# An Enhanced TDMA Cluster-based MAC (ETCM) for Multichannel Vehicular Networks

Nurullah Shahin and Young-Tak Kim
Dept. of Information and Communication Engineering
Graduate School, Yeungnam University, Korea
Email: nurullah@ynu.ac.kr, ytkim@yu.ac.kr

***Abstract*— The Vehicular Ad-Hoc Networks (VANETs) provide communication services for time-critical road safety applications, general purpose ITS services for traffic efficiency, and non-safety value-added infotainment applications. The challenges of multichannel VANET Medium Access Control (MAC) protocol include successful delivery of time-critical safety messages within 100 ms with high reliability, and high channel utilization for non-safety messages. In this paper, we propose an *enhanced TDMA (time division multiple access) Cluster-based MAC (ETCM)* protocol which is based on TDMA slot reservation with clustering of vehicles for multichannel vehicular networks, using single radio vehicular transceiver. The major contributions of the proposed ETCM protocol are: i) the enhanced logical frame structure with allocations of two mini-slots for each vehicle in each synchronous interval (in 100ms) to increase collision-free channel access and reliable time-critical safety message deliveries, ii) enhanced bandwidth utilization of service channels with dynamic reallocations of unused slots for vehicular communications with single radio transceiver, and iii) increased fairness among vehicles by balanced slot allocations even at high traffic load conditions. The proposed ETCM protocol has been analyzed with a series of simulations of a cluster with up to 156 vehicles using ns-3 network simulator. The simulation results show that the packet delivery ratio of safety messages was greatly enhanced to 99% delivery in less than 50 ms delivery time, and the aggregated channel throughput (channel utilization) was greatly enhanced from 10Mbps (in TC-MAC) to 25~30 Mbps (in ETCM) at 7 channels (1 control channel and 6 service channels) of 6Mbps for a cluster of 100 vehicles.**

***Keywords*— *IEEE1609 WAVE, Vehicular Ad-hoc Network (VANET), Clustering, Channel Coordination, TDMA.***

## I. INTRODUCTION

The Vehicular Ad-Hoc Networks (VANETs), as the most important component of Intelligent Transportation Systems (ITS), are key to provision time-critical safety applications (e.g., accident avoidance and mitigation of road intersection collision), general purpose ITS services for traffic efficiency (e.g., current road traffic data, ITS service advertisement), and non-safety value-added infotainment applications (e.g., tourism and shopping information) using vehicle-to-vehicle (V2V) and vehicle-to-roadside (V2R) communications as shown in Fig.1 [1].

IEEE 1609 family of standards for Wireless Access in Vehicular Environment (WAVE) is designed on the dedicated short range communications (DSRC) 5.9GHz frequency band with 7 licensed channels in the United States by the Federal Communication Commission (FCC) [3], using the IEEE 802.11p [1], [2]. In current WAVE standard, no notion of basic service set (BSS) is considered, so a vehicle node is allowed to transmit without becoming a member of a BSS by using a communication mode referred to as *outside the context of a basic service set (BSS)* (OCB) [4].

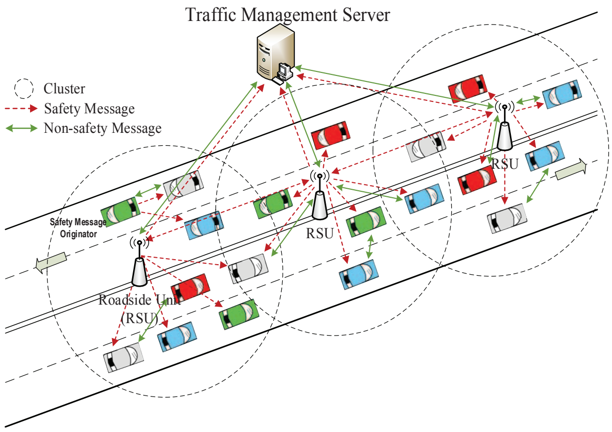


Fig. 1. Network Topology. Vehicle-to-Vehicle (V2V) communication and Vehicle-to-Infrastructure communication (V2I).

