) are similar, then the time slots number in both direction are fixed as illustrated in Fig. 8. Time slots allocation from the fixed size frames

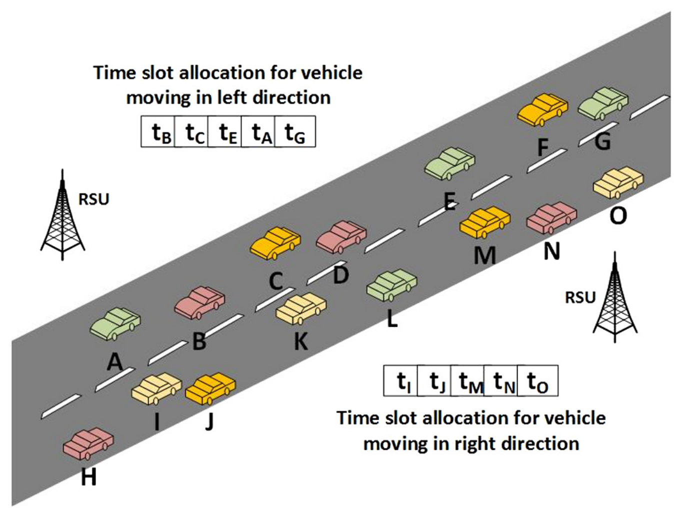

Fig. 8. Fixed time slot allocation for uniform traffic.

Table 2(A)
Comparisons of contention-free distributed TDMA protocols based on Cooperation approach in VANET.

	MS-Aloha [83]	**RTOB [84]**	**eCAH-MAC [21]**	**Black burst [85]**
Approach	Synchronous slotting	Slotted TDMA	Distributed TDMA	Jamming signal
Communication	Broadcast	Broadcast	Point to Point	Broadcast
Channel	Single	Single	Single	Multichannel
Hop Count	Three	One	Two	Two
Type of Road	Urban	Urban	Highway, rural and suburban	Highway
Number of Lanes	Two	One	One-way multi-lane	Two
Movement Direction	Two way	Two way	Free Flow Direction	Two way
Node Distribution	Normal Distribution	Random Distribution	Poisson Distribution	Uniform Distribution
Propagation Model	Nakagami	Nakagami	Nakagami - m Channel	Nakagami
Type of Message	FI, Safety message	FI, Safety message	FI, Type-G, Type-R, Type-C	Emergency message, WSA, RES, ACK
Transceiver	One transceiver with every vehicle	One transceiver with every vehicle	One transceiver with every vehicle	One half-duplex with each vehicle
Communication Mode	Synchronous	Synchronous	Asynchronous	Asynchronous
Collision Resolution	Access collision, Hidden Terminal	Access collision	Cooperation Collision	Access collision
Performance Parameters	Reliability, Access Delay	Cover ratio (CR), PDR, Reliability	Bandwidth, channel utilization, cooperation relay	Efficient time slot allocation
Better Than	IEEE 802.11p	MS-Aloha	CAH-MAC, Adhoc MAC	HTC-MAC
Simulator Used	SUMO [76]	SUMO [76], NS2 [75]	PTV VISSIM [86], MATLAB [74]	OMNET ++ [81], Veins [87]
Limitations	Inefficient reuse of time slots	Not significant for low density traffic	Broadcast of safety messages, access collision	Performance degrades for low density traffic

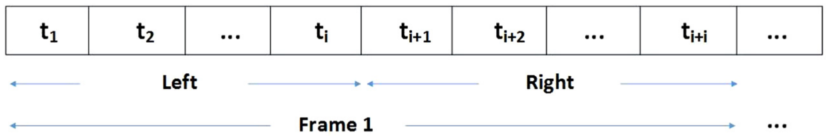

Fig. 9. Time slot division for direction based fixed size frames.

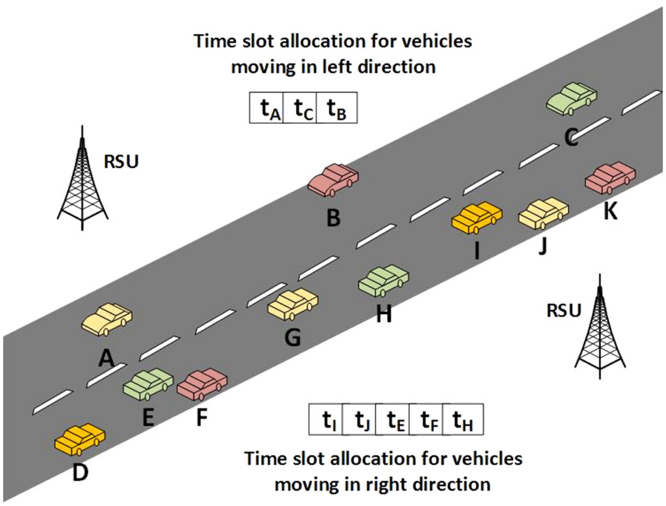

Fig. 10. Adaptive time slot allocation for variable density of traffic in different direction.

