Slotted TDMA Multichannel MAC for Overlapped Vehicular Networks with SDN-based Distributed System

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Abstract —*The IEEE 802.11p, IEEE 1609, and wireless access in vehicular environment (WAVE) standards are developed to be used on multi-channels in dedicated short range communication (DSRC) spectrum. While the vehicular networks will be inevitably installed in overlapped manner in metropolitan area, most research works of VANETs, however, are focused on the coordinated multi-channel MAC protocol operations in a single isolated ad hoc network environment without considering overlapped vehicular network environments that include interferences from neighbor networks. In this paper, we propose a slotted TDMA Multichannel MAC (STMC-MAC) for overlapped vehicular networks (OVN) with software-defined networking-based distribution system (SDN-DS) as infrastructure. The proposed STMC-MAC guarantees reliable delivery of basic safety message (BSM) with bounded delay and scalability on OVN with SDN-DS for metropolitan area with high vehicular density. The proposed STMC-MAC provides higher scalability, reliability, and flexibility in BSM and non-BSM data exchanges at various VN-ESS topologies and different level of vehicular density. The proposed scheme had been implemented on NS-3 network simulator, and the performances of the proposed scheme are measured, analyzed, and compared with existing approaches.[1]*

Keywords – slotted TDMA, multi-channel, medium access control (MAC), overlapped vehicular network, smart handover, software defined networking (SDN)

I. INTRODUCTION

Vehicular networks are essential for safety in intelligent transportation system (ITS) that mainly targets to improve safety on roads by broadcasting time-critical safety messages of the information of vehicles (i.e., position, moving direction, velocity, abnormal traffic and road conditions, expected danger of collision, and imminent crash [1]. Several standards are available for vehicular networks, including IEEE 802.11p, IEEE 1609, and wireless access in vehicular environment (WAVE) that operates in dedicated short range communication (DSRC) which allows mobile wireless communication during high-speed mobility (up to 200Km/h) among vehicles with onboard unit (OBU) or between vehicles and roadside infrastructure within a range of up to 1 km[1-3].

The Federal Communication Commission (FCC) allocated dedicated 75 MHz of bandwidth in the 5 GHz spectrum with 7 licensed channels in United States [1]. IEEE 802.11p standard defines amendments to the IEEE 802.11 medium access control (MAC) and physical layer (PHY) to support data exchange in high-speed mobile vehicular environment [2].

IEEE 1609 standard defines the operations of WAVE in higher communication layers [3]. The IEEE 1609.4 specifies extensions to the IEEE 802.11p standard to perform channel coordination for the devices where the carrier sense multiple access with collision avoidance (CSMA/CA) mechanism is used to access the channel. Recently, the U.S. Department of Transportation, the Crash Avoidance Metrics Partnership, and the Vehicle Safety Communications 2 Consortium have proposed a new deployment option that dedicates CH178 for the exchange of management information only, while CH172 is dedicated to V2V Basic Safety Messages (BSMs).

In this paper, we propose a slotted TDMA (time division multiple access) multichannel MAC (STMC-MAC) for overlapped vehicular networks (OVN) with SDN-DS infrastructure that can be used to support a large number of high-density vehicles in metropolitan areas. The proposed STMC-MAC for OVN with SDN-DS can guarantee bounded delivery latency of basic safety message (BSM) and scalability. With the proposed STMC-MAC, the roadside unit (RSU) provides basic service set (BSS) as an access point (AP) for the vehicles with OBU within a range up to 1 Km, while the SDN-DS interconnects the overlapped vehicular networks. The SDN-DS also supports the vehicles to access public Internet via the APs/RSUs for infotainments and conveniences. This paper provides the detailed operations of the STMC-MAC, the coordinated channel frequency allocations among OVNs and the smart handover of vehicles between APs/RSUs via SDN-DN are explained in detail.

The rest of this paper is organized as follows. In section II, the related works are briefly explained, including IEEE 802.11p, IEEE 1609, WAVE, TDMA-based WAVE networking, and SDN. Section III explains the detailed operations of STMC-MAC, the operations of OVNs with SDN-based distribution system (SDN-DS) as infrastructure. The procedure s in management of control channel and service channels among overlapped vehicular networks minimizing interferences, the hybrid CSMA/CA and TDMA scheme for successful delivery of BSM, and management of registrations of vehicles are explained in detail. Section IV explains the implementations of the proposed schemes in NS-3 network simulation. Section V provides the performance evaluations of

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the proposed scheme, based on simulations on NS-3. Finally, section VI concludes this paper with brief explanation of the future work plan.