The IEEE 1609.4 standard is considered to be a default multichannel medium access control (MAC) standard for VANETs, which defines multichannel operations of a DSRC radio with sync interval of 100 ms that consists of a control channel (CCH) interval and service channel (SCH) interval, each separated by a guard interval (GI).

The IEEE 1609.4 standard specifies extensions to the IEEE 802.11p MAC sublayer management entity to provide channel coordination for OCB-enabled operations. It coordinates the multichannel operation of single-radio devices, where a channel time-division multiplexing of alternating CCH and SCH intervals, altogether making a synchronous interval (SI) with a nominal length of 100ms to meet the requirements of most of the safety applications [4]. It has been shown, unfortunately, that the current standard of WAVE/IEEE 802.11p cannot support both safety and non-safety applications with high reliability at high traffic density, nor provide high channel utilization for non-safety applications with multichannel structure [5]-[7].

Recently, many research results reported that the synchronous split-phase contention-based multichannel access scheme in current IEEE 1609.4 demonstrates poor performance in the aggregated service channel throughput and QoS provisioning in dense VANETs environment [5]-[8]. Especially, the fixed duration of CCHI and SCHI prohibits

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adaptive intelligent allocation of time intervals in response to variable traffic demands, while the contention-based channel access in CCH produces a higher possibility of contentions in SCHs, which may result in inefficiency due to continued collisions in dense large-scale vehicular Ad Hoc networks [5].

To increase the efficient utilization of multichannel, Almalag et al. [7] [8] proposed a novel multichannel MAC protocol called TDMA Cluster-based MAC (TC-MAC) for VANETs. Unlike the IEEE 1609.4 standard architecture, in TC-MAC, the frame is not divided into two intervals CCHI and SCHI. On the other hand, each frame is divided into time slot of fixed size. Therefore, each vehicle can tune to the CCH or to specific SCHs if needed during the SI. Although the simulation results show that TC-MAC performs better than IEEE 1609.4, it also has some failings. This protocol gives significant missing of safety/update messages even at low traffic density and poor SCHs channel utilization at heavy traffic density.

In this paper, we propose an *enhanced time division multiple access (TDMA) Cluster-based MAC (ETCM)* protocol which is based on TDMA slot reservation with clustering of vehicles for multichannel vehicular networks. In the proposed ETCM, mobile nodes are assumed to use a single radio interface that can switch between CCH and SCH. The proposed ETCM protocol enhances the logical frame structure with allocations of two mini-slots for each vehicle in each 100 ms sync interval (SI) to increase the collision-free channel access and the reliability of the time-critical safety message deliveries. The bandwidth utilization of SCHs is improved with dynamic reallocations of unused slots. The proposed ETCM also increases the fairness among vehicles by balanced slot re-allocations even at high traffic load conditions.

The proposed ETCM protocol has been evaluated with a series of simulations using ns-3 network simulator [17]. The simulation results show that the packet delivery ratio of safety messages was greatly enhanced to 99% delivery in less than 50 ms delivery time, and the throughput (channel utilization) was greatly improved from 10Mbps (in TC-MAC) to 25~30 Mbps (in ETCM) at 7 channels (1 CCH and 6 SCHs) of 6 Mbps for a cluster of 100 vehicles.

The rest of this paper is organized as follows. Section II briefly introduces related work on multichannel MAC schemes. The proposed ETCM is explained in Section III, and Section IV depicts the performance evaluation results. Finally, Section V concludes this paper with brief explanation on future work.

