A SURVEY AND QUALITATIVE ANALYSIS OF MAC PROTOCOLS FOR VEHICULAR AD HOC NETWORKS

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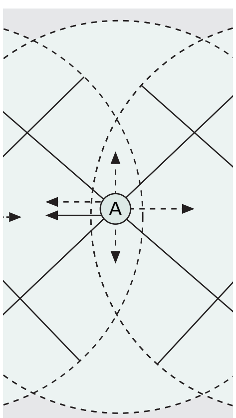

ABSTRACT

In order to avoid transmission collisions in mobile ad hoc networks (MANETs), a reliable and efficient medium access control (MAC) protocol is needed. Vehicular MANETs (VANETs) have vehicles as network nodes and their main characteristics are high mobility and speed. Active Safety applications for VANETs need to establish reliable communications with minimal transmission collisions. Only few MAC protocols designed for MANETs can be adapted to efficiently work in VANETs. In this article we provide a short overview on some MANET MAC protocols, and then we summarize and qualitatively compare the ones suited for VANETs.

INTRODUCTION

In mobile ad hoc networks (MANETs) nodes self-configure themselves and interact without using fixed infrastructures or centralized administration. MANET nodes use radio frequencies which are also called transmission channels, each one considered as a common medium over which two neighboring terminals cannot transmit simultaneously because a transmission collision occurs. So, in order to efficiently share the medium, medium access control (MAC) protocols are proposed by the research community.

Efficient medium sharing is even more difficult in vehicular ad hoc networks (VANETs) due to high node mobility and fast topology changes. Our article does not survey all existing MAC protocols for MANETs, which was already done in other works. Our goal is to analyze existing MAC protocols which are more suitable for VANETs.

The main targeted applications for VANETs are the ones related to so-called Active Safety, that is, the set of hw/sw tools able to prevent accidents instead of acting on cars involved in accidents. As an example, car-to-car (C2C) communications can inform drivers approaching intersections about other vehicles approaching from other directions or dangerously turning. In general, the amount of information to be transmitted is relatively small (e.g., the movement information of each vehicle), but the transmission reliability as well as the latency and packet dissemination are fundamental.

The rest of this article is organized as follows. First, we recall the main MAC protocols for MANETs and some proposed solutions. Then we give a description of existing VANET MAC protocols, over which a qualitative comparison is done after. Finally, we conclude this article.

A SHORT OVERVIEW OF MAC PROTOCOLS FOR MANETS

In MANETs a transmission channel is a shared medium; so, in order to avoid transmission collisions, when a node is transmitting on one channel, all nodes in its neighborhood (before transmitting) have to wait until it releases this channel. Because MANETs do not have a fixed infrastructure, it is not easy for their nodes to know if the medium is in use or not. Many works have been done and others are ongoing to overcome different existing MAC problems in MANETs.

ALOHA [1] was the first MAC protocol proposed for packet radio networks; the ALOHA ("hello" in Hawaiian) process is based on random access: when a node wants to use a common channel, first it transmits on it, then, if a transmission collision occurs, it waits for a random time before retransmitting again. The maximum throughput of this protocol is 18.4 percent of the channel capacity for a fixed message length.

The ALOHA random access causes an important throughput reduction. Hence a slotted version, named S-ALOHA [1], was proposed: this protocol divides the medium into several time slots and a sender attempts to transmit at the beginning of a time slot. Compared to ALOHA, in S-ALOHA the vulnerable period of a transmission is halved, thus doubling the efficiency (maximum throughput) of the system.

Another approach was introduced in the Carrier Sense Multiple Access (CSMA) protocol [2]. In CSMA a node that has data to send senses the common channel at first: if it is idle, it trans-

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mits; otherwise, it attempts again after a random time. Collision detection (CSMA/CD) [2] was then added in order to detect collisions during transmissions, stopping them, and allowing another attempt later. CSMA/CD is still not optimal in the case of a charged network, when a lot of collisions can occur. The main weakness of CSMA/CD is that it does not solve the problem of hidden and exposed terminals.

