A Novel MAC Protocol for Throughput Sensitive Applications in Vehicular Environments

Yunpeng Zang, Lothar Stibor, Bernhard Walke, Hans-Jürgen Reumerman and Andre Barroso

***Abstract*—The current Medium Access Control (MAC) protocol of the Wireless Access in Vehicular Environments (WAVE) system is based on IEEE 802.11 Distributed Coordination Function (DCF) and Enhanced Distributed Channel Access (EDCA), which have drawbacks in supporting throughput-sensitive applications in high density networks, e.g. future Vehicular Ad-hoc Networks (VANET). In order to address the problem, we propose a novel MAC protocol, namely Vehicular MESH Network (VMESH), which is specifically designed for the Control Channel (CCH) and multiple Service Channels (SCHs) architecture of WAVE system. A synchronized and distributed beaconing scheme is employed by the VMESH protocol for the purposes of neighborhood awareness and dynamic channel resource reservation. In this paper, we present the advantage of VMESH protocol under saturated traffic load condition through theoretical analysis. For more realistic scenarios with mobility and unsaturated traffic loads, through the simulative study, we can also show that the VMESH protocol outperforms the WAVE protocol when the traffic load is heavy.**

***Index Terms*—VANET, WAVE, Inter-vehicle communications (IVC), MAC, DCF, EDCA, VMESH, Distributed Reservation Protocol (DRP)**

I. Introduction

One of the major goals of the Intelligent Transportation Systems (ITS) is to enhance driving safety and comfort of automotive users with the help of Inter-Vehicle Communications (IVC) and Vehicle-to-Roadside Communications (VRC). The WAVE system, which is based on the IEEE 802.11 Wireless Local Area Network (WLAN) technology, has been widely accepted as the basis of IVC and VRC because of its ability of providing broadband low latency wireless communication in middle to short distance.

In year 1999, the Federal Communications Commission (FCC) of the U.S. approved 75MHz bandwidth at 5.850-5.925GHz frequency band for ITS wireless communications between vehicles and roadside infrastructures. As shown in Figure 1, the overall bandwidth is divided into seven frequency channels. One of the seven frequency channel is assigned as the CCH, i.e. CH 178, which can only be used by safety relevant applications and for system control and management purposes. The other six channels are SCHs, mainly supporting the non-safety relevant applications.

Generally, applications in VANET fall into two categories, namely safety applications and non-safety applications. Safety applications, providing drivers information about critical situations in advance, have strict requirements on communication reliability and delay. On the other hand, non-safety applications meant for improving driving comfort and the efficiency of transportation system are more bandwidth-sensitive. Typical non-safety applications are on board internet access, electronic map update, driving through payment, and so on. [1]

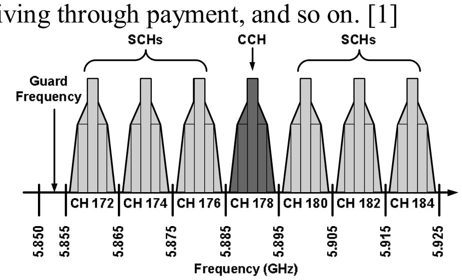

Figure 1. Frequency channel layout of 5.9GHz WAVE system

Unlike data services in other wireless ad-hoc networks, owing to the high mobility of vehicles and the specific architecture of roadside infrastructure non-safety applications in vehicular environments have following unique service patterns:

1. Most of current non-safety applications in vehicular environment rely on VRC, i.e. communications between On-Board Units (OBUs) and Roadside Units (RSUs) and some of them demand high data rate wireless links, e.g., electronic map update.
2. Due to the high mobility of vehicles and the limited communication range of the RSU, the duration that an OBU can communicate with a certain RSU is very limited.
3. Due to the cost reason, a seamless coverage of RSUs on the highway can not be expected. Therefore, no real-time or delay sensitive applications, e.g. Voice over IP (VoIP), can be supported via VRC.

All these patterns determine that the MAC protocol of WAVE has to be very efficient to support the throughput-sensitive services among RSU and OBUs, especially when one RSU is shared by multiple OBUs. By noticing the drawbacks of Distrib-

Y. Zang, L. Stibor and B. Walke are with the Chair of Communication Networks, RWTH Aachen University, 52074 Aachen, Germany (e-mail: zyp|lsr|walke@comnets.rwth-aachen.de).