of disjoint time slot set is shown in Fig. 9. The relation between the total time and time slots for the fixed-size frame is given as:

$$T = \sum_{f=1}^{n} \sum_{s=1}^{2i} t_{f,s} \tag{5}$$

For varying traffic density in both directions, variable time slots are considered as shown in Fig. 10. Allocation of the time slot from the variable size frame of disjoint time slot set is represented in Fig. 11. Total time T for a variable size time slot for disjoint time slot set is given as:

$$T = \sum t_{left} + \sum t_{right} \tag{6}$$

Eq. (6) is further elaborated as follows:

$$\begin{aligned} T = & \overbrace{(\sum_{s_1=1}^{i} t_{s_1} + \sum_{s_3=1}^{k} t_{s_3} + \ldots + \sum_{s_x=1}^{x} t_{s_x})}^{left} \\ & \underbrace{+ (\sum_{s_2=1}^{j} t_{s_2} + \sum_{s_4=1}^{l} t_{s_4} + \ldots + x \sum_{s_{x+1}=1}^{z} t_{s_{x+1}})}_{right} \end{aligned} \tag{7}$$

RSU acts as a central coordinator and is assigned a dedicated time slot. It is responsible for the assignment of the time-slots from the disjoint set to the vehicles. Now, the time frame is divided into three disjoint sets (t_l, t_r, t_{rsu}) consisting of different time slots as represented in Fig. 12. t_l is allocated to $'i'$ vehicles having the left direction of movement, t_r allocated to $'j'$ vehicles having the right direction of movement and t_{rsu} to the $'k'$ RSUs. The number of RSU is very less than compared to the number of vehicles ($k < i, j$). For disjoint partitioning of time T into n number of frames that are further partitioned into time slots t_{s_l}, t_{s_r} and $t_{s_{rsu}}$ are represented as follows:

$$T = \sum_{f=1}^{n} (\sum_{s_l=1}^{i} t_{f,s_l} + \sum_{s_r=1}^{j} t_{f,s_r} + \sum_{s_{rsu}=1}^{k} t_{f,s_{rsu}}) \tag{8}$$

For evenly distributed traffic density, the number of time slots for the vehicles in the left direction and vehicles in the right direction are equal, $i = j$ and total time T is given as follows:

$$T = \sum_{f=1}^{n} (\sum_{s_l=1}^{2i} t_{f,s_l} + \sum_{s_{rsu}=1}^{k} t_{f,s_{rsu}}) \tag{9}$$

2.2.1. Modified VeMAC [88]: Modified VeMAC is an extension of the VeMAC [30] that detects, and reduce access collision and merging collision with increased throughput and timeslot usage. A collision flag is appended with each acquired timeslot in the header to detect and reduce collision. For a duration of n successive time slots, node V_x listens to the channel and collects the information of reserved t_i then passes it to neighboring nodes. So each node has the information of the reserved t_i within its two-hop range. During a collision, the node that acquired the t_i first will not release it and set the collision flag for t_i. The information of the collision flag is broadcast with the header to the neighboring nodes. If node V_x receives the header with the collision flag set, V_x checks the ID of the node associated with the collision flag. Node V_y whose ID is present in the header continues to use the t_i for further transmission of the messages and other nodes will release t_i. V_y that is allocated the t_i cannot reserve it again for the same message and hence the probability of occurrence of access collision is reduced. Fig. 13 illustrates message transmission in Modified VeMAC. The limitation of modified VeMAC is the complexity of maintaining a flag with each time slot. The performance is based on the timeslot occupancy within a two-hop range.

2.2.2. A-VeMAC [89]: Adaptive vehicular MAC protocol based on VeMAC [30] is a multichannel MAC protocol for varying traffic load and improves the channel factors. Unlike VeMAC in this protocol, the frames are divided into adaptive variable time frames to support uneven traffic condition moving in different directions. Vehicles have information such as the traffic density, speed, reserved time slot within two-hop range for both directions. Each vehicle V_x reserves t_i whether it has data to transmit or not. In case there is no data for transmission, the vehicle will continuously send the frame information FI_i over the reserved t_i. FI_i contains the details of the vehicle: a) ID, b) reserved time slot t_i, c) movement direction and d) the number of hops for the destination node V_y. To reserve a time slot vehicles wait for n successive time slots to receive the FI_i sent by other vehicles. If V_y receive the FI_i during t_i then, it determines that t_i is reserved by the neighboring vehicle within one hop distance. V_y keeps a record of the ID, direction and hop count as 1 of the sender vehicle V_x. If the FI_i received by the V_y contains the hop count value as 1 then the V_x is a two-hop distance apart and it will keep this record with hop count as 2. If the FI_i received by the vehicle contains hop count as 2 or $NULL$ then V_y ignores the hop count and keep the record of the hop count as $NULL$. Vehicles gather neighborhood vehicle information within one-hop and two-hop range in both directions.

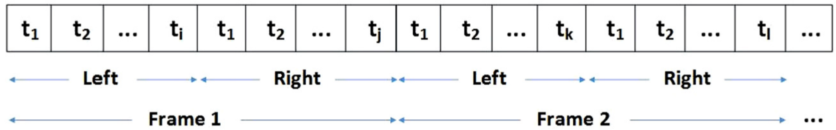

Fig. 11. Time slot division for direction based variable size frames.

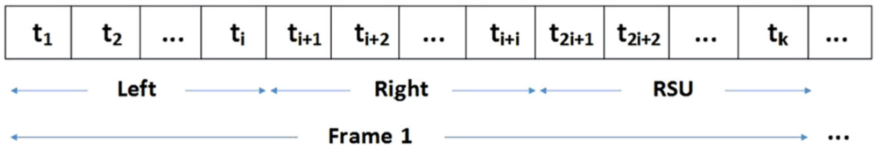

Fig. 12. Time slot division for left direction, right direction and RSU in VANETs.

