MAC Layer Challenges and Proposed Protocols for Vehicular Ad-hoc Networks

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Abstract Vehicular ad-hoc network (VANET) is a special form of mobile ad-hoc network (MANET) in which vehicles communicate with each other by creating an ad-hoc network. Before the deployment of VANET, it is necessary to address some important issues of VANET, specially concerning about architecture, routing, mobility, and security. Medium access control (MAC) protocols specify the way in which nodes share the underlying channel. As no standard exists for VANET, the research community has previously used IEEE 802.11a and 802.11b as the MAC layer access technologies. In this paper, we have discussed that the main challenge for VANET safety applications is to design an efficient MAC, so that all safety-related messages can be sent on time and such a protocol should be reliable because human lives are involved in the case of VANET. First, the challenges and requirements of a medium access protocol for VANET are discussed and then a survey of MAC solutions available in the literature to deal with these challenges in VANET is presented.

Keywords VANETs · MAC protocols · Safety applications

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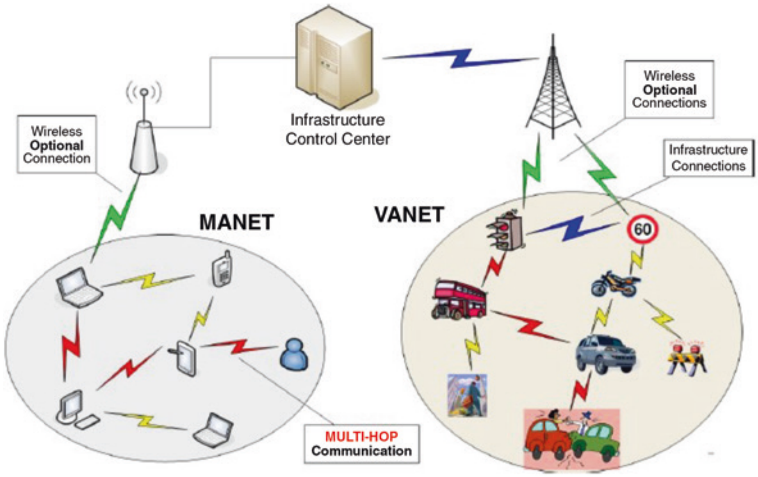

Fig. 1 MANET versus VANET

1 Introduction

Vehicular ad-hoc network (VANET) is a special type of ad-hoc network that is like mobile ad-hoc network (MANET). It can be utilized to improve vehicle safety, enhance traffic efficiency, and provide infotainment in vehicles. VANET has several distinguishing characteristics that differentiate it from MANET. In VANET, topology is very dynamic because vehicles move at a high speed. Blum and Eskandarian [1] stated that multihop paths in VANET are very short-lived because vehicles move at very high speed, as compared to the MANET. Unlike MANET, the mobility of vehicles is regular and predictable in VANET, and there are no power constraints. Vehicles can be equipped with some positioning systems (GPS and GALILEO), through which vehicles' position can be predicted. This predictability allows an improvement in link selection. Figure 1 shows the difference between the MANET and VANET.

VANETs are considered to be a class of MANET. However, VANETs have some distinguishing characteristics. Some of these characteristics, as discussed by Gillani et al. [2], are high node mobility, high dynamic network topology, enough battery power, sufficient storage capacity, high processing power, and availability of GPS. Due to these characteristics of VANET, the medium access control (MAC) solutions presented for MANET are not suitable for VANET. A MAC solution is required to specify the way the nodes share the underlying channel.

While designing a MAC protocol for VANET, the type of messages should also be considered [3]. As there are three types of priority-based messages in VANET applications, hence the MAC protocol should allocate the channel on the basis of message type. The first type of message is periodic messages which give information about the vehicles' current status (position, speed, and direction), these messages are usually needed to broadcast. The second type of messages is of an event-driven messages (emergency message usually related to safety) and these messages have high priority. This type of message is very time-critical, so need high transmission rate. The third type of message is informational messages (non-safety application messages). These messages need prioritized access. In addition to handling the channel access on the basis of message types, a VANET MAC protocol should also consider some other challenges of VANET like its decentralized communication mode (most VANET applications don't rely on any infrastructure) and unpredictable response and reliability.