II. Related Work

A. IEEE 1609.4 Standard for Multi-channel Coordination

IEEE 1609 standard defines the operation of WAVE in higher communication layers, including IEEE 1609.4 that specifies extensions to the IEEE 802.11p standard to multichannel coordination for the devices where CSMA/CA MAC is used in channel access [2]. According to the IEEE 1609.4 specification, MAC coordinates multiple channels by dividing the channel access time interval (sync intervals) of a fixed length (100ms) into a control channel interval (CCHI) and a service channel interval (SCHI). During the CCHI, all OBUs must tune to the CCH frequency for BSM and system control message exchange; while during the SCHI, all OBUs switch to the designated SCH for non-safety message exchanges. The BSM messages exchanged in CCHI contains vehicle identifier (ID), velocity, and position information of the sending vehicle to create cooperative neighbor awareness.

In IEEE 1609.4, the synchronous MAC sublayer operation with fixed duration of control and service time intervals results in inefficient utilization of the CCH and SCHs, and prohibits adaptive and intelligent allocation of time interval in response to variable traffic demands [3]. A variable CCHI can dynamically adjust the duration of the CCHI to improve the service saturation throughput, but the SCH resources are still wasted during the CCHI [4-9].

B. Scalable TDMA Cluster-based MAC (STCM) for Multi-channel Vehicular Networks

The BSM message exchanges in VANETs based on IEEE 802.11p and IEEE 1609 MAC protocol may suffer from unbounded delivery latency at higher traffic loads because of the underlying random access mechanism of CSMA/CA [4-9]. Many research works reported that the multi-channel access scheme with CSMA/CA provides poor performances in reliable broadcast of safety messages with bounded delay, and also provides low throughput of non-safety message exchanges in dense VANETs environments [4-9].

In order to enhance the performances of vehicular networks for reliable broadcast of BSMs, several research works have proposed the time division multiple access (TDMA)-based MAC [4-9]. In the TDMA-based MAC protocol, TDMA slots (T-slots) are reserved for specific OBUs based on preprocessed scheduling by a centralized cluster header. Since the usage of pre-scheduled TDMA slots can avoid channel contentions for BSM exchanges, the performance can be enhanced.

For example, the STCM (Scalable TDMA Cluster-based MAC (STCM)) protocol [11] is based on TDMA slot reservation with clustering of vehicles for multi-channel vehicular networks. The STCM considers single-radio transceivers that can be tuned to either control channel (CCH), BSM channel (BSMC), or service channel (SCH); and each vehicle are allocated with two mini-slots in the CCH and BSMC to deliver BSM in each 100 ms sync interval to enhance the reliability the time-critical safety message exchanges. The simulation results showed that the BSM delivery ratio was significantly improved by on average 97% in less than 50 ms of delivery time. In addition, the STCM can support a cluster of 300 vehicles [11]. The SCTM, however, was designed for a single cluster vehicular network, and it cannot support overlapped vehicular networks.

III. Overlapped Vehicular Networks with SDN-based Distribution System

A. Overlapped Vehicular Networks

There are two simple scenarios of overlapped vehicular network (OVN): (a) bidirectional road with multiple lanes and (b) bidirectional cross road with multiple lanes. In the simple bidirectional road with multiple lanes, the VNs will be overlapped in linear sequence, and communication channels of each VN will get interferences from its two neighbors.

In the bidirectional cross road, the VN in the middle get interferences from its four neighbors. So, any VN cannot use the same frequency channel with its neighbor VNs. In order to avoid any unnecessary collisions in the frequency channel, each neighboring VN_BSS must carefully schedule the frequency channel and transmission time.

B. TDMA-Slot (T-Slot) in SSTM-MAC for OVN

Since the most important feature reliable broadcast of BSMs, non-overlapped BSM channel is allocated for each VN-BSS, while CCH is used for channel management message exchanges. Different previous proposals, SSTM-MAC allocates a BSM channel for each VN-BSS which is not used by its neighbor VN-BSS, selected from the 6 SCHs. The allocations of the BSM channel for each VN-BSS are managed by a centralized management system of VN-ESS (extended service set). Both CCH and BSM channels are synchronously slotted and used in TDMA-based BSM broadcasts in order to increase utilization with minimized contention.