H.-J. Raumerman and A. Barroso are with Philips Research Aachen, 52066 Aachen, Germany (e-mail: hans-j.reumerman@philips.com, andre.barroso@philips.com).

uted Coordination Function (DCF), which is the basis of the current WAVE MAC, in supporting the throughput-sensitive applications, we propose a novel MAC protocol, namely Vehicular MESH Network (VMESH), for the WAVE system. The VMESH protocol is developed within the context of the Wireless Local Danger Warning (WILLWARN) application of the European Research project PREVENT [7]. It is specifically designed for the multi-channel architecture of WAVE system. Besides, it can provide better Quality of Service (QoS) for non-safety applications through neighborhood awareness and contention-free channel access on SCHs.

The rest part of this paper is organized as follows: The multi-channel operation in WAVE is first reviewed in section II. For the purpose of comparison, in section III, we briefly go through the current WAVE MAC protocol, which is followed by the description of the proposed VMESH protocol in section IV. Theoretical analyses of both protocols under the saturated traffic load condition are presented in section V. Simulative results for more realistic highway scenarios under unsaturated traffic loads are given and discussed in Section VI. Section VII concludes this paper and gives some outlooks on the future work.

II. Multi-Channel Operation in WAVE

To solve the multi-channel coordination problem, a globally synchronized channel coordination scheme based on the Coordinated Universal Time (UTC)[1] was developed in IEEE P1609.4 [2] for the WAVE system. As show in Figure 2, the channel time is divided into synchronization intervals with a fixed length of 100ms, consisting of a CCH interval and a SCH interval, each of 50ms. According to the scheme all devices have to tune to CCH during all CCH intervals, where high priority frames, e.g. danger warning messages, are transmitted. During SCH intervals, devices can optionally switch to SCHs, which are used for non-safety applications. This scheme allows a WAVE device to perform non-safety applications on SCHs without missing important messages on CCH.

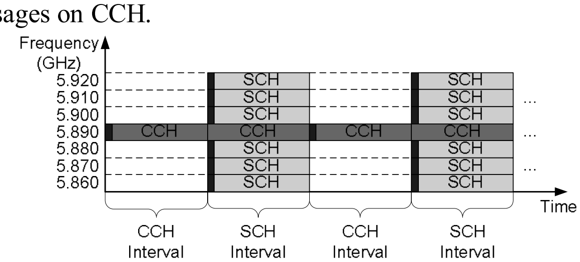

Figure 2. Multi-channel cooperation in WAVE

III. IEEE P1609.4/IEEE 802.11p MAC Protocol

For the purpose of comparison, in this section we shortly review the current WAVE MAC protocol. The basic MAC and MAC extension layers of WAVE are standardized in IEEE 802.11p and IEEE P1609.4, respectively. The basic MAC is the same as the well known IEEE 802.11 DCF and the MAC extension layer adopts some concepts from Enhanced Distributed Channel Access (EDCA) of 802.11e, like Access Category (AC) and Arbitrary Inter-Frame Space (AIFS) for priority differentiation. The channel access process is illustrated in Figure 3, where DCF/EDCA channel access mechanisms are applied to both CCH and SCHs in context of the multi-channel coordination.

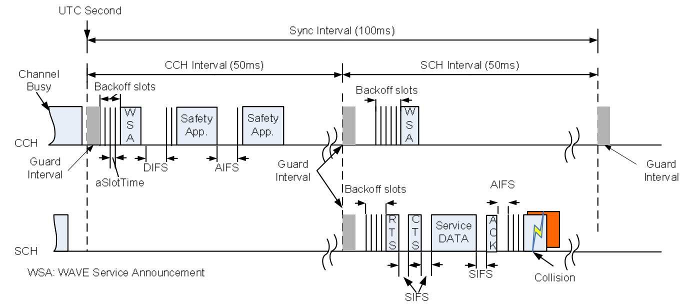

Figure 3. Channel access process of IEEE P1609.4/IEEE 802.11p MAC

As a contention based mechanism, the current WAVE MAC is intuitively questioned on its ability of supporting the throughput-sensitive applications, especially in densely populated scenarios. As we will show in section V the performance of the current WAVE MAC indeed needs improvement.