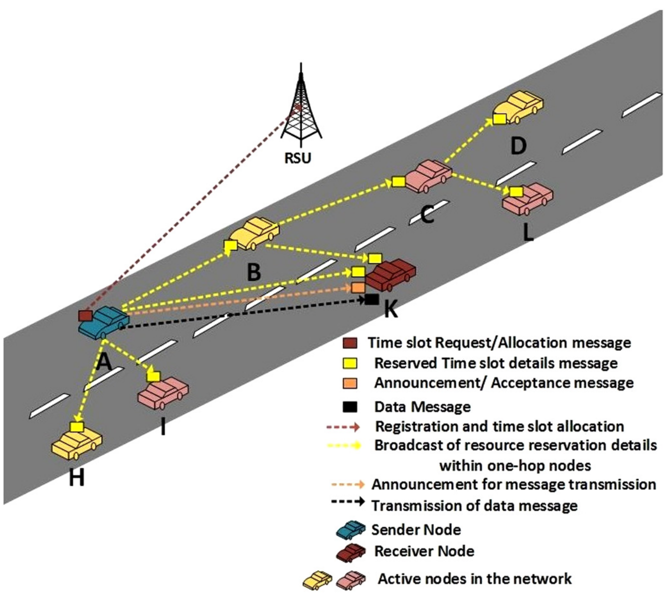

Fig. 13. Message transmission in Modified VeMAC.

Vehicles reuse the time slot that is reserved by vehicles three-hop distance away. V_x listens to the neighboring vehicles for $n-1$ time slots and check their FI_i for a reserved time slot. V_x reserve the t_i when it is available and use it until the merging collision occurs. During merging collision, both contending vehicles release the t_i. The limitation of this protocol is the release of t_i by contending vehicles during merging collision. Performance of A-VeMAC is based on access collision rate, channel utilization and traffic load.

2.2.3. d-TiMAC [90]: d-TiMAC protocol is an extension of TiMAC [91] protocol. In d-TiMAC two different time frames (d-frames) are considered for time slot allocation based on the vehicle moving direction, and are given as follows: i) d-frame t_{i_L} is for the north and west moving direction of vehicles and ii) d-frame t_{i_R} for the east and south moving direction of vehicles. A random polynomial value is assigned to every node in the network. In contrast to TiMAC, d-TiMAC considers neighboring nodes during the polynomial assignment. With the change of vehicle direction, the d_frame allocated to it also changes, but the unique polynomial does not change. Frames are placed alternately based upon the d_frame to which they belong. d-TiMAC protocol improves the time delay, throughput and the number of retransmissions are reduced. The limitation of d-TiMAC is the doubled frame size due to 2D frames. D-TiMAC performance is analyzed using traffic load and delay incurred during the retransmission of the lost packets.

2.2.6. Summary of disjoint time slot set based TDMA MAC

In this category of protocols, time slots are separated into x disjoint sets based upon the traffic density and direction. Majorly the authors have used $x = 2$ disjoint sets. From the available time slots, T_{left} is allocated to the left direction (moving vehicles), T_{right} is allocated to the right direction (moving vehicles) and T_{RSU} is assigned to the RSU. Allocation of time slots from disjoint sets depending on vehicle direction (left/right) resolves the issue of merging collision. The size of these sets can be fixed or variable based on the traffic density. Let the number of left direction moving vehicles be l and for right direction be r. If $l >> r$, then,

$$|T_{left}| > |T_{right}| \tag{10}$$

Table 2(B) gives the comparative analysis of TDMA MAC protocols for disjoint time slot set. These protocols are suitable for the variable traffic density and provide a solution for merging collision. Limitation of these protocols is the time slots maintenance for different disjoint sets. The complexity of these protocols is directly proportional to the number of disjoint sets.

2.3. Prediction based MAC

In prediction-based distributed TDMA MAC protocols, collisions are predicted then measures are taken to limit their occurrence.

2.3.1. PTMAC [18]

Prediction-based TDMA MAC predicts the occurrence of a collision and effectively reduces the rate of collision for 2-way traffic, 4-way intersection points in varying traffic conditions. The prediction is based on average speed, current location and the moving direction of vehicles. PT-MAC works in three steps: i) detection, ii) prediction and iii) elimination of the collision. In collision detection, incremental approach is used to allocate the time slots for each node. Two hop information (reserved time slot) is shared with the adjacent nodes. For node size more than two, four hop information is shared with the adjacent nodes. However, this increases the frame size. This approach restricts the vehicles from reserving the allocated time slots. In collision prediction, first the vehicles having the same direction of movement are considered and then the opposite direction of movement is considered. For vehicles having the same direction of movement, the encounter collision is predicted when vehicle V_x behind the vehicle V_y moves with higher speed. For vehicles having the opposite direction of movement towards each other, encounter collision is predicted if they have reserved the same time slot t_i. Highly dense traffic leads to encounter collision that is resolved by frequently changing allocated time slots. In collision elimination, the currently reserved

Table 2(B)
Comparisons of contention-free distributed TDMA protocols based on Disjoint time slot approach in VANET.

