A Survey of TDMA-based MAC protocols for VANETs

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Abstract

Vehicular ad hoc networks (VANETs) as an essential part of future wireless networks have gained a numerous amount of research attention in past decades. Among all technologies that make VANETs possible, medium access control (MAC) protocol is of greatest importance due to its ability of improving reliability and efficiency of communications among vehicles. This project focuses on surveying TDMA-based MAC protocols for VANETs. The purpose of this project is to obtain a general overview of TDMA-based MAC for VANETs by identifying the challenges associated with VANETs, and the benefits of employing TDMA-based MAC protocols for such network. Furthermore, the idea of several existing TDMA-based protocols in the literature are examined and evaluated to show readers how TDMA-based methods can be leveraged to address some of the challenges in VANETs. Finally, we conclude this project by discussing some open issues that need to be considered in future work.

Index Terms

medium access control, TDMA, access collision, merging collision and vehicular ad hoc networks

I. Introduction

Over the past few years, autonomous driving has attracted an increasing amount of attention from both industry and academia. Communication and sensing enabled autonomous driving is able to provide next level of traffic safety and coordination. Vehicular ad hoc networks (VANETs) as a key enabling technology of vehicular communication play an irreplaceable role in realizing autonomous driving as well as in the future Intelligent Transport System (ITS) [1]. A VANET is comprised of vehicles equipped with on-board units (OBUs) and road infrastructures equipped with road side units (RSUs), vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communications are achieved by connecting each OBU with other OBUs and RSUs via wireless link. Through V2V and V2I communications, various of application such as safety services, traffic management and infotainment can be implemented to improve the reliability of vehicular networks and the passengers' experience [2]. Among all applications that VANETs can provide, safty services is of greatest importance and highest priority. Safety services need to satisfy strict quality of service (QoS) requirements in respect of bounded access delay and transmission delay for prompt safety-related message delivery [2]. Therefore, on account of unique architecture and function of vehicular network, VANET can be characterized as a network with high mobility node, dynamically changing network topology and stringent QoS requirements. By means of reliable and efficient vehicular communications, future transportation system is envisioned as a safety enhanced and congestion relived intelligent system which makes autonomous driving both promising and assuring.

Medium Access Control (MAC) protocol in VANETs is responsible for coordinating packet delivery services among vehicles and infrastructures that share the same wireless link, it also plays a crucial part in satisfying various QoS requirements. Since wireless resources in VANETs are limited and valuable, an ideal MAC in this case should be able to provide efficient and fair access to channel for all vehicles in the network. Although, the research for traditional MAC protocol design has never stopped, but it has been pointed out that traditional wireless MAC protocols are not suitable for VANETs due to the special characteristics of VANETs. Therefore, many research efforts have been put onto designing efficient MAC protocols for vehicle networks. Broadly speaking, MAC protocols can be classified into two categories: contention-based MAC and contention-free MAC. For contention-based MAC protocols, there are no resource pre-allocated for each node, thus whenever nodes have packets to transmit they have to contend with each other for limited resources, which leads to collisions and unbounded access or transmission delay. On the other hand, contention-free MAC protocols try to avoid collisions by providing access schedule and pre-allocating resources for each node, which results in less packet loss and bounded access delay but at the cost of increasing communication overhead since control information need to be exchanged periodically for scheduling and resource allocation. Currently, most of research proposals are based on contention-free MAC protocols such as time division multiple access (TDMA), frequency division multiple access (FDMA), and code division multiple access (CDMA) [2] [3] as they have the potential to provide bounded access delay and more reliable communications. Among all these contention-free protocols, TDMA-based MAC protocols attract the most attention for reasons which will be discussed in details in Section III. Even though, there are several benefits of employing contention-free MAC protocols for vehicle networks, but this type of protocols do not naturally fit in with the VANETs, therefore there are still many challenges need to be conquered in order to explore its full potential.

The main purpose of this project paper is to help author and readers to develop a clear overview of the capability of TDMA-based MAC protocols in VANETs. This goal is achieved by first understanding the special characteristics of VANETs, then identifying the superiority as well as the challenges of employing TDMA-based methods compared to other types of methods. Next, the idea of several existing TDMA-based MAC protocols in the literature are discussed and evaluated to show readers how these methods can be utilized to accommodate those special characteristics and address challenges associated with VANETs.

The rest of this project paper is organized as follows: Section II provides a brief summary of characteristics of VANETs. Section III provides a detailed discussion of why TDMA-based MAC protocols are more desirable for VANETs, it also presents the challenges associated with utilizing such methods in VANETs. Section IV examines a number of TDMA-based MAC protocols for

VANETs, performance evaluation will be carried out for each of those protocols. Finally, we conclude this project by indicating some open issues and pointing out some future direction in Section V.

II. Characteristics of VANETs

Vehicles and road infrastructures are the nodes that constitute VANETs. Due to the inherent nature of vehicular nodes, VANETs are characterized as a network with high node mobility and frequently changing network topology. In addition, vehicle networks are responsible for improving traffic safety, thus stringent QoS requirements such as bounded delay need to be satisfied for safety measures. Outside of these characteristics, there are many other characteristics which separate vehicular network from other networks, however in this section, we only list out a small portion of many special characteristics of VANETs which we think are most relevant to this project, and we direct interested readers to [2] for a more comprehensive summary of all characteristics of VANETs.