As in the scalable TDMA cluster-based MAC (STCM) [11], the synchronous interval (SI) of 100 ms of CCH and BSMCH

is divided into 60 TDMA slots (T-slots), and each T-slot is further divided into 5 mini-slots for BSM message broadcasts and control message exchanges. As a result, the BSMCH provides in total 300 mini-slots in each SI that allows up to 300 vehicles in a VN-BSS.

C. CCH T-Slots Allocations in OVN without Collision

Since the CCH is commonly used for channel managements in each VN-BSS, the 60 T-slots in each SI are carefully allocated to each VN-BSS without any duplication. As shown in Fig. 1, the 60 T-slots in a synchronous interval (SI) are divided into 6 groups according to the SCHs that can be used as BSM channels; so 10 T-slots are used by each BSMCH without any collision. The first T-slot of the 10 T-slots for each BSMCH_x is used to broadcast the beacon frame for the VN-BSS_x that provides the information of T-slot allocation for each VN-BSS, such as VN-BSS identifier (ID), the number and usage of CCH T-slots (i.e., vehicular identifier (VID) of newly registered OBU, registration request, SCH T-slot request/allocation, etc.).

For any VN-BSS with less than 5 overlapped neighbor VN-BSS, some SCH(s) may be used for service traffic. The allocation of SCHs is handled by the centralized VN-ESS management system.

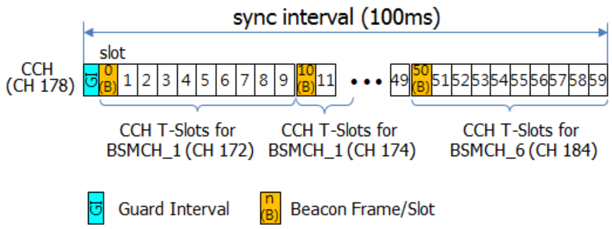

Fig. 1. T-slot Allocations in Control Channel

D. Registration of vehicles into VN-ESS

When a vehicle newly enters the VN-ESS, it must tune to the CCH to find available VN-BSS by monitoring the beacon frame that provides information of T-slots for registration. The channel access for the CCH T-slot for registration is handled with CSMA/CA mode. As shown in Fig. 2, the OBU sends registration request (Reg_Req) in the T-slot allocated for registration. If the Reg_Req is successfully delivered, the RSU sends acknowledgement (Reg_Ack) with the information of T-slot that can be used for association request and response.

In order to increase channel utilization, the registration and association are processed in separated T-slot without contention. The Reg_Ack frame contains the information of T-slot that can be used in the remaining registration procedure with association. Fig. 2 shows an example of allocating a T-slot for registration/association procedure.

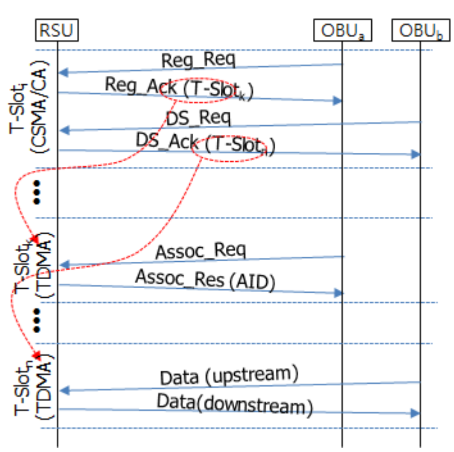

Fig. 2. Registration/Association and Data Exchange

E. Non-BSM Data Exchange

Some T-slots in the CCH can be allocated for non-safety data exchange. In the proposed SSTM-MAC scheme, data T-slot request and allocation is processed in the CCH T-slot that is operated in CSMA/CA. Fig. 2 depicts a scenario of non-BSM data exchange where OBU_b is requesting data T-slot by DS_Req, and RSU informs the allocation of $T\text{-}Slot_n$ for OBU_b. The upstream and downstream data exchanges are handled in $T\text{-}Slot_n$ without contention.

The T-Slot for non-BSM data exchange can be allocated in the CCH or SCH according to the number of vehicles in the VN-BSS and the topology of VN-ESS. For example if the VN-ESS has a linear topology with low density, only three BSMCHs are used and the remaining three SCHs can be used for non-BSM data exchanges. If the VN-ESS has a cross-road topology, at least 5 BSMCHs must be allocated and only 1 SCH can be used for non-BSM data exchanges. The proposed STM-MAC can support higher flexibility, reliability, and scalability in BSM and non-BSM data exchanges at various VN-ESS topologies and different level of traffic density.