Multiple Access with Collision Avoidance (MACA) [2] overcomes the hidden terminal problem by agreeing on transmission with the destination. The sender initiates this *handshake* by broadcasting a request to send (RTS) packet. So, all neighboring nodes are aware of the upcoming transmission. After receiving the RTS packet, the destination, if ready, replays by broadcasting a clear to send (CTS) packet, which informs all its neighbors about the upcoming transmission. By receiving the CTS packet, the sender can start the unicast transmission without any risk of collision, since its neighbors and those of the destination are aware about the ongoing transmission. Although, if a node receives the RTS but not the CTS, it can transmit, causing the exposed terminal problem.

To let the exposed terminals be aware about the transmission duration time in its neighborhood, MACA Wireless (MACAW) [2] proposes to add data sending (DS) and acknowledgment (ACK) packets with regard to RTS and CTS packets. Figure 1 summarizes the packet exchange in MACAW, including control and data packets.

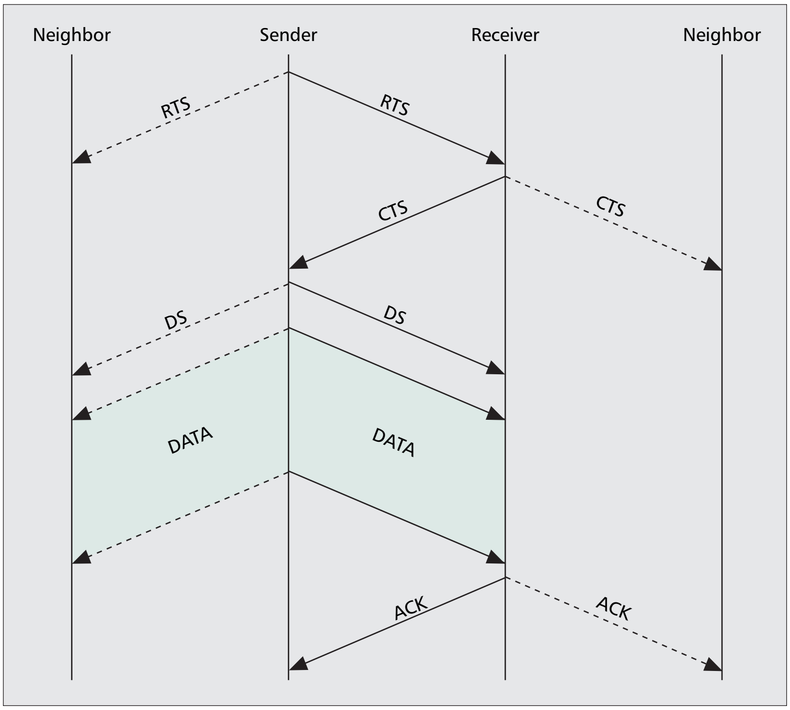


Figure 1. *Packet exchange in MACAW.*

The Busy Tone Multiple Access (BTMA) MAC protocol [2] proposed a new way to overcome the hidden terminal problem, i.e., by splitting the channel transmission into two channels: a data channel and a control channel. The first tone is used to transmit data packets, and the second to transmit the busy tone signal. In BTMA, when a node wants to transmit, it senses the control channel; if the busy tone is free, it transmits the busy tone signal on the channel control and then starts the data transmission on the data channel. All neighbors which sense the busy tone signal transmit it as well. In this way, all two-hop neighbors of the sender are not allowed to transmit, which avoids collisions. Dual Busy Tone Multiple Access (DBTMA) [2] extends BTMA by using two busy tones. The first is used by the sender to inform its neighbors that it is transmitting, and the second is used by the receiver to inform its neighbors that it is receiving data packets.

