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Towards Broadband Vehicular Ad-Hoc Networks - The Vehicular Mesh Network (VMESH) MAC Protocol

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***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 non-safety applications in Vehicular Ad-hoc Network (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) structure of WAVE. A synchronized and distributed beaconing scheme is employed in the VMESH protocol for the purposes of neighborhood awareness and dynamic resource reservation on SCHs. The advantages of the VMESH protocol in supporting the throughput-sensitive non-safety applications in VANET are shown through the theoretical analysis comparing to the current WAVE MAC.**

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 Communication (IVC) and Vehicle-to-Roadside Communication (VRC). The WAVE system, which is based on the IEEE 802.11 Wireless Local Area Network (WLAN) technology and currently being standardized by IEEE P1609 and IEEE 802.11p, has been widely accepted as the basis of IVC and VRC owing to 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 system control and management with high priorities. The other six channels are used as 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. Examples of safety applications are inter-vehicle danger warning, intersection collision avoidance, work zone safety warning, etc. On the other hand, non-safety applications meant for improving driving comfort and the efficiency of transportation system are more bandwidth-sensitive instead of delay-sensitive. Typical non-safety applications are on board internet access, high data rate content download (electronic map download/update), driving through payment, and so on. [1]

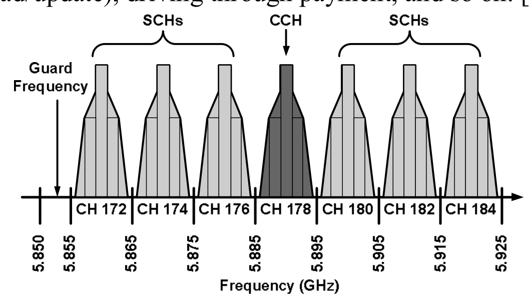

Figure 1. Frequency channel layout of 5.9GHz WAVE system

Unlike data services in other wireless ad-hoc networks, non-safety applications in vehicular environments have different service patterns because of the impacts from high mobility of vehicles and the deployment of roadside infrastructure, as summarized in the follows:

1. Currently, most 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 download from road side infrastructures.
2. Due to the high moving speed of vehicles and the limited communication range of the RSU, the duration that an OBU can communicate with a certain RSU is very limited. Given the vehicle speed of 120km/h and the communication range of 300m, the communication duration between the OBU and a RSU is about 18s. The limited communication duration decides that the MAC protocol of WAVE has to be very throughput efficient, especially when a single RSU is shared by multiple OBUs.
3. Considering the cost, a seamless coverage on the highway by the RSUs can not be expected. Thus, no real-time or delay sensitive applications, e.g. Voice over IP (VoIP), can be supported by VRC. As a result, non-safety applications in vehicular environments are more throughput and bandwidth sensitive, instead of delay sensitive.

The contention based DCF from IEEE 802.11 is the basis of the current WAVE MAC protocol. By noticing the drawbacks of DCF in supporting the throughput-sensitive non-safety applications in vehicular environments, we propose a novel MAC protocol for WAVE, namely Vehicular MESH Network (VMESH). The VMESH protocol is developed within the context of the Wireless Local Danger Warning (WILLWARN) application of the European Research project PREVENT [6]. The VMESH protocol 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: As the context of WAVE MAC protocol, the multi-channel operation in WAVE is first introduced in section II. For the purpose of comparison, in section III, we briefly review the current WAVE MAC protocol, which is followed by the detailed description on the proposed VMESH protocol in section IV. Theoretical analysis and comparison between the current WAVE MAC and the novel VMESH protocol regarding their performances on non-safety applications are presented in section V. Section VI concludes this paper and gives some outlooks on the future work.

II. MULTI-CHANNEL OPERATION IN WAVE

In WAVE the most challenging issue for a single radio device is how to efficiently coordinate the channel access to the CCH and multiple SCHs. To solve this problem, a globally synchronized channel coordination scheme based on the Coordinated Universal Time (UTC)[1] was developed in IEEE P1609.4 [2]. 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 and management frames, 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. It has to be noticed that the channel coordination scheme is facilitated by the accurate global time synchronization, which is exactly the point that leads us to seek for a more efficient MAC protocol for WAVE, as we will address in section IV.