	Modified VeMAC [88]	**A-VeMAC [89]**	**d-TiMAC [90]**
Approach	Additional bit in Header	Time slotted Channel	Disjoint-set of the time slot
Communication	Broadcast	Broadcast	Broadcast
Channel	Multichannel	Multichannel	Single
Hop Count	Two	Two	Two
Type of Road	Highway, City	Highway	Highway, Urban
Lane Numbers	Two	Four	Two
Direction	Two Way	Two Way	Two Way
Node Distribution	Normal	Normal	Random
Mobility Model	Random	Predictive	Realistic
Disjoint time slot set	Three (left, right, RSU)	Two (Variable size)	Two (Fixed size)
Type of Message	Periodic messages, Event driven safety messages	Frame information (FI) message	Safety message
Transceiver	Two transceivers with each vehicle	Two transceivers with each vehicle	Two transceivers with every vehicle
Mode	Synchronous	Synchronous	Synchronous
Collision Resolution	Access and merging collision	Access and merging collision	Hidden Terminal, Access and Merging Collision
Performance Parameters	Average number of collision, Throughput, Timeslot usage	Channel utilization, Traffic load and Collision rate	Time delay, Throughput, Reduced retransmission, Traffic load
Better Than	VeMAC	VeMAC	VeMAC, TiMAC
Simulator	MATLAB [74]	MATLAB [74]	OMNeT++ [81]
Limitations	Complexity of maintaining a flag with every time slot.	Unnecessary release of time slot during merging collision.	Double frame size.

Table 2(C)
Comparison of contention-free distributed PTMAC, Distributed TDMA and GAH-MAC protocol for VANET.

	PT-MAC [18]	**Distributed TDMA [92]**	**GAH-MAC [20]**
Approach	Prediction	Prediction	Game Theory
Communication	Broadcast	Broadcast	Broadcast
Channel	Single	Single	Multi-channel
Hop Count	Four	Two	One
Type of Road	Highway, Urban	Highway, City	City
Number of Lanes	Four	Four	One
Movement Direction	Two Way	Two Way	Random Two Way
Node Distribution	Real-world Mobility	Constant	Random Distribution
Propagation Model	Realistic Mobility Model	-	Markov Chain
Type of Message	Event-driven message, periodic message	Basic safety messages (BSMs)	Control message, safety messages
Transceiver	Two transceivers with every vehicle	Single Transceiver per vehicle	Two transceivers with every vehicle
Communication Mode	Asynchronous	Synchronous	Synchronous
Collision Resolution	Encounter Collision detection and elimination	Transmission Collision	Reservation Collision
Performance Parameters	Rate of collision, Probability of occurrence and removal of collision	Number of Collision, Packet Delivery Rate	Throughput, Slot reservation
Better Than	Adhoc MAC	VeMAC	Ve-MAC
Simulator Used	SUMO [76], MATLAB [74]	MATLAB [74]	MATLAB [74]
Limitations	Changing time slots in high density	Merging collision resolved only if an intermediate node can predict its occurrence	Special slots

slots are varied for any of the potential collided vehicles. Since multiple intermediate vehicles (three hops) exist in the neighborhood, the one hop intermediate node alerts the potential collided vehicle to release its allotted time slot. This approach eliminates the collision in the system. The limitation of PTMAC is the frequent change of allocated t_i for highly dense traffic. Performance is analyzed as the probability of collision occurrence (contention collision and encounter collision) and collision removal. The density of traffic affects the probability of removing the collision. Comparative analysis of PTMAC is summarized in Table 2(C).

2.3.2. Distributed TDMA [92]

Distributed TDMA approach provides effective message delivery by controlling the range of transmission. This protocol predicts the occurrence of the merging collision and takes precautionary measures to limit its occurrence. Nodes periodically broadcast their information to the neighbors. Vehicles are distributed into the high-quality region and basic-quality region. The region near the sender is considered as a high-quality region. Vehicles can communicate with low power in the high-quality region, however high power is required, for message delivery in low-quality region. Two or more contending nodes can reuse the same time slot if their transmission range is not colliding. Merging collision is pre-determined when vehicles having the same time slot collides. If merging collision is predicted, an intermediate node notifies one of the colliding nodes to acquire a new time slot. Before sending a notification, the intermediate node must confirm the actual occurrence of the collision, based on vehicle position and direction of movement. The limitation of this protocol is that the merging collision can be resolved only if an intermediate node can pre-determine the occurrence of a collision. It is compared with other distributed TDMA MAC in Table 2(C).

2.4. GAH-MAC [20]

Game-based TDMA MAC protocol resolves reservation collision, improves throughput and success rate of slot reservation in a highly dense network. This approach is based on the game theory where the nodes can either have status R (original time slot t_i) or W (new slot t_j). Nodes play a game to decide if they can reserve t_i or t_j based on the probability calculated through the game. RSU

Table 2(D)
Comparison of contention-free enhanced TDMA distributed protocol for VANET.