F. Smart Handover between neighbor VN-BSSs in OVN

The registration procedure requires several short control message exchanges, including registration request (reg_req) / response (reg_resp) and association request (asso_req) / response (asso_resp). If all these short control messages are exchanged in CSMA/CA mechanism, the contention will be increased and the overall performance of reliable delivery of BSM message will be deteriorated. In order to solve this problem in registrations of newly arriving vehicles at each VN-BSS, this paper proposes a smart handover procedure between neighbor VN-BSSs in OVN.

When a vehicle arrives at the boundary VN-BSS, it sends registration request using the T-slot in CCH with CSMA/CA contention-based channel access. The RSU allocates on T-slot for association procedure which are used to exchange association request/response control messages without contention. Once association request is successfully delivered, the RSU send vehicle registration message to VN-ESS CM that assigned an association ID (AID) for the newly joined vehicle. The newly registered vehicle periodically broadcast BSM message using the designated mini-slot for the AID/vehicle without any contention.

When the OBU/vehicle moves to the boundary of the current VN-BSS where the neighbor VN-BSS is overlapped, the current RSU checks the position, direction and velocity of the vehicle, and initiates smart handover procedure. The current RSU firstly send smart handover recommend request to the central VN-ESS-CM on behalf of the vehicle. The VN-ESS-CM asks the availability of the smart handover to the next RSU that is determined by the current position, moving direction and velocity of the vehicle. If the next RSU confirms the smart handover, it provides the association ID (AID) in the next VN-BSS for the vehicle. The VN-ESS-CM sends response message to the current RSU which in turn exchanges smart handover request and response using T-slots without contention.

In the proposed smart handover between neighbor VN-BSSs with SDN-DS, there is no need to exchange registration control messages for each VN-BSS, except the boundary VN-BSS in the VN-ESS. After the smart handover, the next RSU sends re-association confirm request using a CCH T-slot with the information of the T-slot for re-association confirm message.

IV. Implementations on NS-3 Network Simulator

A. *WAVE simulation module in NS-3*

The proposed STMC-MAC has been implemented on NS-3 network simulator [12], using WAVE and WIFI module. The WIFI module in NS-3 provides the basic distributed control function (DCF) MAC functions based on CSMA/CA and WIFI physical layer functions. The OcbWiFiMac block provides the outside the context of a BSS (OCB) feature that supports ad hoc MAC functions. The IEEE 1609.4 block provides multichannel management functions, such as service channel scheduler, channel manager, vendor specific action (VSA) repeater, and channel coordinator. The channel scheduler provides API to switch channels.

Currently available default channel scheduler (DefaultChannelScheduler) of IEEE 1609.4 block supports functions of assigning channel access for sending packets. The channel coordinator is used to generate channel coordination events. The default channel intervals are 50ms CCHI, 50ms SCHI, with 4 ms Guard. Before each transmission, the transmission parameters must be registered as TxProfile. Channel schedule can support continuous, alternating, immediate, and extended mode. The IEEE 1609.4 functional block of current NS-3 does not provides slotted TDMA multichannel MAC (STMC-MAC) functions.

The WaveNetDevice block has multiple internal MAC entities, each one used to support each channel. It allows multiple PHY entities and permits single or multiple PHY configuration of the WAVE device as OBU of vehicle.

B. *Implementation of STMC-MAC Simulation Module*

Since the NS-3 WAVE module does not provide slotted TDMA MAC protocol functions, the IEEE 1609.4 submodule has been modified for STMC-MAC functions. Registration/association module handles the initial registration and association message exchanges using contention-based channel access at the T-slot allocated for registration requests and data slot requests. When the registration and data slot request message is successfully delivered at the RSU side, a T-slot is allocated for message exchanges without contention. The information of the T-slot (i.e., channel number and T-slot number) is delivered by the acknowledgement (Ack) message.

Handover manager at the RSU side continuously checks the status of each vehicle in the VN-BSS (by checking the position, moving direction, and direction), and initiates smart handover with VN-ESS-CM module. If smart handover is agreed, the smart handover request message is delivered to the vehicle through CCH. The response of the smart handover request is delivered via the designated T-slot in the CCH. At the next RSU, re-association confirmation messages are exchanged through CCH. BSM manager periodically sends the basic safety message using the designated mini-slot in the BSM channel. The T-slot and mini-slot of the BSM is determined according to the AID (association identifier) of the registered vehicle. Service manager supports the service data exchanges through SCH.