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

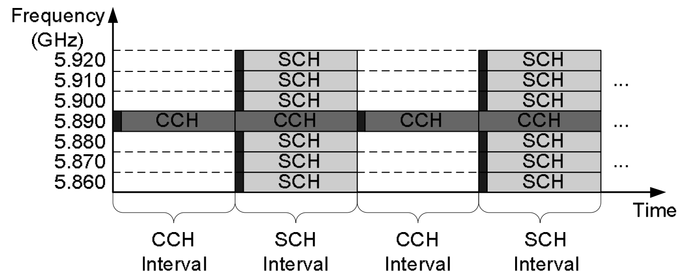

Figure 2. Multi-channel cooperation in WAVE

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 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.

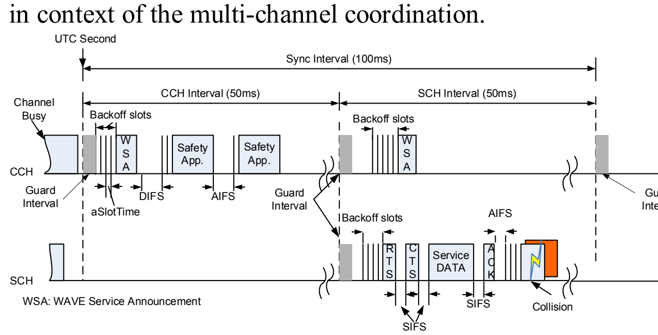

Figure 3. Channel access process of IEEE P1609.4/IEEE 802.11p MAC

DCF is based on CSMA/CA, according to which each station determines individually when to access the medium. Collision Avoidance (AC) scheme based on a random backoff procedure is applied for reducing the probability of collision. To reduce the hidden station problem, a Request-To-Send/Clear-To-Send (RTS/CTS) mechanism combining with the Network Allocation Vector (NAV) is used. The EDCA specified in IEEE 802.11e standard is meant for the distributed QoS support in IEEE 802.11 WLAN. By mapping the traffic of different priorities to different virtual stations and assigning different channel access parameters to each virtual station, EDCA can statistically differentiate multiple levels of QoS.

As a contention based mechanism, the current WAVE MAC is intuitively questioned on its ability of supporting the throughput sensitive applications, especially in a densely populated scenario. 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 is compliant with the multi-channel operation scheme defined in IEEE P1609.4. Four new attributes are introduced in the novel VMESH protocol in comparison with the current WAVE MAC.

A. VMESH superframe structure

On top of the synchronization interval specified in IEEE 1609.4 for multi-channel operation 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 VMESH MAC the CCH interval defined in IEEE 1609.4 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, which will be described in the next subsection. And the SP is exclusively reserved for the safety applications. In SP, the devices have to follow the EDCA rule for transmitting their messages, as depicted in Figure 4.

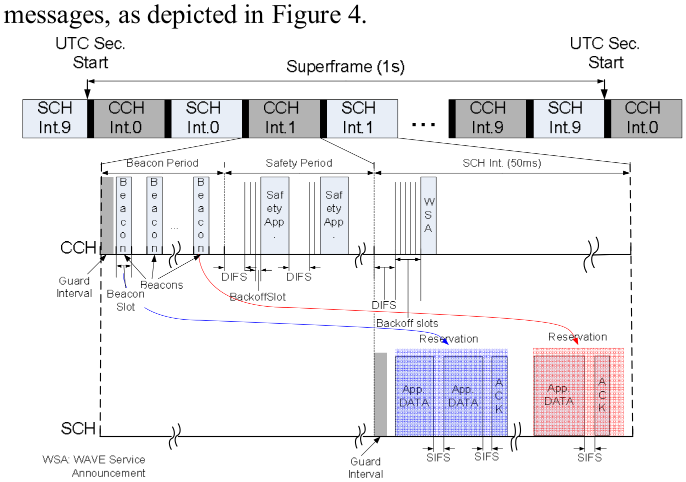

Figure 4. Channel access process of VMESH MAC

C. Distributed VMESH beaconing scheme

The key asset of the VMESH MAC is the synchronized and distributed beaconing scheme. According to the protocol, each 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], which can guarantee a relatively low beacon collision probability. The information carried by beacons includes:

- Local information of the transmitter, e.g. MAC ID, beacon slot number and GPS position data, etc.
- BP occupancy status viewed by the transmitter in the last BP, i.e., its one-hop neighbor map.
- DRP information for the collision free access to SCHs.