IV. VMESH MAC Protocol

The novel VMESH protocol, as introduced in [6], is compliant with the multi-channel operation scheme of the WAVE system. In comparison with the current WAVE MAC, four new attributes are introduced in the novel VMESH protocol.

A. *VMESH superframe structure*

On top of the WAVE synchronization interval we define the concept of VMESH superframe, which contains multiple 1609 synchronization intervals. As show in Figure 4, ten consecutive synchronization intervals started at the beginning of each UTC second form a VMESH superframe.

B. *Beacon period and safety period in each CCH interval*

In the VMESH MAC the CCH interval is further divided into two parts, namely the Beacon Period (BP) and the Safety Period (SP). The BP, consisting of a number of beacon slots, is designed for a synchronized distributed beaconing protocol, as being described in the next subsection. And the SP is exclusively reserved for the safety applications, which use the EDCA rules for channel accesses, as depicted in Figure 4.

C. *Distributed VMESH beaconing scheme*

The key asset of the VMESH MAC is the synchronized and distributed beaconing scheme. According to the protocol, each

[1] Synchronization to UTC is assumed to be achievable through the time synchronization function of Global Positioning System (GPS).

device has to choose a unique beacon slot in the BP, and transmits its beacon in every CCH interval. The access to beacon slots is ruled by the Reservation-ALOHA (R-ALOHA) protocol [3]. Usually, a beacon carries (1) the local information of the transmitter, e.g. MAC ID and GPS position data; (2) the BP occupancy status detected by the transmitter in the last BP, for beacon collision resolution and neighborhood awareness; (3) Distributed Reservation Protocol (DRP) information for the collision free access to SCHs. The distributed beaconing scheme establishes a signaling channel for making dynamic resource reservation on SCHs, which is meant to improve the performance of the throughout-sensitive applications in VANET.

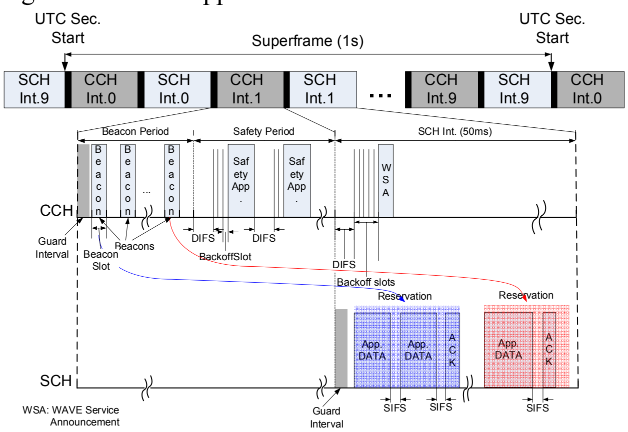

Figure 4. Channel access process of VMESH MAC

D. Distributed Reservation Protocol (DRP) for SCH access

VMESH devices follow a reservation based Time Divided Multiple Access (TDMA) for utilizing SCHs. A device can transmit its packets without sensing the channel state in its channel time reservation, as shown in Figure 4. The channel time reservation is performed by the DRP, which utilizes the distributed beaconing scheme to negotiate the channel resource reservation among the transmitter, the receiver(s) and neighboring vehicles [6].

Owing to the four major attributes, the VMESH protocol has following advantages in vehicular communications:

1. The distributed beaconing scheme enables neighborhood awareness of each vehicle, which is important for other protocols, e.g. message routing in VANET.
2. Assigned with specific beacon slots, the RSUs can efficiently coordinate the channel access within its range.
3. The separated Beacon Period and Safety Period in CCH interval eliminate the interference between the management packets and the high priority safety packets.
4. The DRP protocol enables the contention free channel access on SCHs, which is important for the throughput-sensitive applications.

In the following two sections, we compare the performance of the proposed VMESH MAC with the current WAVE MAC in terms of the supports on throughput-sensitive applications through the theoretical analyses and simulative studies.