This paper presents the MAC layer challenges of VANETs and state-of-the art solutions proposed in literature to meet those challenges. The MAC protocols are classified into three classes depending upon the mechanism they use for channel access.

2 Applications of VANET

VANETs offer possibilities for new applications, which will make our transportation system secure and efficient. But for various requirements, VANET's applications can be divided into different types. Here, some representative existing applications and several potential future applications of VANET are discussed. Xu et al. [4] and Qian et al. [5] described the categories of VANET's applications as: life critical, safety and warning, e-Toll collection, Internet access, group communications, and roadside service finder. In this work, we have divided VANET's applications into three main categories: safety applications, traffic management applications, and user applications.

2.1 Safety Applications

Most desirable group of applications for VANETs is safety applications. To avoid the accidents, road safety applications can play an important role. Even in the case if the accident is unavoidable, these applications can at least minimize the impact of accidents. Safety applications are delay sensitive and they mainly rely on reliable inter vehicle communication. All safety applications require the exchange of messages with other vehicles. The data in these applications are obtained from sensors or other vehicles. The data are processed in each application and after processing it sends messages to nearby vehicles or to the infrastructure. There are two reasons of sending these messages:

1. Awareness of the environment (Periodic Messages)
2. Detection of an unsafe situation (Event-Driven Messages)

An example of safety application is an early warning system. In such type of systems, a driver can be alerted about the road situation, for example, there is an accident on the road ahead, thus giving enough time to the driver so that he can apply the brakes well in time before hitting the accidental car ahead. According to Wang and Thompson [6], if half a second before the collision the warning message is given to the driver, then more than 50 % of the road accidents can be avoided. With the help of early warning system, this number can also be reduced. In addition to the car accident warning messages, some other warning systems can also be installed to avoid the accidents, for example, work zone warning, speed breaker warning, low bridge warning for trucks, etc.

As mentioned earlier, the safety applications are strictly delay sensitive. A fraction of a second is important in decision-making. Hence, there is a requirement for hard deadline for message delivery, so some special handling is required at the lower layers of the TCP/IP protocol stack. As a concern of the network layer, the safety applications do not require or involve in routing. It is because the neighbours of the source node are usually the target audiences for these messages. Therefore, there is no need to send these messages to the nodes that are more than one hop away from the source node. Hence, putting the whole burden on the MAC layer for delivery of messages with minimum delay.

2.2 Traffic Management

The congested road notification (CRN) is a traffic management application for VANETs. Through this application traffic, congestion on the road can be notified. For route and trip planning, we can use this application. Through this application, road congestions can be controlled and the information about the best route can be provided to a driver with efficient road conditions. In this application, some roadside units like intelligent traffic signals or electronic sign boards can also be involved to capture and to disseminate the information. The traffic congestion information about the road ahead can positively help to reduce the congestion and to improve the capacity of roads.

Another interesting application for traffic management is the e-Toll plaza, where vehicles do not need to stop to pay toll fee. By using intelligent traffic signals, congestion at road intersections can be efficiently handled. In reaction to the traffic situations at an intersection, these traffic signals can adjust themselves and can also communicate the status to neighboring intersections. This information can be displayed on the e-sign boards by these neighboring intersections.

Another traffic management application is parking availability notification (PAN). Through this application, available slots in parking lots can be found.

The majority of the traffic management applications use the roadside infrastructure. It is possible that some infrastructure is free and can be used by any user while some of them will need a subscription and will not be available to all users. For example, e-Toll infrastructure will require a subscription to offer its services. For these applications, the infrastructure needs to be managed and updated. For these applications to work, the infrastructure with relevant information needs to be managed and controlled.

2.3 User Applications

In addition to the road safety applications, information and entertainment applications can also play a vital role in pushing new technologies in VANET. Hot spots for transferring maps are one example of user applications. The passengers in a vehicle can enjoy the facility of Internet connectivity where other traditional wireless internet connectivity options (Wi-Fi, Wi-MAX etc.) are not available. Peer-to-Peer applications can also find their place in VANETs, e.g., gaming, chatting, file sharing, etc. But in all these applications, a large amount of data are transferred so there is a need of specialized means of delivery.