A. High Mobility Nodes

VANETs are characterized as a network with high node mobility because the network is made up of vehicles. In different traffic environment vehicles tend to travel in different speeds, for example, in urban city scenario the speed of vehicles is typically between 30 km/h and 50 km/h, in rural area the speed of vehicles is between 50 km/h and 80 km/h, and in highway the speed of vehicles is between 90 km/h and 150 km/h [2]. Owing to the dynamic nature of vehicles' speed, network topology will be frequently changing and in succession greatly affect the performance of MAC protocols due to the present of access collisions and merging collisions which are two challenges that are particularly associated with VANETs and we will have a more detailed discussion of them in Section III. Consequently, the MAC protocols which can only handle a specific speed range generally have poor performance in VANETs, thus in order to adapt to the constantly changing speed, MAC protocols which are able to adapt to dynamic environments and different speeds are more desirable.

B. Different Traffic Scenarios

As a consequence of having high mobility nodes, the network topology are continuously changing. Situation such as one vehicle enters into a new traffic scenario (e.g., highway) from another completely different traffic scenario (e.g., rural area) can happen very frequently. In modern society, traffic scenarios can be categorized into three classes: urban, rural, and highway. In urban city scenario, traffic environments are relatively more complex than other the two scenarios since the density and speed of vehicles usually change over time, for example, the density of vehicles during evening peak is much higher than the density of vehicles at 2 am in the morning, and as a result vehicles can move faster at 2 am in the morning than during the evening peak. In rural area scenario, the density of vehicles is usually much lower and vehicles tend to move faster in this situation. Highway scenario is very similar to urban city scenario as the density of vehicles in these two cases both vary over time, the difference is that the speed of vehicles in highway is typically much faster due to looser speed limitation in highway. In anyone of these three scenarios, different parameters and considerations need to be taken into account for MAC design, and an ideal MAC protocol for VANETs should be able to accommodate all these three situation.

C. Different QoS Requirements

The purpose of vehicular networks is not all about providing secured and efficient message exchange related to traffic safety and management. Being able to provide user-oriented application such as infotainment is also very important for passengers to have a safe and fun road trip. Therefore the services that VANETs need to provide are real-time safety services such as the speed and direction of each vehicles, traffic management services that monitor traffic condition and avoid traffic congestion, and user-oriented services that are motivated by user behaviors. These services distinguish from each other in terms of QoS requirements. Real-time safety services have the most stringent QoS requirements. This type of services require each vehicle to have fair access to the channel and the access delay must be bounded to a tolerable range in order to ensure every vehicles in the network can disseminate real-time information equally without prejudice. On the other hand, user-oriented services can tolerate delay since they are not real-time services, however the data rate need to be sufficient enough to support a diversity of applications. As a result, broader bandwidth is required for user-oriented services. Traffic management services have the QoS requirements between the other two types of services, however given smaller access delay and faster data rate will make traffic management services such as traffic congestion prediction more accurate. Therefore the MAC protocols for VANETs should be able to cater the needs for different services.

In conclusion, VANET is a special network consist of nodes with fast and also constantly varying speeds. The high mobility issue cause network susceptible to traffic environment changes, and also makes network less predictable. QoS requirements for different services provided in VANETs are diffferent in terms of delay, packet loss, and transmission rate. The MAC protocol for VANETs thus need to be adaptive for various node speeds and QoS requirements, and scalable for different traffic scenarios. In the next section, we will discuss in details why TDMA-based MAC protocols are preferred in VANETs, how can they adapt to aforementioned special characteristics of vehicle network, and how do they address challenges particularly associated with VANETs.

III. Advantages and Challenges of TDMA-based Methods

One important lesson we learned from previous section is that traditional wireless MAC protocols are not suitable for usage in VANETs due to the special characteristics of VANETs such as high mobility nodes, frequently changing network topology, and various QoS requirements.

In VANETs, wireless resources are even more limited and precious than that in regular ad hoc network, thus how to efficiently use those resources to accommodate for those special characteristics of vehicle network as well as satisfying stringent QoS requirements is the topic that interests people the most. Therefore, MAC protocols designed specifically for VANETs are highly desirable. Over years, many MAC protocols in the context of vehicle networks have been proposed. Among those methods, majority of the ideas are based on TDMA-based method as there are some certain benefits that TDMA-based method can bring to the vehicle network system. In addition, to fully explore the potential of TDMA-based methods some challenges associated with employing TDMA-based MAC in VANETs need to be conquered.