V. Performance Comparison with Numerical Results

In order to have valid analytical models for both protocols, the following assumptions are made for this study. (1) The underlying channel is ideal and has no transmission error. Packet error occurs only when two packets collide. (2) No hidden station exists in the scenarios, i.e. all stations are within the communication range of each other. (3) The impact from mobility of devices on the packet transmission is ignorable. (4) The system is in a saturated and stable state, i.e. each device always has packet to transmit. We calculate and compare the saturation throughput reached by each protocol on a single SCH.

Both MAC protocols work on the IEEE 802.11p physical layer and utilize the IEEE 802.11 MAC frame structure. The PHY and MAC relevant parameters used in our analyses are listed in Table 1.[4]

Table 1
PHY&MAC Relevant Parameters

Parameter	Value
OFDM symbol duration	8 µs
PLCL preamble length	32 µs
PLCP header length	8 µs
pSlotTime	16 µs
pSIFS	32 µs
pDIFS	64 µs
MAC frame header size	30 B
ACK/CTS frame header size	10 B

A. Theoretical analysis of IEEE P1609.4/802.11p MAC

The analytical model developed by G. Bianchi [5] for IEEE 802.11 DCF is adopted here for revealing the maximum saturation throughput of the current WAVE MAC protocol on SCH.

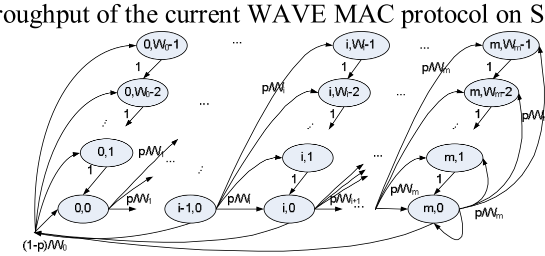

Figure 5. Bidimensional Morkov chain model for DCF backoff

According to the Bianchi mode, the behavior of the DCF backoff entity at each device can be modeled by a bidimensional Markovian model, as shown in Figure 5. The transitions in this discrete-time Markov chain take place at each DCF slot time.

p is the probability of a packet being collided, conditioned on the probability it is transmitted. In this analysis, the *p* value is assumed to be constant and independent. *n* is the number of devices in the scenario. $W=W_0$ denotes the minimum contention window size and $W_m=2^mW$ is the maximum contention window size with *m* being the maximum backoff stage. By solving the Markovian model, we can get the following nonlinear system, which has the unique solution for τ and *p*, in $\tau \in (0,1)$ and $p \in (0,1)$. τ is the probability that a device will transmit a packet at an arbitrarily chosen slot time.

$$\begin{cases} \tau = \dfrac{2}{1+W+pW\sum_{i=0}^{m-1}(2\cdot p)^i} \\ p = 1-(1-\tau)^{n-1} \end{cases}$$

The probability of at least one device transmits at the considered slot is expressed as $P_{tr} = 1-(1-\tau)^n$. And we can calculate the probability a transmission is successful, i.e., no collision happens in the considered slot time:

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{P_{tr}}$$

Based on the assumption of stationary system state, the saturation throughout of DCF MAC is given by

$$S_{1609} = \frac{1}{2}\cdot\frac{P_s P_{tr} E[PacketSize]}{(1-P_{tr})pSlotTime + P_{tr}P_sT_s + P_{tr}(1-P_s)T_c} \quad (1)$$

The factor of ½ in (1) is introduced because SCH takes only half of the channel time. The numerator of the second part represents the average amount of information successfully transmitted in one transmission, given the average packet load size. The denominator of the second part counts for the average length of a slot containing transmission and consists of the average time a slot being empty (pSlotTime), the average time used for successful transmission (T_s) and the average time wasted by a packet collision (T_c). Figure 6 shows the T_s and T_c based on the IEEE 802.11p specification for the cases with and without RTS/CTS scheme.

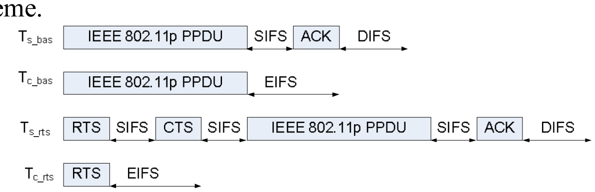

Figure 6. Slot length of successful transmission and collision, with and without RTS/CTS

Figure 7 shows the saturation throughput of IEEE 802.11p DCF MAC with respect to the number of station in the scenario and the packet size. To simplify the calculation we assume a fixed packet size for all devices. The values of W and m are taken from IEEE 1609.4 for the Access Category 3 (AC3) W=4, m=2. From the result, serious degradation on the saturation throughput is observed when the number of neighbor *n* increases and the packet size decreases.