3 MAC Protocols for VANET

A MAC protocol specifies the mechanism in which nodes share the channel. There are many MAC issues in VANET like prioritized access, unpredictable response, and reliability. All these are needed because these are basic requirements of safety applications. To provide a reliable broadcast communication can be difficult in wireless networks due to hidden terminal and exposed node problems. A key challenge of VANET is that there are frequent changes in the network topology because the vehicles travel at a high velocity. So, VANET MAC protocols have to care about the rapid topology changes, and for safety applications, there is a need to reduce the medium access delay. In this work, we have categorized the MAC protocols for VANET in three categories. These are:

- Contention-Based Protocols
- Delay Bounded/Contention Free
- Hybrid MAC Protocols

This classification of MAC protocols is shown in Fig. 2.

3.1 Contention-Based Protocols

In contention-based protocols, nodes that want to communicate compete for the channel access and the node which wins can use the shared medium for negotiated time. However, there is no delay boundness so the real-time delivery of safety messages may not be guaranteed through these protocols. These protocols are suitable in scenarios where network traffic is bursty so that the bandwidth can be utilized effectively. These protocols are not appropriate for multimedia and real-time traffic as well. The efficiency of these protocols is affected when there are large numbers of users.

The carrier sense multiple access (CSMA) is a well-known example of contention-based MAC. In CSMA, to avoid the collision the transmitting device first listens to the network before transmission. In these types of protocols, collision may

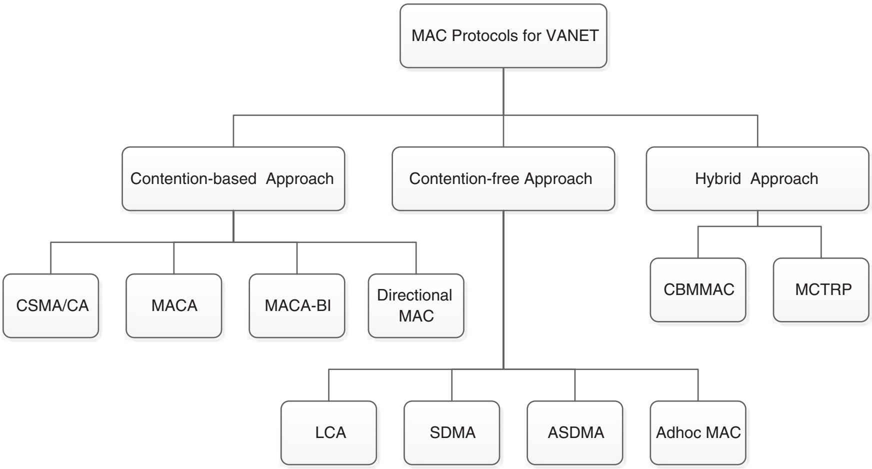

Fig. 2 MAC protocols for VANET

occur, and due to collisions, packets may suffer unbounded delays. For VANET safety applications, MAC protocols need to reduce the medium access delay.

The IEEE 802.11 standard (802.11a/b/g) is based on CSMA/CA. IEEE 802.11b uses direct sequence spread spectrum (DSSS) as the modulation scheme which reduces multipath fading. IEEE 802.11b/g both are used in many VANET prototypes.

For the purpose of increasing access fairness, Karamad et al. [7] proposed a contention-based MAC for vehicle-to-infrastructure (V2I) communication. This MAC protocol is proposed for the road side unit (RSU) based communication and is based on IEEE 802.11. In this scheme, the distributed coordination function (DCF) is adjusted for node speed. For the fair access of shared medium, an increase in the contention window of each vehicle is done. The proposed approach is not suitable for vehicle-to-vehicle (V2V) communication as it has many limitations that include: requirements for a high coordination, awareness, and overhead that will enable each node to adjust the DCF relative to the other nodes. In addition, the contact time for V2V communication is very short and the speed of other nodes in the communication range is known once only. Hence, the justification of the huge cost of data transfer time for a small benefit of channel access fairness is difficult.

Yang et al. [8] and Pal et al. [9] enhanced the CSMA-based protocols by providing different priority levels. By using different back-off time spacing, packets with higher priorities allow to access the channel faster as compared to the low priority packets. IEEE 802.11e standard also provides different priority levels that allow packets with high priority to access channel fast because the listening period before an attempt is made for channel access is shorter.