A. Benefits of TDMA-based MAC in VANETs

1) Contention-based VS Contetion-Free: Generally speaking, the MAC protocols can be categorized into two major classes: contention-based and contention-free. Contention-based MAC protocols such as CSMA/CA has no pre-defined transmission schedule or pre-allocated resources for each nodes and nodes need to contend with each other for successful channel access. As a result this type of methods usually have unbounded access delay since the access for each nodes depend on whether other nodes are trying to access the channel at the same time. Under good situation where no other nodes want to access the channel, the node might be able to access the channel immediately, however if there are other nodes who also want to access the channel at the same time, then collisions will happen and there is no guarantee of access because the amount of time that current node needs to wait is unpredictable. In order to avoid collision, IEEE 802.11p [4] which employs the idea of CSMA/CA uses sensing mechanism to reduce the chance of having collisions. However, CSMA/CA is still not desired for VANETs because many services provided by vehicle network are very sensitive to time delay, so there is no time to perform CTS/RTS or other three way hand-shaken mechanism for those real-time services. Therefore, contention-based MAC can not provide bounded access delay with or without carrier sensing mechanism. Also, inevitably contention-based MAC protocols tend to have more collisions, which lead to more packet loss during transmission. This property is also not desirable in vehicle networks since safety message which exchange periodically among vehicles need to be delivered both in time and accurately, fail to do so may result in compromise in passengers' safety. Another disadvantage of contention-based method is inefficient channel utilization due to frequent occurrences of collisions. When collisions happen too frequently, only a small portion of packets are actually using the channel resources for transmission and thus most of resources and time are wasted. For vehicle network which only has very limited resources, such waste is prohibited. Lastly, as we mentioned in previous section that every vehicles in VANETS need to have equal and fair access to the channel in order to make sure all safety messages are spread out and heard by other nodes. In this regard, contention-based methods can't provide fair access to channel for each node due to the present of contention window which controls the backoff period of each node. In other words, if one lucky node collides with an unlucky node, the lucky node who gets a small value from contention window can retransmit almost immediately, but the unlucky node who receives a large number from contention window might need to wait for a long period of time before retransmission. Such case should not be happening in VANETs which treat nodes equally. To sum up, contention-based MAC protocols usually provide unbounded access delay, more collision and packet loss, which lead to inefficient use of channel, and unfair access to channel, thus this type of methods is not suitable for VANETs. Contrastingly, because contention-free MAC protocols have pre-defined transmission schedule and pre-allocated resources, the channel is utilized in a way that vehicles' access to that channel are more coordinated, thus less collisions or packet loss will happen. Also every vehicles are guaranteed to have equal access to the channel.

2) TDMA VS FDMA VS CDMA: We have shown that contention-free methods are more suitable for VANETs due to its ability of providing bounded access delay, less collision and packet loss, efficient channel utilization, and fair access to channel. However, all these four advantages can be provided by any contention-free MAC protocols such as frequency division multiple access (FDMA) or code division multiple access (CDMA). Why do we have to stick with TDMA-based MAC? The reason for that is both FDMA and CDMA require significant amount of communication overhead before transmission takes place. For example, FDMA-based MAC protocols assign a unique frequency band to each vehicle within a certain communication range, thus frequency synchronization process is required for two communicating vehicles. The synchronization process is performed by first generating another control channel frequency which is committed for frequency negotiation, the two communicating vehicles then exchange information in that frequency channel to negotiate the frequency that they will be using for the rest of communication. Doing so adds more complexity and communication overhead for each round of vehicle communication. Similarly, CDMA-based MAC protocols assign a unique code sequence to each vehicle within the communication range, and two communicating vehicles will use that code sequence for a communication round in order to reduce the chance of having collision. Before the code sequence is allocated and used for two vehicles, two communicating vehicles need to first negotiate the code by exchanging control messages in an existing frequency channel. This code negotiation and allocation process need to be repeated for every communication. These operations again add more complexity and communication overhead to the system. The complexity and communication overhead added by FDMA or CDMA-based MAC will become more and more overwhelming as the network topology become more complex or the density of vehicles increases, and these overhead in turn increases the transmission delay and affect the normal operation of real-time services in VANETs.

On the other hand, TDMA-based MAC protocols have several advantages over FDMA or CDMA-based methods. As shown in figure 1, TDMA-based MAC protocols divide the time into multiple different time frames and each time frame is further divided into multiple fixed number of time slots, each vehicle within a certain communication range can only have access and use one time slot in that time frame to transmit its messages, and then it can only listen

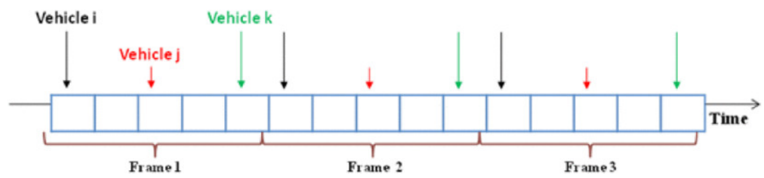


Fig. 1: The concept of time division multiple access (TDMA) [2]