	Enhanced D-TDMA [19]	ASTSMAC [93]	AS-DTMAC [94]
Approach	Deep Learning	Sharing	Active Signaling
Communication	Broadcast	Broadcast	Broadcast
Channel	Single	Multi-channel	Single
Hop Count	Two	One	Muli-hop
Type of Road	Highway	Highway	Highway
Number of Lanes	Three	-	Two
Movement Direction	One Way	Two Way	Two Way
Node Distribution	Poisson Distribution	Normal Distribution	-
Propagation Model	Markov Chain, Nakagami-m-Channel	-	-
Type of Message	Periodic safety message	Basic safety messages (BSMs)	Decentralized Environmental Notification Messages (DENMs)
Transceiver	Two transceivers with every vehicle	Single half-duplex transceiver	Single Transceiver per vehicle
Communication Mode	Synchronous	Synchronous	Synchronous
Collision Resolution	Transmission Collision	Transmission Collision	Access Collision
Performance Parameters	Average Channel Error, One step Transition probabilities	Packet Delivery Ratio, Collision Rate, Throughput	Access Time, Overhead
Better Than	D-TDMA	Traditional TDMA	DTMAC
Simulator Used	PTV VISSIM [86], MATLAB [74]	MATLAB [74]	MOVE [95], SUMO [76]
Limitations	Release of time slot by all contending nodes, Differentiation method	Restricted usage of time slot, Identification of transmission collision reason	Conflict due to use of same random key

is not required in this approach and hence the reservation speed is improved. Whenever a conflict occurs in the time slot reservation, each node maintains a counter to record its waiting time. Value of counter for a node is initialized as the highest value of a counter in the one-hop range. In case of a reservation collision, the waiting counter is increased by 1. A node having the higher counter value is given a priority for original time slot t_i reservation. A time frame is split into M slots. $M - L$ slots are reserved for passing control messages, where L are special slots used for passing other messages. The number L is decided based on network density. In a dense network, GAH-MAC outperforms VeMAC in terms of reservation speed, packet drop rate and collision. GAH-MAC increases the node priority for long awaiting time slot reservation as compared to other protocols. The limitation of this approach is special slots which are reserved from the available slots. Due to this, the number of time slots available is reduced. Hence, it is required to optimize the number of special time slots. For performance analysis, the probability of time slot distribution is calculated using a matrix. Rows of the matrix represent the time slot distribution, columns represent the nodes (vehicles) and the corresponding value represents the allocated time slots to the nodes. According to the Markov Model, to reserve the nth time slot, only $n - 1$ time slots are considered. The transition probability is the probability of reserved slots to the available slots. The probability of successfully reserving the time slot is minimum for a similar value of the waiting counter. The comparative analysis of GAH-MAC is given in Table 2(C).

2.5. Enhanced TDMA

TDMA protocols are enhanced to provide a solution for transmission collision and reusability of time slots. Enhanced D-TDMA protocol identifies the exact reason behind transmission collision. ASTSMAC protocol improves reusability of the time slot by constraining its usage. Active Signaling is used to resolve the issue of access collision in AS-DTMAC.

2.5.1. Enhanced D-TDMA [19]

Enhanced D-TDMA approach distinguishes the reason for transmission failure using deep learning technique. It reduces unnecessary time slot contention and assures that the nodes release the time slot only when it is required. Nodes use position and velocity for the estimation of the state of the channel and source of failure. Due to transmission collision, if the failure occurs, then the node V_x releases its reserved time slot t_i. During transmission failure, the source is distinguished by determining the channel state. Node obtains the frame information FI_i from the neighboring nodes within one-hop range and uses this information to estimate the channel state and error for channel estimation. If FI_i received by the neighboring node contains the ID of V_x then average channel estimation error is updated else channel state is checked. For good channel state, the nodes consider that the reason for failure is transmission collision and releases the acquired time slot with p probability. When the reason for failure is poor channel, then the node releases the acquired time slot with $1 - p$ probability. Performance of D-TDMA is improved when the unnecessary release of the acquired time slot is avoided by identifying the reason for transmission failure. This approach uses the differentiation method for detection of the transmission failure. Enhanced D-TDMA performance is based on the successful time slot reservation. The comparative analysis of Enhanced D-TDMA is given in the Table 2(D). AS-DTDMA [94] is an enhancement of DTMAC based on the active signaling and reduces the access collision and slot allocation time.

2.5.2. ASTSMAC [93]

In ASTSMAC protocol, the time slots are shared by multiple nodes to accommodate a large number of nodes with improved packet delivery and reduced collision rate. Using the same time slot and different frequencies, the nodes transmit the messages. All the nodes are categorized as direct, indirect and relative neighbor set. The direct neighbor set S consists of vehicles within the communication range of V_x. The neighboring nodes of S that are not in direct communication range of V_x are considered the members of indirect set I. The members of set S and I are collectively considered the members of relative set R. The vehicle V_x knows about the reserved time slot of nodes in set S and I but has movement information of the nodes in S only. The total available time is divided into fixed-size time frames that are subdivided into time slots. Nodes listen to the neighboring nodes for a full-time frame to gain information of reserved time slots. Nodes can reuse the same time slot in two cases: a) the distance among the nodes is large enough that doesn't lead to transmission collision, b) the nodes belonging to S transmit in alternate transmission cycles. The limitation of this protocol is that it restricts the independent usage of the time slot by a node, to improve reusability. Loss of message is due to transmission collision. The comparative analysis of ASTSMAC is given in the Table 2(D).