With the distributed beaconing algorithm, each device can get the instant topology of its neighborhood, exchange information with its direct neighbors and learn the information about the neighbors' neighbors. More important, 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 non-safety applications.

D. Distributed Reservation Protocol (DRP) for SCH access

In stead of contention based 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. The work flow of DRP is described as follows:

- Upon receiving the beacon from a service provider, usually a RSU, the device initiates its reservation request based on the traffic load and the current SCH occupancy information it learned from its neighbor's beacons.
- The reservation request is broadcasted within the next beacon from the initiator. The reservation request contains the information of communication partner ID and the channel resource requirement, e.g. the SCH ID, the SCH interval ID(s) in a superframe and the starting time and the duration of the reservation.
- On the reception of the reservation request the intended communication partner, i.e. the service provider, checks the availability of the proposed reservation. In case a collision is detected, a revised channel resource proposal or a rejection indication is fed back to the initiator within its next beacon for another round of DRP negotiation. Otherwise, a DRP Information Element (IE), describing this reservation is included into the beacons of both the service provider and the service user, in order to inform all their neighbors about the upcoming transmission.
- At the reserved time, both service user and the service provider switch to the booked SCH and exchange the data.
- As long as the reservation is valid, its DRP IE has to be enclosed in the beacons of the service provider and the service user for the purpose of indicating the channel usage and prevent the hidden station problem.
- The channel resource is released by removing the DRP IE from the beacons of communication partners, e.g., when the service provider and service user are

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out range of each other due to the mobility reason.

As specified above, DRP is designed for service providers and service users to establish collision free channel usage on SCHs. The DRP may be used as well for vehicle-to-vehicle applications, as long as some of the vehicles can play the role of service provider.

Owing to the four major attributes, the VMESH protocol has advantages in vehicular communications, which can be summarized as follows:

1. The distributed beaconing scheme enables neighborhood awareness at each device, which is important for other applications, 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 section, we will theoretically compare the performance of the current WAVE MAC and the proposed VMESH MAC in supporting the throughput-sensitive applications in vehicular environments.

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, because the duration we analyze is short enough, i.e., SCH interval (50ms). (4) The system is in a saturated and stable state, i.e. every device always has packet to transmit. We calculate and compare the saturation throughput reached by each protocol on a single SCH.

Both MAC protocols equally work on the IEEE 802.11p physical layer and utilize the IEEE 802.11 MAC frame structure. All PHY and MAC relevant parameters used in our calculations 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
RTS frame header size	16 B
Frame Check Sequence size	4 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 discovering the maximum saturation throughput of the current WAVE MAC protocol on SCH.

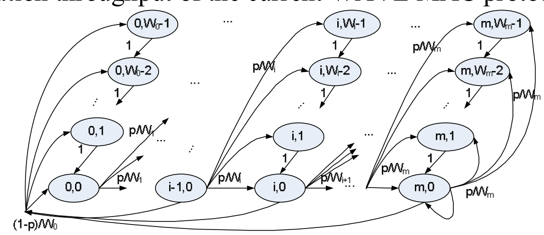

Figure 5. Bidimensional Morkov chain model for DCF backoff

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.

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

The probability of at least one device transmits at the considered slot is expressed as:

$$P_{tr} = 1-(1-\tau)^n \tag{2}$$

And we can calculate the probability a transmission is successful, i.e., no collision happens in the considered slot time:

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{P_{tr}} \tag{3}$$

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

$$S_{1609} = \frac{1}{2}\cdot\frac{P_s P_{tr} E[PacketSize]}{(1-P_{tr})pSlotTime + P_{tr}P_sT_s + P_{tr}(1-P_s)T_c} \tag{4}$$

The factor of ½ in (4) 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.