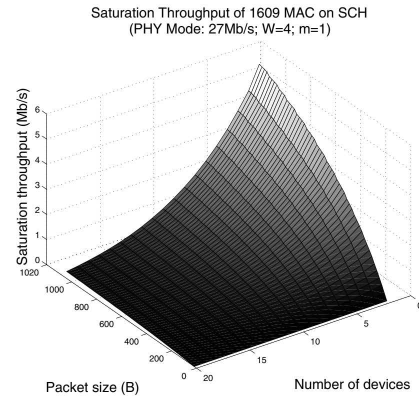

Figure 7.Saturation throughput of 1609 on SCH

B. *Throughput calculation of VMESH MAC*

Based on the assumptions given at the beginning of this section, the channel resource on SCHs can be reserved by devices following the DRP protocol. The reservation is done through beaconing on CCH and no signaling overhead introduced to SCHs. The saturation throughput of VMESH MAC on SCH can be easily calculated by dividing the amount of information successfully transmitted in one DRP reservation by the duration of the DRP reservation length:

$$S_{VMESH} = \frac{InformationDeliveredInOne\mathrm{Re}servation}{\mathrm{Re}servationLenght} \quad (2)$$

The DRP transmission process is illustrated in Figure 4, and (2) can be written as (3), where N_p is the maximum number of packet can be transmitted in a reservation, given the reservation length T_{res}.

$$S_{VMESH} = \frac{N_p \cdot E[PacketSize]}{T_{res}} \quad (3)$$

Figure 8 shows the calculated maximum throughput of VMESH on SCH vs. the packet size.

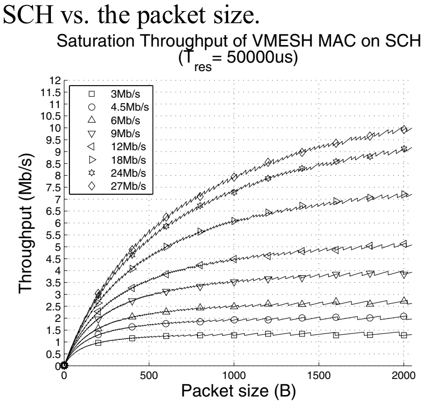

Figure 8. Saturation throughput of VMESH MAC on SCH

C. *Performance comparison and discussion*

Figure 9 compares the reachable throughput on SCH with respect to the number of device in the scenario by the current

WAVE MAC and the proposed VMESH MAC. It can be seen that the throughput of VMESH MAC performs 18% better than that of the current WAVE MAC. Besides, the performance of the WAVE MAC decreases with the increasing number of devices, while the performance of VMESH MAC keeps constant, because the VMESH MAC use the "outband" signaling for coordinating channel access. The curve of the current WAVE MAC with RTS/CTS enabled and with the optimized contention window size, i.e., W=15, m=6, performs also independently from the number of devices. However, due to the additional RTC/CTS overhead and more backoff slots, the overall throughput value is severely lower than the one from VMESH.

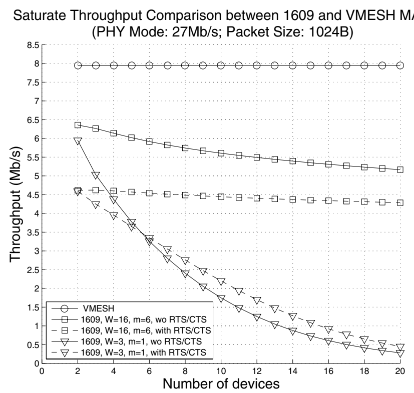

Figure 9. Comparison between IEEE P1609/IEEE 802.11p MAC and VMESH MAC regarding the reachable system throughput on SCH

VI. Simulative Studies with Non-Saturated Traffic Load in Highway Scenarios

In this section we release all the assumptions used in the theoretical analyses above, and present the performances of both protocol in realistic highway scenarios with non-saturate traffic load conditions using stochastic simulation with the WARP2 simulation environment [8].