Another way to split the medium is to divide it into several fixed frames in time, and each frame eventually into several slots. This approach is generally called Time Division Multiple Access (TDMA). Five Phase Reservation Protocol (FPRP) [2] was the first proposed TDMA protocol. It divides the medium into information frames (IF), which are used to send data, and reservation frames (RF), used for IF reservations.

In Frequency Division Multiple Access (FDMA) protocols the medium is slotted, but in terms of frequencies, so several nodes can transmit simultaneously. The previous MAC proposals can be applied on each frequency channel, like in MCSMA [2] that uses CSMA on each frequency channel.

In Code Division Multiple Access (CDMA) protocols several orthogonal codes are available, and each node uses one code to encrypt messages before transmitting them. For example, the Multicode MAC (MC MAC) [2] uses, among the several available codes, one common code for control packet transmissions and other codes for data transmissions. In MC MAC a sender node indicates in its RTS the code that it will use for the transmission. When receiving an RTS, if there is no code conflict with another transmission, the receiver replies by CTS; otherwise, the receiver exchanges its usable codes with the sender that will select one of them then retransmits a RTS packet again. When receiving a CTS, the sender starts its transmission.

MAC Protocols for VANETs

Vehicular Ad hoc Networks (VANETs), also called Vehicle to Vehicle Communication (V2VC) or Inter-Vehicle Communication (IVC) networks, can be considered as a specific case of traditional MANETs. In VANETs, the mobile nodes are vehicles, and because of their high mobility and speed, the main VANET disadvantage is that the network topology changes frequently and very fast. On the contrary, in VANETs vehicles move only on predetermined roads, and they do not have the problem of resources limitation in terms of data storage and power. Furthermore, we can assume that it is always possible for a vehicle to obtain its geographic position by using GPS (or Galileo), which can provide good time synchronization through the network as well.

In general, good VANET MAC protocols should take power constraints or time synchro-

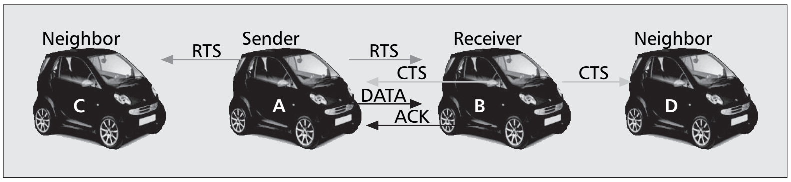


Figure 2. *Packets control exchange in IEEE 802.11.*

nization problems less into consideration. But they have to be concerned with the fast topology changes, as well as the different kinds of applications for which the transmission will be established. Moreover, VANET MAC protocols have to reduce the medium access delay, which is important, for example, for safety applications.

IEEE 802.11 Standard

IEEE 802.11 [3] is a wireless communication standard that can operate in two modes: in a centralized mode, where mobile terminals communicate with (and through) one or more access points, and in an ad hoc mode, where mobile nodes are allowed to communicate and to interact directly, without using any infrastructure. The IEEE 802.11 standard is often used for implementations of VANETs prototyping, thanks to the large availability in the market of inexpensive IEEE 802.11-based wireless devices. IEEE 802.11 addresses the MAC and the physical layer.

IEEE 802.11 MAC Layer — In IEEE 802.11, the Distributed Coordination Function (DCF) is responsible of the medium access based on CSMA with Collision Avoidance (CSMA/CA), that is, the device listens to the network before transmitting in order to avoid collisions. The Point Coordination Function (PCF) is another method to access the medium designed for centralized networks and real-time services; it is beyond the scope of this article.

Two methods can be used in IEEE 802.11 to determine if the medium is idle or not. The *physical carrier sensing* depends on the physical layer and the hardware used; it cannot overcome the hidden terminal problem, since the hidden terminal can not be heard physically. The *virtual carrier sensing* is instead based on the Network Allocation Vector (NAV). The NAV is just a timer that indicates the duration for which the medium will be busy; if the NAV is different from zero, the medium is indicated as busy.