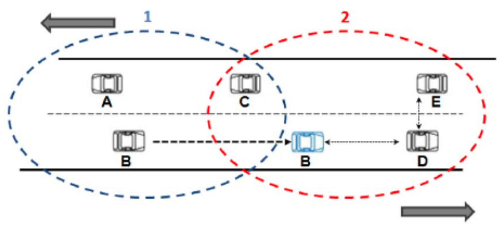
during other time slots in that frame. In this method, no frequency or code need to be negotiated or allocated before transmission, each vehicle only need to have knowledge about the different time slot that they are allowed to use. Furthermore, unlike FDMA or CDMA, interference might still happen among vehicles which use the same frequency band or code sequence at the same time, messages transmitted using TDMA-based MAC protocols are guaranteed not going to get interfered from other simultaneous transmissions within the same communication range because during that time slot the transmitting vehicle is the only vehicle that is allowed to transmit. Another nice property that TDMA-based MAC protocols have is that this method is scalable. As we mentioned, in TDMA-based methods time is divided into multiple time frames and each time frame is further divided in multiple time slot, the number of time slots allocated for each frame can be adjusted according to different situations. For example, when vehicle density is high, each time frame may contains more time slots to allow more vehicles to share the resources and transmit their message in each frame. When vehicle density is low, each time frame may contain less time slots, which results in either shortening the time duration of each time frame to allow more frequent transmission of each vehicle if the time duration of each time slot is fixed, or lengthening the time duration for each time slot to allow each vehicle to transmit more information in each slot if the time duration of each time frame is fixed. This property makes sure that resources in the network such as bandwidth can be assigned to vehicles according to their needs, which gives the protocol the ability to adapt to different traffic scenarios and reduce waste of resources. Last but not least, in VANETs traffic infrastructures equipped with road side units (RSUs) are also part of the network, and TDMA-based methods treat RSUs like any other vehicles with on-board units (OBUs), so RSUs are allowed to obtain a time slot from TDMA reservation schedule just like vehicles.

In conclusion, TDMA-based methods are able to provide many desired properties such as bounded access delay and equal channel access for vehicle networks without introducing too much complexity or communication overhead. This type of methods also have the ability to adapt to different traffic environment, and their scalability allows them to handle more complex and dynamic situations than other contention-free methods. Therefore, TDMA-based MAC protocols are more suitable for VANETs.

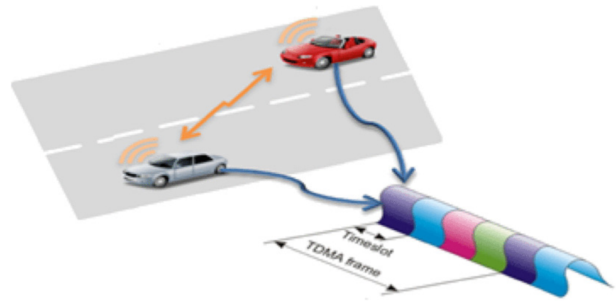
B. Challenges of TDMA-based MAC in VANETs

As discussed in above section that TDMA-based MAC protocols have a lot to offer for VANETs, however they do not naturally fit in with the vehicle networks since there are still many challenges related to employing TDMA-based MAC protocols in vehicle networks. Thus, in order to explore the full potential of TDMA-based methods, several related challenges need to be identified first. In this section, we provide a detailed discussion on what are the challenges associated with employing TDMA-based MAC in VANETs.

1) Access Collisions: We mentioned in previous section that one of the main reason why contention-free MAC protocols are more preferred than contention-based MAC protocols is that they can reduce the chance of having transmission collisions for vehicles within the same communication range. However, even if contention-free methods such as TDMA is used for vehicle networks, collisions still can not be eliminated due to either the mechanism of TDMA or characteristics of vehicle networks. When TDMA-based MAC protocols are used in VANETs, access collision which is shown in figure 2 will always occur. Access collision happens when two or more nodes within the same two-hop set (THS) attempt to acquire the same available time slot. In order to understand the concept of access collision, one needs to first understand



(a) Two-hop set (THS)



(b) Access collision caused by TDMA

Fig. 2: The concept of access collision [2]

what is a two-hop set. A two-hop set is the set which contains not only the neighbors of current vehicle(node) but also current node's neighbors' neighbors, for example, in figure 2(a) vehicle A and the other two vehicles B and C can form a one-hop set since vehicles B and C are within the communication range of A so they are A's neighbors. Notice that vehicle D and E are vehicle C's neighbors, which means vehicles D and E are vehicle A's neighbor's (C's) neighbors, thus together vehicles A, B, C, D, E form a two-hop set. The reason why forming a two-hop set is very important in employing TDMA-based MAC protocols in VANETs is that this mechanism can help address the hidden terminal problem of wireless network by allowing each node within the two-hop set to have knowledge about all the time slots that are already used by other nodes in that two-hop set. In this way, each vehicle can avoid using those time slots which are already occupied, thus two simultaneous transmission at the same time will not happen.

Recall that in TDMA after the time is divided into multiple time frames and each time frame is further divided into multiple fixed number of time slots, each vehicle need to reserve one of the time slots in a frame in order to use that time slot to transmit information. The reservation process usually has two phase. During first phase, the vehicle who do not possess with any time slot need to first listen to the channel for n successive time slots (n is the number of time slots allocated for each time frame), these n successive time slots need not necessarily be in the same time frame. After listening to the channel for an entire frame, the vehicle will be able to determine its two-hop set which contains its neighbors and also its neighbors' neighbors, as well as the time slots those neighbors are currently using in each frame. Once the vehicle has successfully collected these information, it will be able to form a list which indicates all time slots that are already occupied by other vehicles in the two-hop set in each frame. Then, in the next phase this vehicle will randomly select a time slot from the remaining available time slots which are not used by other vehicles, and it broadcasts a message during that selected time slot in the next frame to tell every vehicles within its two-hop set that it wants to secure this time slot as its legitimate place to transmit message. That time slot is finally secured by that vehicle if all other vehicles within that vehicle's two-hop set have registered it as the legitimate user of that time slot, and after securing the time slot that vehicle will keep using the time slot for the rest of the time if there is no collisions. The problem of this TDMA scheme is that when two or more vehicles select the same time slot and they all broadcast to the channel during that time slot to claim the ownership of that time slot, then those broadcast messages will collide with each other and thus no vehicles in the network will be able to receive the messages or register any of those vehicles as the legitimate user of that time slot. As a result, none of those vehicles can have access to that time slot because of the access collision.