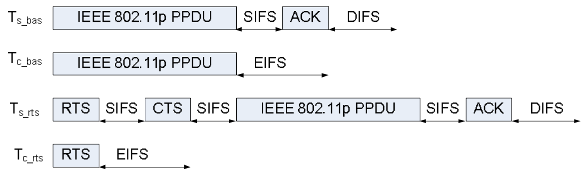

Figure 6. Slot length of successful transmission and collision, with and without RTS/CTS

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) with the highest priority on SCH, i.e., W=4, m=2. From the result, serious throughput degradation is observed when the number of device increase and the packet size decreases.

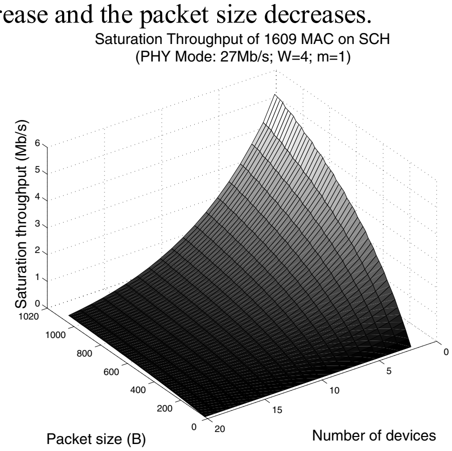

Figure 7.Saturation throughput of 1609 on SCH

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. Therefore, 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:

$$S_{VMESH} = \frac{InformationDeliveredInOne\mathrm{Re}servation}{\mathrm{Re}servationLenght} \quad (5)$$

The DRP transmission process is illustrated in Figure 4, and (5) can be written as (6), where N_p is the maximum number of packet can be transmitted in a reservation, given the reservation length T_{res}.

$$S_{VMESH} = \frac{N_p \cdot E[PacketSize]}{T_{res}} \quad (6)$$

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

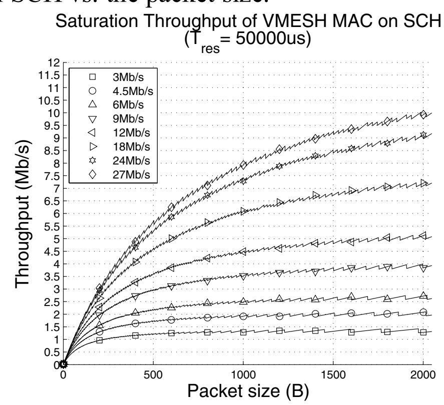

Figure 8. Saturation throughput of VMESH MAC on SCH

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 the maximum throughout reachable by 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 idle backoff slots, the overall throughput value is severely lower than the one from VMESH.

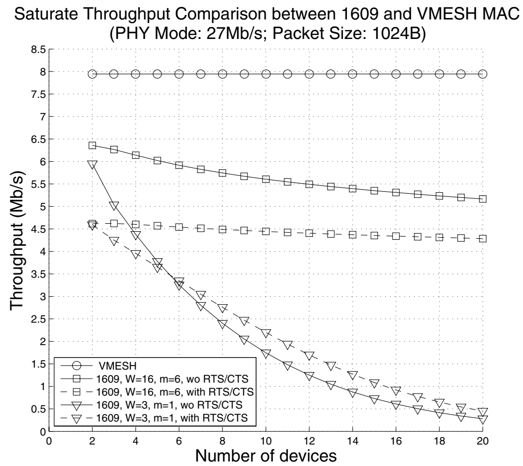

Figure 9. Comparison between IEEE P1609/IEEE 802.11p MAC and VMESH MAC regarding the reachable system throughput on SCH

VI. CONCLUSIONS & OUTLOOKS

In this paper, we propose the 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 access efficiency. Theoretical analysis shows that the novel protocol has advantages over the current WAVE MAC in terms of system saturation throughout. In the next step, we will investigate the performance of the VMESH MAC protocol in more realistic scenarios with stochastic simulations with more realistic mobility, channel and traffic models.

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