In wireless networks some interval spaces, called Inter-Frames Spacings (IFSs), are set between two successive transmission frames in order to manage the medium access process.

When using IEEE 802.11 in ad hoc mode for VANETs, before attempting to transmit, each vehicle has to first check the medium state. If it is sensed to be idle for a certain duration time (DIFS), the vehicle can transmit. Otherwise, it backs off and attempts again after an amount of time chosen within a contention window (CW).

To access the medium, IEEE 802.11 is mainly based on RTS/CTS/ACK packets exchange, as shown in Fig. 1. When a vehicle wants to access the medium, it senses if it is idle, then sends an RTS packet including its ID and the duration time of the whole transmission. All neighbors of the receiver vehicle hear the RTS packet and set their NAV according to the transmission duration time indicated in the RTS packet. After receiving the RTS, if the receiver is ready to receive the transmission, it waits for a Short IFS (SIFS) time and then replies by sending a CTS packet including the transmission duration time. All neighbors receiving this CTS set their NAV according to the indicated transmission duration time. When receiving the CTS, the sender vehicle waits for SIFS before starting the data transmission. The receiver vehicle, after successfully receiving the data frame, waits for another SIFS then it sends an ACK only to the sender. Each terminal set its NAV to zero after receiving the ACK packet.

Thanks to the use of RTS/CTS/ACK packets exchange and the different inter-frames spaces, 802.11 minimizes the risk of frame collisions (Fig. 2).

Toward a IEEE 802.11 Physical Layer for VANETs — Several IEEE 802.11 versions related to the physical layer have been proposed. The most famous ones are 802.11b, 802.11a, and 802.11g. Many other versions are proposed as enhancements or extensions of the previews ones, for example, 802.11i, which includes security.

802.11b is the most popular and the first widely accepted wireless networking standard. Like 802.11g, 802.11b uses the unlicensed 2.4 GHz band, where interference is possible with cordless phones, microwave ovens, wireless IP cameras, and other devices using the same band. Theoretically, IEEE 802.11b data rates can reach 11 Mb/s, but in practice, due to CSMA/CA protocol overhead, it can reach only about 7.5 Mb/s.

In contrast to 802.11b and 802.11g, 802.11a uses the 5 GHz frequency band. The theoretical maximum throughput is 54 Mb/s, but the useful one goes up to 25 Mb/s at most. The 5 GHz band lets 802.11a have the advantage of less interference, but unfortunately, it does not allow it to penetrate walls and other obstacles well.

802.11g technology can reach the same highest theoretical bit rate of 802.11a (i.e., with about 25 Mb/s maximum net throughput). 802.11g and 802.11b are compatible and can work together. Super G, a new proprietary feature used by some products in the market, should allow network speed to reach up to 108 Mb/s by using the channel bonding over the 802.11g, that can bond two 20 MHs channels together.

WAVE (IEEE 802.11p) — An IEEE working group is investigating a new PHY/MAC amendment of the 802.11 standard designed for VANETs: the Wireless Access in Vehicular Environments (WAVE), which is referred as well as IEEE 802.11p. Requirements for this amendment are mostly coming from vehicular Active Safety concepts and applications (communications among vehicles or between vehicles and road infrastructures), where reliability and low latency are extremely important. For example, the Vehicle Infrastructure Integration (VII) initiative in the United States proposes that the information about an accident should be communicated through VANET within half a second to all equipped vehicles in a 500 m range.

In terms of MAC operations, WAVE uses CSMA/CA as the basic medium access scheme for link sharing and should probably use one control channel to set up transmissions, which then should be done over some transmission channels.

At the PHY layer, 802.11p should work in the 5.850–5.925 GHz spectrum in North America, which is a licensed ITS Radio Services Band in the United States. By using the OFDM system, it provides both vehicle to vehicle and vehicle to infrastructure wireless communications over distances up to 1000 m, while taking into account the environment, that is, absolute and relative high velocities (up to 200 km/h), fast multipath fading and different scenarios (rural, highway, and city). Operating in 10 MHz channels, it should allow a data payload communication capabilities of 3, 4.5, 6, 9, 12, 18, 24, and 27 Mb/s. And using the optional 20 MHz channels, it allows data payload capabilities up to 54 Mb/s.