2.5.3. AS-DTMAC [94]

AS-DTMAC provides signaling based distributed TDMA MAC to resolve the issue of access collision. Total time is divided into two intervals a) time slot selection interval with active signaling, b) transmission period. During the selection period, nodes can either transmit or receive the message from other nodes at different intervals. Nodes broadcast a signal to notify its presence using a random key. If a node is sending the signal, then other nodes will suspend their transmission. The node that doesn't receive any signal can use another key for notifying its presence. This process continues allowing a single vehicle to access the channel at any instance of time and hence reduce access collision. For accessing the time slot immediately, the priority of the messages is considered during the selection period. The limitation of this approach is that the same random key usage by multiple nodes may cause conflict. The comparative analysis of AS-DTMAC is given in the Table 2(D).

3. Hybrid TDMA MAC

Hybrid TDMA MAC protocols for the vehicular network is a combination of two or more contention-free MAC approaches or CSMA/CA with TDMA. In this paper, we discuss hybrid MAC protocols that combine TDMA with CSMA and SDMA.

3.1. Scalable CS-TDMA [96]: Scalable CS-TDMA is an adaptive multichannel MAC protocol that combines SDMA, TDMA with CSMA. It provides maximum resource utilization, network throughput and less transmission delay, packet collision based on channel access and scheduling. Based on traffic density CCH and SCH are adaptively switched that resolves the issue of the hidden terminal. Vehicles within a fixed limited range 'R' form the cluster size that is the communication range of the vehicle. For time slot reservation, vehicles listen to the channel for the *hello* message. On receiving *hello* message V_x with smallest MAC address is assigned the first time slot t_1 and so on. For low traffic density, the time duration of the CCH is reduced to improve throughput. For high traffic density, the time duration of the CCH is increased to assure guaranteed delivery of safety messages. For adaptive CCH, two periods are considered: a) period of transmission: based on the time-division approach and b) period of reservation: based on the CSMA approach. Safety and control messages are transferred during the transmission period. Time slots are reserved during the transmission period and high priority safety messages are sent during the reservation period. Due to CSMA in the reservation period, nodes sense the collision immediately and retransmit the data. Whenever there are more than two nodes back-off occurs simultaneously during the collision. The number of access collision is high in case of dense traffic condition. The performance of Scalable CS-TDMA is based on average access time, the number of collision in the cluster and throughput for one synchronization period.

3.2. DC-MAC [97]: DC-MAC resolves the issue of synchronized collision by dynamically combining the TDMA approach with the CSMA approach. Virtual time frames are used to vary the CCH contention period. The control channel's total time is divided into virtual frames that are further divided into contention period slots and emergency slots. The control channel is accessed using TDMA during the contention period and CSMA during the emergency slot. The multi-hop forwarder forwards Multi-hop messages using emergency slots. The control channel's contention period is used for the handshake of the nodes to reserve the service channel. The

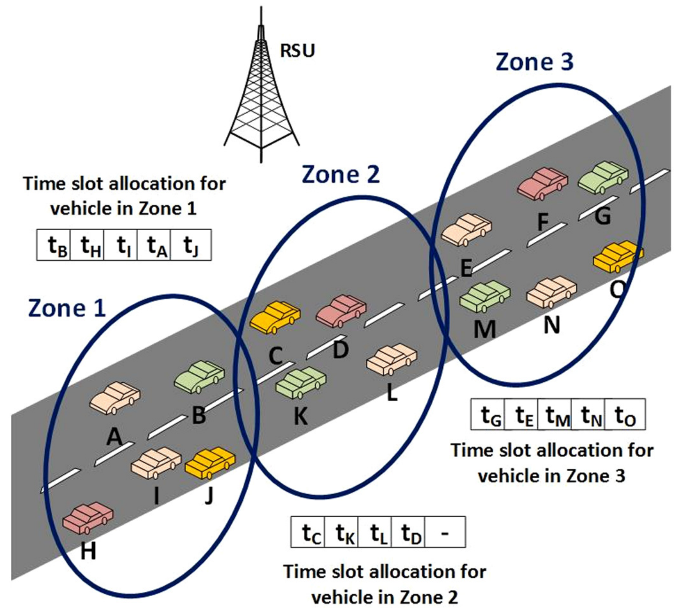

Fig. 14. Time slot assignment for traffic based upon geographic location.

contention period is also responsible for the transmission of emergency messages. The performance of DM-MAC is directly affected by the complexity of calculating the evenness of the contention period slots and emergency slots.

3.3. TCGMAC [98]: TCGMAC protocol is a combination of TDMA and CSMA protocol for efficient utilization of resources under large traffic density. Time frame is divided into two parts: a) CSMA period and b) TDMA period. During the CSMA period, vehicles sense the channel for idle time slot reservation. In the TDMA period vehicles send the messages during the assigned time slots. In case of access collision during the CSMA period, game theory is applied to resolve the collision. Node releases the time slot and contends for new time slot in next CSMA period. Nodes within the one-hop range of V_x are considered as a direct neighbor, if in past V_x has received the messages from these nodes successfully. Nodes broadcast the information of the direct neighbors and their reserved time slots. According to game theory, based on the position and speed, a weight factor is associated with every contending node. The node with a higher weight factor has priority to use the same time slot during access collision. Other contending nodes will release the time slot and wait for the next CSMA period. The limitation of this protocol is that the exact reason of transmission collision cannot be identified. In the case of poor channel condition, the time slot is unnecessarily released as the message transmission fails.