2) Merging Collisions: Another type of collision which happen very frequently in VANETs is called merging collision. This type of collisions is not limited to vehicle networks only, and it is particularly associated with the network with high mobility nodes. A merging collision happens when two or more nodes acquiring the same time slot become members of the same two-hop set (THS) due to node mobility [5]. For example, in figure 3 if vehicle X and vehicle Z possess with the same time slot, then it is perfectly fine for vehicle X and Z to use the same time slot if the network topology does not change, since X and Z's communication range have no intersection and thus the messages they transmit at the same time will not interfere with each other. However, since it is VANETs that we are talking about, due to the high mobility of each vehicle node it is possible that vehicle X can move from one set to another within a certain amount of time. If vehicle X leaves one set and joins the two-hop set formed by vehicle Z then they can no longer transmit at the same time slot since their communication range overlap with each other and the messages transmit at the same time will collide and interfere at the intersection of their communication range.

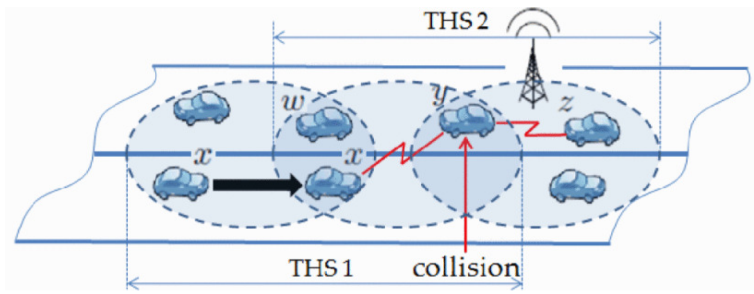


Fig. 3: Merging collision caused by node mobility [5]

Access collisions and merging collisions may caused by different reasons, however they are in fact very closely related to each other. Recall that in TDMA scheme that when one vehicle has successfully secured a time slot it will keep using that time slot for the rest of the time if there is no collisions and the collisions here refer to the merging collisions. This rule has reduced the number of time a node needs to acquire a time slot, and in turn it has reduced the chance of having access collisions since less reservation processes are needed. However, if a merging collision happens then two colliding nodes are forced to release the time slots that they are currently using and repeat the whole reservation process again. This release and reserve operation will usualy lead to more access collisions because more time slot reservation processes need to be performed. Therefore, if one can find a method to reduce the chance of having merging collision then the number of access collisions will be reduced accordingly.

In conclusion, access collisions and merging collisions are two main challenges that need to be addressed during the design process of TDMA-based MAC protocols. Their close relationship also simplify the design a little bit since the reduction of merging collisions usually lead to reduction of access collisions. In the next section, we will examine the idea of several existing TDMA-based MAC protocols, specifically we will look into details about how do they bring TDMA-based method's superiority into full play while addressing these challenges.

IV. TDMA-based MAC Protocols

A. VeMAC Protocol

1) Idea: In [5] and [6] a novel multichannel TDMA protocol which use two transceivers to accommodate control and service channels was proposed to address the access and merging collision issues for both channels. The time synchronization of each frame is performed by 1PPS signal of GPS receiver. The authors of this article have first identified that even though merging collision can happen among vehicles which are moving in the same direction, it is more likely for them to happen among vehicles that are moving in opposite direction since the relative speed of vehicles that are moving in opposite direction is much higher than vehicles that are moving in the same direction. Therefore, this protocol partitions each time frame into three separate and disjoint time slots set which are dedicated for use of vehicles move in left direction and right direction, and for road side units (RSUs) as well. Figure 4 illustrates the disjoint assignment of time slots.

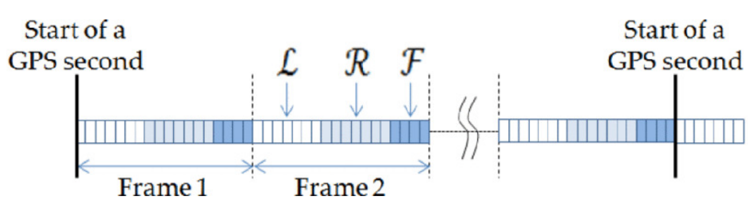


Fig. 4: Partitioning each frame into $\mathcal{L}$, $\mathcal{R}$, $\mathcal{F}$ sets [5]

With this simple idea, vehicles that are moving in different directions can only reserve and have access to time slots that are belong to disjoint sets, for example, for a vehicle that is moving in left direction can only reserve a time slot from $\mathcal{L}$ set. The benefit of doing this is to reduce the chance of having merging collision for vehicles that are moving in opposite direction. In the example of figure 3, a merging collision will happen if vehicle X and Z use the same time slot and vehicle X leaves one set to join the two-hop set of vehicle Z. However, if we employ the idea of VeMAC then this merging collision will not happen since vehicle X and vehicle Z are guaranteed not going to possess with the same time slot because their time slots are from two disjoint set $\mathcal{L}$ and $\mathcal{R}$. In addition, since road side units also have their own time slot set, the number of merging collision will be reduced among vehicles and road side units as well. Another novel idea in VeMAC protocol is the use of a split-up parameter. The split-up parameter is used to control the number of time frames that a node can fail in acquiring a time slot before it starts looking for available time slot in a larger set. This parameter can affect the rates of access collision and merging collision since when larger set is used, nodes are looking for time slots in sets that are not just dedicated for its own direction but also sets that are belong to vehicles with different direction or even for road side unit.