Bilstrup et al. [10] discussed that the prioritization mechanism of IEEE 802.11e is also included in IEEE 802.11p, which is forthcoming standard for VANET. This forthcoming standard will use DCF and enhanced distributed channel access (EDCA) as MAC. This standard can play an anchor role for future inter-vehicular communication. But it does not support reliability because in CSMA, nodes compete to access the channel and if the channel is busy, the node must defer its access and waits to attempt channel access for next time and this wait can lead to unbounded delay, which increase the unreliability.

MACA and MACA-BI are also contention-based protocols, so these are also not delay-bounded. Young et al. [11] stated in their work that such protocols (MACA and MACA-BI) are suitable for burst data but they are not suitable for real-time communication. However, when the number of vehicles is increased then the efficiency of these protocols becomes poor.

3.2 Contention-Free Protocols

In the contention free or controlled access protocols, like time division multiplexing access (TDMA) and frequency division multiplexing access (FDMA), the access to the medium is pre-allocated. A MAC protocol is contention-free if the nodes do not need to compete for the channel access. Different TDMA-based protocols, as described by Blum and Eskandarian [12], use different methods to assign time slots. Explicit time slot allocation approaches suffer from underutilization of bandwidth. Through this explicit time allocation, MAC may provide guaranteed quality of service (QoS). The drawback of these protocols is that they need a central entity responsible for fair distribution of channel resources among nodes.

Yang et al. [13] proposed a cooperative TDMA MAC protocol for broadcasting. In his paper, the author first described a way to make clusters in VANET. These clusters are based on vehicles directions, i.e., all vehicles are moving in one direction will be a part of one cluster. In each cluster, a node is selected as a cluster head (CH) and other nodes are cluster members (CM) and all they can communicate directly to CH. When any CM notices an accident, it informs to CH. The CH consolidates all messages that come from CM and then broadcast to all its members. The reception of message is verified by ACK. Every receiving member adds ACK in the next frame. If any member does not receive this message, then any member node that has received that message can be acted as a potential helper and maintains a list of all nodes that have not received that message and send this list to CH. The CH finally selects the helper node that will perform cooperation in idle slots for all unsuccessful members. In this way, reliability of safety messages can make possible. The authors did not discuss different priority messages, they just consider safety messages, but to design any MAC protocol for VANET it should be described how channel switching will occur because VANET performs a multichannel operation.

Wang et al. [14] presented a multichannel coordination MAC protocol for contention free access to service channels. This protocol dynamically adjusts the length of intervals between control channel and service channels based on traffic loads of each channel. For this purpose, they used a Markov chain model to find stationary probability and then finally derived the optimum ratio between control channel interval and service channel interval. In this paper, for calculating optimum control channel interval, the authors used the total number of nodes that are sending safety messages, but they did not explain how they will calculate total number of such nodes in dynamically changing traffic conditions in VANET environment. The authors also did not explain how their protocol will avoid interference from hidden nodes.

CDMA is based on spread spectrum (SS) technique that allows several transmitters to send information simultaneously over a single communication channel. Nagaosa and Hasegawa [15] proposed a multi-code sense (MCS) protocol for inter vehicle communication. This protocol is based on CDMA system in which vehicle that wants to communicate senses the currently used codes in the network and through this procedure it determines unused codes. When the number of vehicles increases, then the sequence search for free code can take longer time.

Bana et al. [16] proposed a self-organizing architecture division multiple access (SDMA) for MANETs in which they use space division multiplexing (SDM) in which road is divided into pieces that called spaces and in each space TDMA scheme is mapped. Each vehicle will use different time slots and it will depend on where the vehicle is at this time. If we consider applying this scheme in highway scenario where traffic is sparse, then the overall network utilization will be low because many slots will be unused to low traffic.

For VANET environments where network topology changes rapidly, these types of protocols are not suitable because they do not incorporate the dynamics of the network.

Katragadda et al. [17] proposed location-based channel access (LCA) protocol. In this protocol channel, allocation to nodes is based on their current geographical location. The geographical location of nodes can be obtained by GPS or any other geo localization systems. For this protocol, no central device is needed. The geographical area is divided into cells and each cell is allocated a unique channel. Any node located in a given cell will communicate on the channel associated with that cell. At regular intervals, this protocol assigns channel to vehicles on the basis of current location. Hence, the communication in VANET is delay bounded and real-time. Every user gets a fair chance to communicate. In LCA, we can use TDMA, CDMA, or FDMA as multiple access schemes. In inter vehicle communication, mostly applications need for simultaneous reception of multiple channels, so if LCA is using FDMA and CDMA, the receiver complexity will increase.