## II. Background and Related Work

### *A. WAVE/IEEE 802.11p and Multichannel Vehicular Networks*

The IEEE 1609.4 is the standard of multichannel operation for VANETs works on the top of the 802.11p in the MAC layer [1]. The channel access time is divided into sync interval of 100ms that consists of guard intervals and alternation of fixed length intervals, called the CCH interval (CCHI) and the SCH interval (SCHI). The duration of both intervals are fixed as 50ms. For the safety related applications, the Vehicle Safety Communication (VSC) consortium defined two types of broadcast message generations: event-driven and periodic [9]. Event-driven messages are sent when a dangerous situation is detected, while periodic messages proactively inform to neighbor vehicles about its status (e.g., the identity, position, speed) of the sending vehicle. The VSC recommends that life-critical safety application require a frequency of 10 messages per second with a maximum latency of 100ms.

Major challenges related to multichannel management are inefficiencies of spectrum utilization, possible timeout of safety data delivery, and poor bandwidth allocation for non-safety data delivery [4]. The current version of the IEEE 1609.4 standard MAC cannot support both safety and non-safety applications with high reliability at high traffic density, nor provide high channel utilization for non-safety applications [7].

Several enhancements have been proposed to improve the IEEE 1609.4 multichannel MAC performance, which can be categorized into i) synchronous adaptive adjustment of CCH/SCH intervals [5], ii) asynchronous distributed multichannel negotiation [6], and iii) TDMA cluster-based slot allocation [7-9]. As an example synchronous adaptive adjustment of CCHI/SCHI, Wang *et al.* [5] present a variable control channel interval approach, which dynamically adjusts the duration of the CCHI and SCHI according to the number of active nodes in the network. The dynamic adjustment improves the saturation throughput compared to the IEEE 1609.4 standard. However, during the CCHI the SCH resources are still wasted, while during the SCHI the CCH resources are still wasted. At high traffic density, there is high collision at the beginning of each CCHI. Moreover, in the variable control channel interval approach, it is assumed that the number of vehicles and packet size are known by the RSUs, which may not be possible in distributed scenario. From the three categories of multichannel MAC schemes, the conflict-free multichannel MAC with TDMA protocols provide better performance in safety message delivery and overall throughput of service channels [7-8], [11]. Yu and Biswas [10] proposed Vehicular Self-Organizing vehicular MAC (VeSOMAC) which reduces the delay of the safety messages by giving sequential TDMA time slot based on the vehicles relative position. The limitation of VeSOMAC is that it does not provide managements of multiple SCHs, and is based on location aware slot ordering. This protocol takes longer round-trip delay than that of IEEE 1609.4 [1].

A multichannel MAC protocol for VANETs, called VeMAC, is proposed in [11], where time slots are assigned based on the direction of vehicles. VeMAC assumes two transceivers for the control channel and the service channels, respectively. VeMAC can make use of the seven DSRC channels, however, they did not give any mechanism for accessing the SCHs.

### *B. Self-organizing TDMA (STDMA)*

The STDMA approach is based on a standardized scheme for the shipping and aircraft industry to implement Automatic Identification System (AIS) as well as VHF Digital Link (VDL) Mode 4, respectively. K. Bilstrup *et al.* [12] and [13] presented a self-organizing TDMA (STDMA), all vehicles in the network periodically send their own position information. Based on the position information vehicles choose slots in the frame. The presence of hidden terminals problem seriously affects the network performance because of the lack of position information about the vehicle outside its communication range. Moreover, after all slots are assigned by the vehicles, there is collision for reallocating a slot that belongs to the farthest neighbor within the communication range. Therefore, packet delivery ratio is drastically decreased with the increase of vehicles. In addition, STDMA needs to implement with the consideration of multichannel for safety and non-safety message exchange, V2R communication as well as sync interval with a fixed length of 100ms.