3.4. SD-TDMA [99]: SD-TDMA is an adaptive MAC protocol that combines SDMA and TDMA in a distributed manner to improve channel utilization, the fairness of data transmission and reduce transmission collision. Clusters are formed based on the geographic location of the vehicles. Space is divided into zones (clusters) and nodes within these zones are allocated time slots using a TDMA approach as shown in Fig. 14. This protocol includes three phases: a) user detection phase, b) data transmission phase and c) competitive access phase. In the user detection phase, geographic location and probe messages determine the number of nodes in a cluster. Node V_x sends the UDI message (User Detection Interval) to the neighboring nodes and waits for their feedback. If feedback is not received from any node then V_x is considered as a new user and allocated time slot T_i. Allocation of time slot and order of transmission is decided in the user detection phase. In the data

Table 3
Comparison of contention-free hybrid TDMA protocol for VANET.

	Scalable CS-TDMA [96]	DC-MAC [97]	TCGMAC [98]	SD-TDMA [99]	Enhanced SDMA [70]
Approach	CSMA + TDMA + SDMA	CSMA + TDMA	CSMA + TDMA + Game Theory	SDMA + TDMA	SDMA + TDMA
Communication	Unicast + broadcast	Broadcast	Broadcast	Broadcast	Broadcast
Channel	Multichannel	Multichannel	Single	Multichannel	Single
Hop Count	One	Multi-hop	Two	Two	Two
Type of Road	Geographic Area	-	Highway	Urban	Highway
Lanes	One	-	Two	8 Lanes	6 Lanes
Direction	Two Way	-	Two Way	Two Way	Two way
Distribution	Uniform Distribution	-	Normal Distribution	Real world Mobility	General Distribution
Model	Realistic	2D-Markov chain	-	Simple path loss model	Markovian Model
Type of Message	Beacon message, WSA(WAVE service advertisement)	Emergency and Service Messages	Safety Message	Beacons, Event-driven safety message, Frame synchronization message	Safety and Non-safety Messages
Antenna Type	Omni-antenna	-	-	Omni-antenna	-
Transceiver	Two Transceiver per vehicle	Two half-duplex transceivers	Single Transceiver per vehicle	Multi-radio Transceiver	-
Communication	Synchronous	Synchronous	Synchronous	Synchronous	Synchronous
Collision Resolution	Hidden terminal problem	-	Transmission collision	Transmission collision	Transmission collision, Hidden Terminal
Performance Parameters	Resource Utilization, Transmission delay, Collision, Network Throughput	PDR, Successful WSA Transmission	Throughput, Rate of Collision	Channel Utilization, Fairness, Beacon Load, Throughput, Neighborhood Awareness, Overhead	Bandwidth utilization, Spatial reuse
Better Than	IEEE802.11p/1609.4 MAC, VeMAC, SOFT MAC	IEEE 1609.4	VeMAC, MoMAC	TSRA, SDMA based MAC, IEEE 802.11p	SD-TDMA
Simulator Used	MATLAB [74]	-	MATLAB [74]	NS2 [75], SUMO [76], MATLAB [74]	NCTUns 5.0 [100], NGSIM [101]
Limitations	Collision when more than two nodes back-off at the same time. Access collision in case of high density traffic.	Complexity in evenness of contention period slots.	Identification of reason for transmission collision.	Retransmission in dense traffic conditions.	Optimized allocation leads to less utilization

transmission phase, V_x transmit the message using SCH channel during reserved t_i. In the competitive access phase, a new node V_y contends with V_x to acquire SCH. The limitation of this protocol is message retransmission overhead due to the increase in traffic density. Performance of SD-TDMA is based on parameters beacon load, age of beacon, awareness of neighborhood and effective throughput.

3.5. Enhanced SDMA [70]: In enhanced SDMA protocol, TDMA slots are assigned to logically divided road space for efficient transmission of safety messages. Based on the traffic density, the logical distinction of the road is made. SINR is used for the throughput improvement by optimizing the allocation of the time slot to the sparse and dense traffic conditions. RSU is responsible for the allocation of the time slots to the vehicles. The spatial division is done based on the vehicle's virtual length, which consists of vehicle length and safe distance. A range is defined in the mapping function for reuse of the allocated channel to avoid the collision. For sparse traffic, the available time slots are sequentially allocated to vehicles; however, SINR is used for the allocation of time slots in the dense traffic conditions. Optimized assignment of the time slots based on traffic density leads to lesser utilization of bandwidth as compared to SDMA.

3.6. Summary of hybrid TDMA MAC for vehicular networks

These protocols combine TDMA with other access mechanisms such as CDMA, SDMA and FDMA to provide an optimized solution. Hybrid TDMA MAC is compared on the basis of different parameters and analysis of these protocols are given in Table 3. Scalable CS-TDMA combines CSMA and TDMA with back-off method for more than two nodes when the collision occurs. SD-TDMA combines SDMA and TDMA, and assigns time slots to the vehicles based on their spatial location. Here, the message retransmission occurs in dense traffic conditions. In [102] a hybrid TDMA MAC provides guaranteed delivery of time-sensitive data. During transmission failure, the data is sent to the base station which in turn prioritizes the data for future transmission. TCGMAC is a game-theory based MAC protocol that combines TDMA and CSMA features to provide efficient utilization of resources.