A scenario is setup to simulate 50 vehicles driving towards the same direction on two lanes with the inter-vehicle distance of 60m. 15 of them have OBUs equipped and are able to communicate with two RSUs located 500m away from each other. Both OBUs and RSUs have transmission power level of 100mW and use 16QAM1/2 PHY mode (12Mb/s). All protocol parameters used in this simulation are the same as in the previous section.

The throughput and delay performances of uplinks, i.e. from OBUs to RSUs when OBUs and RSUs are in communication range of each other, are shown in Figure 10 for both protocols. It can be seen that under low traffic load, the throughput achieved by both protocols are quite similar, while the delay performance of WAVE is superior over that of VMESH. This is because under light traffic conditions, the probability of having collision in WAVE MAC is relatively low. However, along with the increasing traffic load, the VMESH protocol outperforms the WAVE protocol in terms of both throughput and delay. The results illustrate the benefit of collision free access protocol in guaranteeing the stable throughput as well as the bounded packet delay.

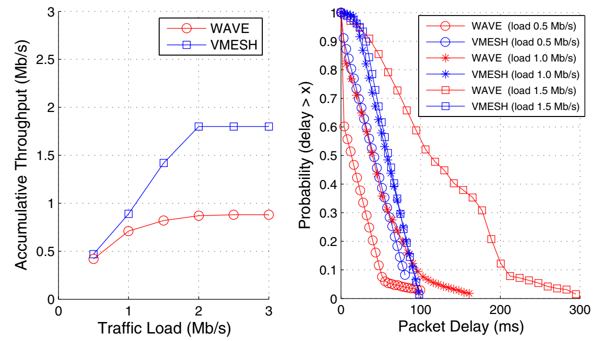

Figure 10. Simulation results of WAVE and VMESH in highway scenarios

VII. Conclusions & Outlooks

In this paper, we propose a novel VMESH MAC protocol for enhancing the performance of non-safety applications in vehicular environments based the WAVE infrastructure. The proposed MAC protocol makes use of a distributed beaconing scheme and a reservation based channel access (DRP) on SCH to improve the channel usage efficiency. Theoretical analysis and simulative studies show that the novel protocol has advantages over the current WAVE MAC in terms of system throughout. In the next step, we will investigate the performance optimization of the VMESH MAC protocol using topology information obtained via beaconing.

References

[1] Vehicle Safety Communications Project, Task 3 Final Report, Identify Intelligent Vehicle Safety Applications, National Highway Traffic Safety Administration, 2005

[2] IEEE P1609.4, Wireless Access in Vehicular Environments (WAVE) Multi-Channel Operation, Draft Standard, D06, Nov. 2005

[3] Lam, S.S., Packet Broadcast Networks -- A Performance Analysis of the R-ALOHA Protocol, IEEE Trans. on Computers, vol.C-29, no.7, July 1980, pp.596-603

[4] *IEEE Standard for Information technology –Part 11: Wireless Medium Access Control (MAC) and Physical Layer (PHY) specifications: Amendment 3: Wireless Access in Vehicular Environments (WAVE)*, IEEE Draft Amendment P802.11p/D1.0, Feb. 2006

[5] G. Bianchi, Performance Analysis of the IEEE 802.11 Distributed Coordination Function, IEEE JSAC, vol. 18, no.3, March 2000

[6] Y. Zang, L. Stibor, B. Walke, H.-J. Reumerman and A. Barroso, Towards Broadband Vehicular Ad-Hoc Networks – The Vehicular Mesh Network (VMESH) MAC Protocol, to be appeared on Proceeding of IEEE Wireless Communications and Networking Conference, March, 2007, Hong Kong

[7] PREVENT: Preventive and active safety; 6th Framework program integrated project http://www.prevent-ip.org/

[8] Y. Zang, L. Stibor, G. Orfanos, S. Guo, and H.-J. Reumerman, An Error Model for Inter-Vehicle Communications in Highway Scenarios at 5.9GHz, In Proceedings of PE-WASUN 2005, p.p. 49-56, Montreal, Quebec, Canada