2) Performance: From the result presented in [5], VeMAC protocol has shown better performance than IEEE 802.11p protocol, additionally there are significant reduction on access collisions and merging collisions. However, this protocol has shown poor performance in unbalanced traffic scenario in which traffic is concentrated in one direction and there are no or little traffic on the other direction. In unbalanced traffic scenario, the set of time slots that are allocated for the other direction is wasted since there are very little traffic in the other direction, thus the time slot resources for that direction is underutilized. Moreover, since all traffic is concentrated in one direction and all vehicles will be reserving time slots in that direction set only, more access collisions will happen due to more nodes are trying to access fewer resource, which results in over-utilization of time slot resources for that direction. Lastly, the use of split-up parameter has provided a bounded access delay and meanwhile incurs more access and merging collisions because the time slot search range is expanded to sets that are originally belong to vehicles with different direction, and thus the event which two vehicles with different directions occupy a same time slot is more likely to occur.

B. CFR MAC Protocol

1) Idea: In [7] a near collision-free reservation based MAC protocol which based on previous VeMAC protocol was proposed to further address the merging collision issues. The basic idea of this protocol is very similar to VeMAC protocol in which each time frame is partitioned into three disjoint set of time slots for left/right direction traffic as well as road side units. The authors of this article realize that even though merging collisions are more likely to happen among vehicles with opposite direction, it doesn't mean that merging collisions will not happen among vehicles with same direction. This situation is particular more aggravating in urban city traffic scenario since the communication range of vehicles with same direction can still merge due to acceleration or deceleration. Having this observation, the authors of this article further divide each direction set ($\mathcal{L}$ and $\mathcal{R}$ set) into another three disjoint subsets according to vehicles' relative speed: High, Medium, and Low ($\mathcal{H}$, $\mathcal{M}$, $\mathcal{W}$ sets). Figure 5 illustrates the disjoint assignment of each direction set according to relative speed.

Direction	*R*			*L*		
Relative speed	$\Delta v < -\upsilon$	$-\upsilon < \Delta v < \upsilon$	$\Delta v > \upsilon$	$\Delta v < -\upsilon$	$-\upsilon < \Delta v < \upsilon$	$\Delta v > \upsilon$
Speed level	*Low*	*Medium*	*High*	*Low*	*Medium*	*High*

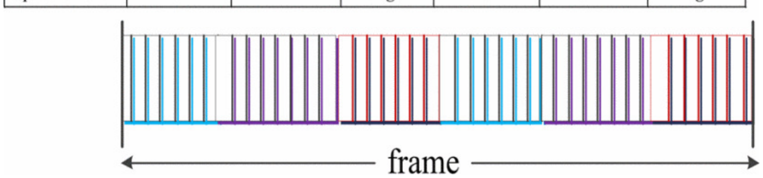


Fig. 5: Partitioning each direction set into $\mathcal{H}$, $\mathcal{M}$, $\mathcal{W}$ sets [7]

The relative speed of each vehicle is computed by first collecting speed data from neighboring vehicles to compute the average speed, then relative speed of a vehicle is computed by finding the difference between the average speed and its own speed. If the relative speed is negative, then this vehicle is slower than its neighbors, similarly positive relative speed suggests that this vehicle is faster than its neighbors. The operation of this idea is that vehicles which are moving in different directions and with different relative speeds can only have access to time slots that are belong to disjoint speed set from disjoint direction set. For example, a vehicle which is moving in right direction and has high relative speed can only acquire a time slot which belongs to $\mathcal{H}$ subset of $\mathcal{R}$ set. The benefit of employing this idea is two-fold, the first benefit is similar to VeMAc protocol, which it can reduce the chance of having merging collision for vehicles moving in both opposite and same direction. Consider the case which a faster vehicle is chasing a slower vehicle, if we use the VeMAC protocol in this case, then a merging collision will happen as soon as the faster vehicle has caught up with the slower vehicle. However, by using this idea the merging collision can be avoided since faster vehicle and slower vehicles will be using time slots from two disjoint speed set ($\mathcal{H}$ and $\mathcal{M}$ set) which are guaranteed not to be the same time slot. The second benefit is that it allows vehicles which occupy the same time slot and are moving in the same direction to keep using that same time slot for a much longer period of time. Because two vehicles occupy the same time slot usually suggests that these two vehicles have similar relative speed, thus it is going to take longer period of time for one vehicle to catch up with the other one and in the ideal case one vehicle will never catch up with the other one if they have the same speed. Therefore, two vehicles with same direction and same transmission time slot don't have to reserve for another time slots or deal with the merging collision immediately, they can use that time slot for a longer period of time, and the number of access collision is reduced in this way.