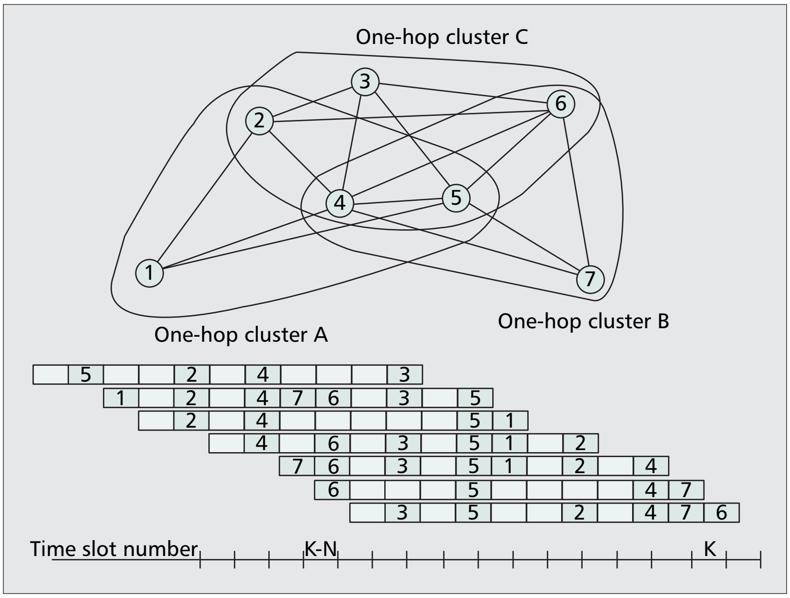
ADHOC MAC

ADHOC MAC [4] is a MAC protocol conceived within the European project CarTALK2000 (FleetNET has been the follow-up) with the purpose to design novel solutions for VANETs.

ADHOC MAC works in a slotted frame structure, but independently from the physical layer, and it uses a dynamic TDMA mechanism that can be easily adapted to the UMTS Terrestrial Radio Access Time Division Duplex (UTRA-TDD), which was chosen as physical target system in the CarTALK2000 project.

The Reliable R-ALOHA (RR-ALOHA) protocol [4], which is used in ADHOC MAC, was proposed by extending the Reservation ALOHA (R-ALOHA) [5] to achieve the Dynamic TDMA mechanism in a distributed way, where each active vehicle needs to select for itself one basic channel (BCH), which is one time slot periodically repeated in successive frames. Furthermore, each vehicle has to have a global view of the transmissions in a two-hop neighborhood to overcome the hidden terminal problem. For that, in RR-ALOHA each vehicle sends on its BCH its frame information (FI), which is a vector with *N* entries that indicate how were sensed the status of the previous *N* time slots in the previous frame.

In detail, the medium is divided into several repeated time frames. Each frame is divided into *N* time slots. And each vehicle has to get one time slot as its BCH. During each frame time, all vehicles listen to their neighborhood transmission, and when hearing a successful transmission from some vehicles on some time slots, they mark in their FIs the corresponding entries with the corresponding transmitter vehicles ID. Each vehicle sends its FI every time frame on its BCH. All the time slots that correspond to the marked entries in an FI are considered reserved and busy. When a new vehicle comes, it listens during one time frame before attempting to transmit on one selected free time slot. Then, if in the next time frame the corresponding time slot is marked by its ID in the whole received FIs, it means that this time slot is reserved for it in the two-hop neighborhood, and it can consider it as its BCH.