C. *Implementation of VN-BSS on NS-3*

The VN-BSS block provides the control and management functions of VN-BSS, such as beacon broadcasting and T-slot scheduling for CCH and SCH. It also connects to OpenFlow switch that configures the SDN-DS.

V. Performance Evaluation

A. *Simulation Configuration*

The performance of the proposed STMC-MAC has been evaluated with implementation on NS-3 network simulator. Table 1 shows the MAC layer parameters used in the simulation. The transmission range of each VN-BSS is configured as 300 meter. The synchronous interval (SI) is 100 ms. The guard interval (GI) and inter-frame gap (IFG) are configured as 30 us and 700 us, respectively. The durations of T-slot and mini-slot are configured as 1.625 ms and 0.301 ms.

Table 1. MAC Layer Parameters used in Simulations

Parameters	*Value*
Physical rate of CCH and SCH (BSMCH)	6 Mbps
Size of BSM (basic safety message)	200 Bytes
Transmission Range	300 meter
Sync Interval (Beacon Interval)	100 ms
Guard Interval (GI)	30 us
Inter Frame Gap (IFG)	700 us
T-slot	1.625 ms
mini-slot	0.301 ms
Vehicle movement velocity	20 meter/sec

B. *Performance Analysis of Reliable BSM Delivery*

Fig. 3 shows the comparisons of packet delivery ratio of the CSMA/CA-based IEEE 1609.4 and the proposed TDMA-based STMC-MAC in a single VN-BSS. As the number of

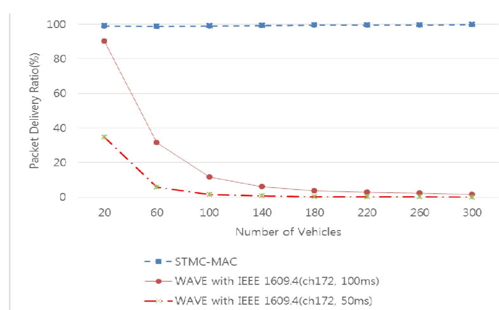

Fig. 3. Comparisons of Packet Delivery Ratio in a single VN-BSS

vehicles increases up to 300, the packet delivery ratio of IEEE 1609.4 becomes poor because of the increased contention. The packet delivery ratio of the proposed STMC-MAC, however, remains near 99% even at the 300 vehicles. The basic reason of the good performance in packet delivery ratio is contention-free TDMA mini-slots for each vehicle in the proposed STMC-MAC.

VI. Conclusion

In this paper, we proposed a slotted TDMA multichannel MAC (STMC-MAC) for overlapped vehicular networks (OVN) with SDN-based distributed system (SDN-DS). By using slotted TDMA mechanism, the proposed STMC-MAC guarantees reliable delivery of BSMs with bounded latency. In each VN-BSS, up to 300 vehicles can be accommodated by allocating non-overlapped BSM channel (BSMCH) for each VN-BSS.

The proposed STMC-MAC has been implemented on NS-3 network simulator with WAVE module and OpenFlow switch module. The IEEE 1609.4 block of WAVE simulation module has been modified to provide slotted TDMA MAC function. The performance analysis showed that the proposed STMC-MAC provides greatly enhanced packet delivery ratio for highly dense vehicular network. In single VN-BSS, the proposed STMC-MAC scheme provides near 99 % of BSM packet delivery ratio (PDR) for up to 300 vehicles, while the WAVE with IEEE 1609.4 only provides less than 5% PDU for 200 vehicles. In overlapped network topology, the performance enhancement is more significant. In simple linearly overlapped VN-BSS with 500 meter range and 900 meter distance between RSUs, the WAVE with IEEE 1609.4 provides less than 1.5% even when each VN-BSS is using different BSM channel, while the proposed STMC-MAC provide 99.78% when different BSM channels are allocated for each VN-BSS/RSU.

The contributions of this paper are summarized as follows: (i) proposed a slotted TDMA multichannel MAC (STMC-MAC) for overlapped vehicular network (OVN) for metropolitan area with higher density vehicles, (ii) proposed infrastructure for overlapped vehicular networks with software defined networking as distribution system (SDN-DS), and (iii) proposed network-initiated smart handover of vehicles at boundary of VN-BSS to minimize the overhead of control message exchanges.

As future research works of the proposed STMC-MAC and the OVN with SDN-DS, we are continuously developing NS-3 simulation modules for the slotted TDMA-based multichannel MAC protocol, and doing simulations for various network topology.

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