2) performance: The performance result given in [7] has shown that CFR MAC is more adaptive and reliable in terms of reducing reservation delay and collision rate compared with the IEEE 802.11p and VeMAC protocols. CFR MAC protocol has mitigated the effect caused by high mobility of each node and as a consequence it is able to provide deterministic access delay since the number of access and merging collisions has been greatly reduced. However, similar to VeMAC protocol CFR MAC protocol performs badly under unbalanced traffic scenario, and it also has poor performance when vehicles in the network all have similar speed. This protocol even suffers more from previously mentioned two cases than VeMAC protocol since each disjoint direction set is further divided into another three disjoint speed set, any unbalanced traffic or traffic with similar speeds will result in more serious under-utilization of channel resource, which in turn incurs more access collisions.

C. ATSA MAC protocol

1) Idea: An adaptive TDMA slot assignment MAC protocol was proposed in [8] and [9] to improve the TDMA scheduling strategy. In VeMAC and CFT MAC protocols, the chance of having merging collision is reduced by partitioning each time frame into disjoint sets, however by doing that these two protocols can no longer effectively cope with unbalanced traffic scenario. Therefore, the authors of these two articles enhanced the previous two protocols' performance under unbalanced traffic scenario by using an adaptive algorithm. The basic operation is to keep track of the number of neighbors of each vehicle that are moving in different directions by examining the signal transmitted by GPS. A ratio between number of left(right) directional neighbors and the total number of time slots which are belong to left(right) direction set is computed using these data. When the ratio for left direction traffic is greater than a certain threshold U or the ratio for right direction traffic is smaller than a certain threshold L, for example:

$$\frac{N_L(x)}{S_L(x)} > U \; or \; \frac{N_R(x)}{S_R(x)} < L$$

where $N_L(x)$ denotes the number of x's two-hop neighbors with left direction and $S_L(x)$ denotes the number of time slots which belong to left direction set. Then the network will adjust these ratio and update the time slot allocation scheme according to following formula:

$$\frac{N_L(x)}{S_L(x)} = \frac{N_R(x)}{S_R(x)}$$

so that when almost all time slots for one direction set are occupied and only a few time slots are used in the other direction set, the network will allocate more time slots for the direction with more traffic and less time slots for the direction with less traffic. For example, when the amount of left direction traffic become insignificant compare to right direction traffic, then more time slots will be allocated for right direction set and less time slots will be allocated for left direction set to make sure vehicles in dense traffic can all be served properly.

Another nice property of ATSA MAC protocol is that it can also adapt to traffic with different vehicle density. In this case the idea of using direction set occupancy ratio to adjust the time slots allocation scheme is generalized to using the occupancy ratio of entire frame to adjust the frame length allocation. The basic idea is very similar, A ratio between the number of one node's two-hop neighbors ($N(x)$) and the total number of time slot allocated for each frame ($S(x)$) is computed, if this ratio is greater than a certain threshold, for example:

$$\frac{N(x)}{S(x)} > U$$

then the frame length is doubled, or if this ratio is smaller than a certain threshold, for example

$$\frac{N(x)}{S(x)} < L$$

then the frame length is halved. By employing this scheme, for traffic with variable vehicle density, if suddenly more than ninety percent of time slots in a time frame are occupied then it's very likely that the vehicle just enters into a dense traffic area, thus it's beneficial to increase the number of time slots for each frame to embrace this transition.

2) Performance: As shown in these two paper that this protocol has enhanced the performance of VeMAC and CFR MAC protocols by reducing the number of access collisions and improving the channel utilization ratio especially for unbalanced traffic and traffic with variable node density. However, the performance of this protocol is greatly affected by the choice of U and L, poor choice of these two parameter can result in even worse performance than VeMAC and CFT MAC protocols, thus optimal values for U and L need to be found in order to reach this protocol's maximum potential.

D. PTMAC Protocol

1) Idea: In [10] and [11] a prediction-based TDMA MAC protocol was proposed and used to predict and eliminate the potential merging collisions happen in VANETs. The authors of these two articles have observed that merging collisions can be detected or predicted long before collisions can actually take place. The operation is performed by monitoring the frame information (FI) exchanged periodically among intermediate vehicles which are in the middle of a three-hop set (the intersection between two-hop set ahead and two-hop set behind) and other vehicles within the three-hop set, information such as members of the three-hop set, their safety related information such as direction, speed, location, and their occupied time slots can be obtained. Using these information intermediate vehicles can detect possible future collisions between vehicles within the three-hop set, and the potential merging collision is resolved by the intermediate vehicle which is closest to one of the colliding nodes and assigning a new time slot to that colliding vehicle.