■ **Figure 3.** *The FIs propagation in RR-ALOHA.*

As an example, terminal 1 in Fig. 3, by receiving the FI-2, FI-4, and FI-5 from terminals 2, 4, and 5, respectively, determines the time slot used by those direct neighbors which correspond to the exact time slots on which they sent their FIs. Then, by reading the received FIs, terminal 1 determines the time slots used by terminals 3, 6, and 7, which are two-hop neighbors.

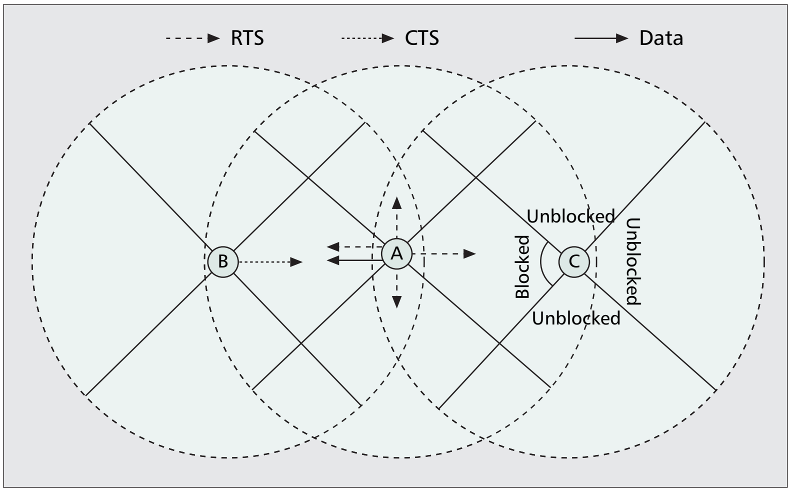
The periodic propagation of the FI lets terminals know the entire ongoing transmissions in a two-hop neighborhood, which allows RR-ALOHA to easily overcome the hidden terminal problem, and thus reduce transmission collisions. And, by using the TDMA mechanism with the possibility to reserve one time slot in periodic repeated time frames for transmissions, RR-ALOHA can guarantee a relatively good QoS in VANETs.

Directional Antenna-Based MAC Protocols

With a directional antenna, terminals can transmit in a specific direction. Generally, when using that technology, the transmission space around a terminal is divided into *N* transmission angles of (360/*N*) degrees. The main advantage when using this approach is reducing transmission collisions, as well as increasing the channel reuse possibility.

Directional antenna transmission has a promising place in VANETs, in particular, for MAC issues. In VANETs, the nodes' movements are limited by roads and driving rules (e.g., opposite driving directions on the same road), so directional antennas would surely help in reducing interference and collisions with transmissions ongoing over parallel neighboring vehicular traffic.

Two directional antenna-based MAC protocols have been proposed, as described in [6, 7].



■ **Figure 4.** *The D-MAC process.*

In [8], the Directional MAC (D-MAC) protocol is proposed. It requires that each terminal knows its geographic position and those of its neighbors, which is easily done in VANETs by using positioning systems like GPS or Galileo. In D-MAC, based on IEEE 802.11, a sender initiates a handshake before transmitting based on RTS, CTS, and ACK packets transmission. The RTS is sent on directional or omnidirectional according to the ongoing transmissions in the neighborhood. A directional antenna that receives an RTS or a CTS becomes blocked and does not transmit during the neighbor's transmission time indicated in RTS or CTS. Suppose to have three terminals, A, B, and C, as shown in Fig. 4, where A is in the transmission range of both B and C, and B and C are outside the transmission range of each other. When A wants to transmit to B, and all its directional antennas are unblocked, it sends an omnidirectional RTS to B. When receiving this RTS, C blocks the antenna, on which it received the RTS, for the whole ongoing transmission duration time. Thus C avoids sending an RTS to A when B is transmitting.

By using directional antennas, transmission collisions can be reduced, and channel transmission reuse can be increased. They can theoretically improve the performances of the existing MAC protocols, in particular for VANETs, but unfortunately, directional antenna systems still seem too complex and hard to manage in real implementations.