5. Collision resolution in TDMA MAC

TDMA based MAC protocols resolve different types of collisions as follows:

- Hidden terminal: Vehicles transmit the details of the allocated time slot in its frame information FI_i [30,83] that is utilized by contending vehicles to decide the status of the time slot. If the status is busy, vehicles avoid reservation of the particular time slot that resolves the occurrence of the hidden terminal. Protocols [79,80] creates the queue for requesting vehicles and uses TDMA MAC during the reservation period to avoid the hidden terminal issue. Protocol [89] considers neighborhood nodes to assign a unique polynomial to every node and avoid the hidden terminal issue. Multi-channel MAC protocols [78,96] send a control message to reserve a channel and provide adaptive channel switching with dynamic channel length and resolve the issue of the hidden terminal. The logical distribution of the road segment is assigned disjoint timeslots that reduce the hidden terminal issue in [70].
- Exposed terminal: Vehicles determine [83] the status of the time slot from the received frame information and doesn't reserve the allocated time slot within its three-hop range. Protocols [31,84,89] allow the vehicles to reuse the time slot beyond the three-hop range that reduces the issue of exposed terminal.
- Access collision: Vehicles before reserving the time slot [30,31,83,84,88,89] utilize n consecutive time slots for determining

the channel state and reserves the available time slot. Protocol [85] sends a B_i to notify the neighboring nodes about its reserved time slot. In [71,77,99] protocols, vehicles register themselves with the central coordinator that is responsible for allocating the free time slot to the vehicles. The active signal [94] is used to resolve the issue of access collision.

- Merging collision: Vehicles moving in different directions [30,31,88–90] are allocated the time slot from the disjoint sets. For vehicles with the same direction of movement, the status of the time slot in FI_i is determined. In [71,77,99] protocols, the central coordinator allocates the unique time slot to the vehicles after analyzing the probability of merging collision occurrence.
- Encounter collision: Protocol [18] frequently changes the allocated time slot to resolve the issue of encounter collision. Protocols [30,31,88–90] use disjoint sets to avoid the occurrence of encounter collision.
- Reservation collision: In [84] protocol, cooperating node notifies the contending nodes about the same time slot reserved by them. Protocol [20] checks for the higher value of waiting counter to resolve the issue of reservation collision.
- Cooperation collision: In protocol [21] destination node notifies the cooperating node and the sender node about the cooperation collision.
- Transmission collision: This collision is resolved by the allocation of a disjoint set of time slots to adjacent clusters as in [77,99] and the vehicles moving in different directions as in [31]. It can be resolved by prioritizing the nodes based on power [73,92] and transmission frequencies [93]. Timeslots are assigned based on the logical distribution of the road segment reduces the issue of transmission collision in [70]. Game theory is used to resolve the issue of transmission collision as in [98].

6. Challenges of TDMA MAC protocols for vehicular network

The challenges of TDMA MAC protocols for vehicular networks are given as follows:

- Unnecessary release of time slot: During merging collision, all the contending nodes release their reserved time slot and contend for a new time slot. This increases access collision. However, one node can continue the usage of the same time slot without any conflict.
- Delay for time slot reservation: Allocation of time slot takes time to avoid access and reservation collision. This delay has to be minimized.
- Time slots switching: Allocated time slot of the vehicle is released only if merging collision occurs or transmission completes. Message priority is not concerned for switching of the time slot, however switching of the time slot for the higher priority is required.
- Multiple time slot allocation: Vehicles are allocated a single time slot even if there are multiple distinguishable messages. Allocation of multiple time slots enables high data rates.
- Reuse of time slot: To avoid merging collision, reuse of time slot is disabled in TDMA. However, reuse of time slots for the vehicles four-hop (or more) distance apart can be done without conflict.
- Time slot handover: Vehicles moving between adjacent RSU release time slot while entering the new RSU and reserve the new time slot. However, the availability of the current time slot must be checked before releasing the current allocated time slot.
- Sparse traffic density: Allocation of time slot from variable size disjoint set resolves the issue of sparse traffic density in a different direction. For the sparse traffic density in the same direction, variable size frame is not used.
- Adaptive cluster: Cluster formed is not adaptive in terms of election of cluster head, cluster stability, cluster mobility.

7. Conclusion

The centralized TDMA MAC approaches use RSU-based and cluster-based coordination. RSUs coordinate, control, and collect information from the associated nodes, access channel quality, and assign the appropriate time slots. Whereas in the cluster-based MAC techniques, the time slots are assigned based on incoming and outgoing cluster members, message size and duration. However, the message complexity, vehicle registration rate, frame size variation, and merging traffic are the challenging issues in centralized MAC approaches. Distributed TDMA MAC approaches consider the cooperation/relaying, disjoint time slot sets, prediction, and game-based models. One-hop/multi-hop communication range and traffic density define the broadcast message frequency. The distributed MAC approaches adjust the time-slots to prevent collisions, message jamming and retransmission rates in VANETS. Dedicated time slot allocation reduces the access collision, and disjoint set time slot allocation resolves the merging collision. In TDMA based hybrid MAC approaches, TDMA is combined with other contention-based and contention-free MAC protocols to improve their efficiency. In this paper, we have analyzed the combination of TDMA with CSMA and SDMA MAC protocols.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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