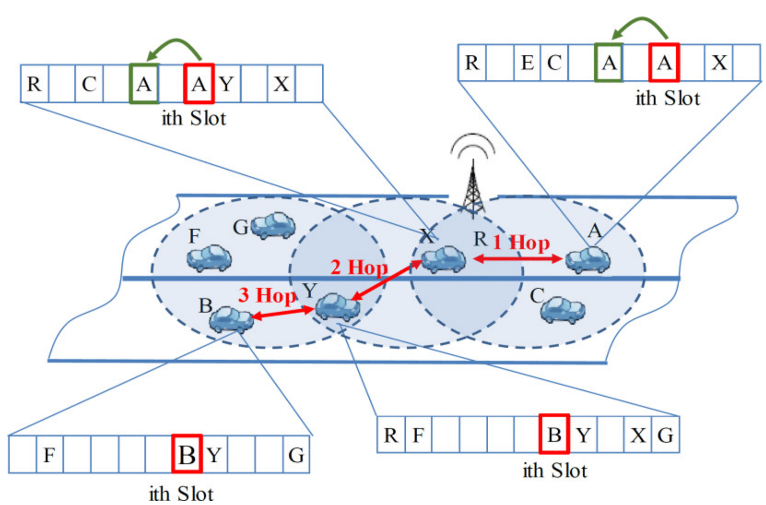


Fig. 6: Merging collision avoidance by PTMAC protocol [4]

The merging collision avoidance is depicted in figure 6. If vehicle A and vehicle B which are moving in different direction and possess with the same time slot i, then for the moment they are free to transmit information simultaneously since their communication range do not have overlap and vehicle B is 3-hop away from vehicle A. However, as vehicle A and B approach to each other a merging collision will definitely happen, by employing the idea of PTMAC protocol intermediate vehicle X and Y which are in the middle of the three-hop set can predict this merging collision by analyzing frame information collected from other vehicles within this three hop set. In this case, vehicle X which is closest to vehicle A will notify vehicle A to switch its time slot to avoid collision, and the frame information will be updated accordingly for next collision detection.

2) performance: In this protocol the number of merging collision is reduced by predicting and eliminating potential merging collisions before they can happen. The prediction and detection of collisions are performed without introducing significant communication overhead, and the resource utilization ratio is kept in a high range. From the result of these two paper, PTMAC protocol performs better in terms of having fewer collisions and higher throughput than non-prediction based TDMA MAC protocols for both two-way traffic and four-way intersection traffic in an urban area. In addition, unbalanced traffic or traffic with similar speed will not affect the performance of PTMAC protocol either.

V. Conclusion

In this project, we first presented a brief overview of special characteristics that VANETs have and how these characteristics should be taken into consideration for MAC deisgn in vehicle network. Then, we had a comprehensive discussion and comparison about the degree of adaptability of many existing MAC protocol in VANETs, and we concluded that TDMA-based MAC is the most suitable MAC protocol for vehicle network, the benefits and challenges of employing TDMA-based MAC in VANETs were elaborated in details. Finally, the idea of several existing TDMA-based MAC protocols were examined to show readers how to utilize TDMA-based MAC protocols in VANETs so that the network can take advantage from its benefits and meanwhile tackle some challenges, also the performances of these protocols were evaluated to manifest their effectiveness and weakness.

TDMA-based MAC protocols have shown their potential in VANETs. However, many challenges and issues are remain unsolved even until today. The issues of access/merging collision as well as the classical hidden/exposed terminal problems in vehicle networks were tried to solve by many papers over the past decades, yet there is no balanced solution which can efficiently solve all these four issues without introducing too much communication overhead or implementation complexity. These issues will remain as an active research problem for next few years. In addition, most protocols that we discussed in this project are restricted to one or two traffic scenarios, thus the design of a MAC protocol which can cater the need for all traffic scenarios is highly desired. Lastly, in this project we mainly considered MAC protocols which are operating on a fully distributed VANET in which channel access is performed in a distributed way. Other types of MAC protocols which can either operate on a cluster-based topology (one vehicle is selected as channel access coordinator) or on a centralized topology (a central point is used to coordinate channel access within the coverage area) are also existed in the literature. These protocols sometimes can offer more desirable properties than distributed MAC protocols, and there is still a lot of room to explore for these types of MAC protocols in VANETs.

REFERENCES

[1] M. Alam, J. Ferreira, and J. Fonseca, “Intelligent transportation systems,” *Studies in Systems, Decision and Control*, 2016.

[2] 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, no. 4, pp. 2461–2492, 2015.

[3] C. Campolo and A. Molinaro, “Multichannel communications in vehicular ad hoc networks: a survey,” *IEEE Communications Magazine*, vol. 51, no. 5, pp. 158–169, 2013.

[4] A. U. Haq and K. Liu, “Review of tdma-based mac protocols for vehicular ad hoc networks,” in *2018 IEEE 18th International Conference on Communication Technology (ICCT)*. IEEE, 2018, pp. 459–467.

[5] 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, no. 9, pp. 1724–1736, 2012.

[6] ——, “Vemac: A novel multichannel mac protocol for vehicular ad hoc networks,” in *2011 IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*. IEEE, 2011, pp. 413–418.

[7] R. Zou, Z. Liu, L. Zhang, and M. Kamil, “A near collision free reservation based mac protocol for vanets,” in *2014 IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE, 2014, pp. 1538–1543.

[8] 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*, vol. 10, no. 8, p. 579791, 2014.

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

[10] 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, no. 11, pp. 9209–9223, 2016.

[11] J. Wu, H. Lu, Y. Xiang, F. Wang, and H. Li, “Satmac: Self-adaptive tdma-based mac protocol for vanets,” *IEEE Transactions on Intelligent Transportation Systems*, 2022.