Borgonovo et al. [18] proposed a new distributed MAC protocol that is the extension of R-ALOHA protocol that avoid hidden-terminal problem. Through this protocol, reliable single hop broadcasting in ad-hoc networks is possible. It is based on UTRA-TDD slotted physical channel, but can use any other physical standard. In this protocol, every active node can reserve the channel by capturing a frame. A terminal that wants to communicate selects a basic channel (BCH) and if it requires using high speed channel then it can reserve more slots. Still no simulation results of this protocol are reported so cannot say how it will perform under high mobility networks.

Flaminio and Antonio [19] proposed AD-HOC MAC, a new, flexible, and reliable MAC architecture for ad-hoc networks that is based on a completely distributed access technique, RRALOHA. It was developed for the CarTALK 2000 project. The AD-HOC-MAC protocol is used where the communicating nodes can be divided into groups or clusters and all the nodes in a group uses broadcast radio communication. At the physical layer, nodes that are present in different clusters will not communicate with each. The drawback of AD-HOC-MAC is that the vehicles in the same communication range have not to be greater than the number of slots in the frame time.

Ko et al. [20] stated that IEEE 802.11 standard is designed for Omni directional antennas so if we use directional antennas for such MAC protocols then we cannot get additional benefits. Kulkarni [19] states that directional antennas can be beneficial for ad-hoc networks because directional antennas offers higher data rates, better connectivity, and Improved spatial channel utilization due to directional communication. The directional antennas are used to reduce the contention, caused by the transmission of multiple nodes, by dividing the area into regions. A single directional antenna is used at the receiver that is directed at a single region, so the transmissions from the nodes of different regions may not interfere. A new directional MAC (D-MAC) scheme that works similar to IEEE 802.11 except that the ACKs are sent using a directional antenna was also proposed.

3.3 Hybrid MAC Protocols

A multichannel token ring protocol (MCTRP) for VANET was proposed by Bi et al. [21]. The objective of this protocol is to develop a MAC method that independently organizes the nodes into token passing rings so that the delay for safety messages can be decreased with an increase in the throughput for other applications. A TDMA-based token passing mechanism is used to control the medium access for intra ring transmissions. While, for inter ring transmission, emergency messages, and for ring administration transmissions CSMA/CA is used to control medium access.

There are many shortcomings in the MCTRP. These include the nodes that founded the ring topology are the main nodes and it makes the system severely dependent on these founder nodes. If any of the leader nodes have problem or becomes unreachable in the topology, then the whole ring collapses. This requires the re-initiation of the ring association. Such type of MAC is more suitable for the scenarios where vehicles move in a platoon form. For the token passing and safety-related messages, CSMA is used by the MCTRP, while data transfer is done through TDMA. In case of heavy loads, this will lead to scenarios where an unbounded delay can be faced by the safety messages. The system also requires GPS for external timing and for location information. This protocol requires two radios per vehicle and for each radio a complete transmission slot is used that may result in inefficient transmission as a node may not need to transmit.

A clustering-based multichannel MAC (CBMMAC) similar to the MCTRP [21] was proposed by Su et al. [22]. A cluster-based technique is used in which the cars in close proximity and traveling in the same direction are grouped into clusters.

A self-elected CH is chosen that controls the cluster. Each node is equipped with two transceivers, one using IEEE 802.11-based contention and the other using contention-free TDMA. The CBMMAC is intended for highway traffic and the system is only activated when a vehicle enters a highway. The approach is dependent upon a CH that relies on vehicles grouping at low levels of relative mobility. An advantage that is diminished by using this technique is the use of all seven channels within one group. In case of one group, high channel utilization will be done. But in the case when two or more groups are in close proximity high collision levels are there. Just like MCTRP, it also requires two radios per vehicle and the GPS.

4 Conclusion

In this paper, some basic concepts of VANET were discussed. The applications of VANET were identified and were classified into three classes: safety application, traffic management applications, and user applications. For safety applications, there is a need to reduce the medium access delay as these applications involve human lives. This paper presented a survey of MAC protocols for VANET. The MAC protocols were classified into three categories: contention-based MAC protocols, contention-free MAC protocols, and hybrid MAC protocols.

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