Qualitative Comparison of VANET MAC Protocols

Based on CSMA/CA and the interframe spacing system, the 802.11 MAC standard can overcome the hidden terminal problem in VANETs. But unfortunately, while waiting for the new IEEE 802.11p version, throughput decreases quickly in loaded and/or large networks. And because of the CSMA/CA mechanism, 802.11 cannot guarantee a deterministic upper bound on the channel access delay, which makes 802.11 not suitable for real-time traffic.

ADHOC MAC, which was adapted for VANETs, is based on a slotted frame structure which allows for a reliable one-hop broadcast service, easily avoiding the hidden terminal problem and guaranteeing a relatively good QoS, which is important for real-time traffic. It works independently from the physical layer, and can be used over the 802.11 physical layer by providing a frame structure. Relative to the IEEE 802.11 standard, the main disadvantage of ADHOC-MAC is that the medium is not used efficiently, and the number of vehicles in the same communication coverage must be not greater than the number of the time slots in the frame time.

Table 1 shows a brief comparison between the IEEE 802.11 and ADHOC MAC protocols. The goal here is not to determine the better MAC protocol in all environments (urban, suburban, highway, etc.), since these two MAC protocols both appear to be interesting for VANETs; for example, IEEE 802.11 will handle high mobility better and does not need time synchronization, while ADHOC MAC should allow higher reliability, QoS, and real-time compatibility. So, we believe that a combination of the IEEE 802.11 standard and ADHOC MAC can provide a good and more complete solution for VANETs.

Many research results [9, 10] show that using directional-antenna-based MAC mechanisms can improve the network throughput by decreasing the transmission collisions and increasing the medium reuse possibilities. But inexpensive implementations of practical directional antenna systems are missing, which consequently makes it difficult to test and validate real directional communications over VANETs and prove these potential benefits.

Conclusions

In this article we have reviewed the main MAC protocols for mobile ad hoc networks (MANETs), so that readers will better understand their challenges and their processes. Then we focused on MAC protocols that are designed or adapted for vehicular MANETs, giving a qualitative comparison of them. One is the IEEE 802.11 protocol, based on CSMA/CA and interframes spaces, implemented in both the 802.11b and 802.11g standards, which are used by many VANETs research teams in their simulations and prototype designs. A promising amendment of the 802.11 standard is ongoing; it focuses on vehicular environments and will be referred to as 802.11p or the WAVE version. Another protocol is the ADHOC MAC, which is RR-ALOHA based and working in a slotted time structure. We also introduced MAC protocols based on directional antennas, with their potential performance benefits for VANETs despite their implementation complexity.

In spite of the big ongoing academic and industrial research efforts on VANETs, the proposed solutions allow VANETs to work well only in some limited scenarios (e.g., with low network load and not with high mobility). Reliable solutions able to guarantee truly efficient and collision-free transmissions for Active Safety VANET applications are not yet proposed.

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	802.11 (MAC layer)	ADHOC MAC
Based on	CSMA/CA	RR-ALOHA
Implementation maturity	Mature and evolving	Medium
QoS and real-time capability	Small	Medium
Mobility	Medium evolving to high	Medium
Reliability multicast/broadcast	No	Yes
Time synchronization	Not needed	Mandatory

Table 1. *802.11 vs. ADHOC MAC protocols.*

Biographies

HAMID MENOUAR (menouar@ieee.org) received a computer science engineering degree from USTHB University, Algeria, in 2003. In 2004 he received a D.E.A. degree in systems and information technologies from UTC University, Compiegne, France. In 2004 he held an internship for six months at the LiP6 Laboratory, Paris, France, where he worked on user location in wireless mobile networks. Since February 2005 he is doing a Ph.D degree as an ENST student at EURECOM in cooperation with Hitachi Europe R&D, Sophia Antipolis, France, where he is working as a research engineer. His major research interests include MANETs, VANETs, and MAC, routing, and cross-layers.

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