### *C. TDMA Cluster-based MAC (TC-MAC)*

The TC-MAC [7][8] integrates the centralized approach of cluster management and a new scheme for TDMA slot reservation. The main objective of this work was to allow vehicles to send and receive non-safety messages without any impact on the reliability of sending and receiving safety messages, even if the traffic density is high. The TC-MAC also aims to decrease collisions and packet drops in the SCHs, to provide fairness in sharing the wireless medium, and to minimize the effect of hidden terminals. TC-MAC is able to deliver non-safety messages within reasonable time constraints (i.e., meeting the requirements of minimum latency safety messages). At light traffic load of vehicles, however, the ratio of missing safety/update messages is up to 30%, because the TC-MAC allows SCH slot allocations for vehicles while some vehicles are transmitting safety/update messages at the time slot using CCH. Even in heavy traffic there is some missing at least 4% of safety packets. In addition, the TC-MAC only allocates default SCH slot, so the utilization of SCH slots is limited up to 50% depending on the traffic load of vehicles. Both CCH and SCHs provide low throughput and poor utilization of channels. It does not expect all vehicles in the cluster to be communicating, or active, simultaneously. Moreover, it does not consider Guard Interval (GI) and Inter-frame Gap (IG) among the slots and logical frames, respectively.

## III. The Enhanced TDMA Cluster-based MAC (ETCM)

In this section, we explain the enhanced TDMA cluster-based MAC (ETCM) for multichannel vehicular networks.

### *A. Enhanced TDMA Cluster-based MAC (ETCM) protocol*

In the current VANET scenario, communication channel faces congestion problem which seriously affects the performance of the safety applications. Most of the safety/update applications produce safety/update messages at a higher frequency (e.g., 10 Hz). When a large vehicle network generates safety/update messages at higher rate, the channel capacity can be exhausted easily. As a consequence, packet collision occurs. So, if the channel is already congested, then the safety/update messages are either lost or delivered to receivers with higher delay. The loss of safety/update messages has a significant impact on the safety of a vehicle. Because of the serious implication of the congestion, it is necessary to keep the channel at minimized congestion. In this paper, we propose a multichannel media access scheme which ensures enough bandwidth to be allocated for safety/update messages so that delay and reliability does not affect by a large number of vehicles in the network.

VANETs can have either a flat topology or a hierarchical clustered topology. Due to large networks and lack of routers, a flat topology faces scalability and hidden terminal problems. Routing in flat topology requires flooding function to find routes, and in large networks this flooding leads to severe congestion [14]. This issue develops more severe as the network is more mobile where the topology changes frequently. The TC-MAC is a dynamic TDMA slot reservation technique for cluster-based VANETs [7] [8]. In TC-MAC, each vehicle gets one mini-slot and one SCH slot in a logical frame of each sync interval. The local ID is assigned by Cluster Head (CH) from 0 to $N-1$ in sequential manner. There are two major differences between the proposed ETCM and the existing TC-MAC. First, in ETCM, each vehicle gets two mini-slots in two consecutive CCH slots for increased reliability of safety messages and channel negotiations among vehicles. Second, some vehicles that need more than one SCH slots can use the unused slots according to the availability of the not-allocated slots. In this mechanism, the size of the network is controlled by the CH, so that based on the size of the network all vehicles can create same TDMA map for making a collision free intra-cluster communication. The CH locally uses ID 1 which can be vehicle or RSU. Fig. 2 depicts TDMA frame structure of ETCM, and mini-slot allocations of CCH and slot allocation of SCH. Here, $CCHSlot_X$ $(X = 0, \dots 25)$ indicates the slot number on the CCH channel and $miniSlot_Y$ $(Y = 0, \dots 11)$ indicates the mini-slot number on the $CCHSlot_X$. Two mini-slots are always reserved for the new entering vehicles whose ID is 0. When a new vehicle wants to join the cluster, it sends the association request to the CH using one of the two mini-slots on CCH; $miniSlot_1 = (id + nSCH)\ mod\ (2 \times nSCH) = 6$, and $miniSlot_2 = id\ mod\ (2 \times nSCH) = 0$ on $CCHSlot_1 = 23$ and $CCHSlot_2 = 24$ CCH slots, respectively (see Fig. 2). We can make two pairs as, pair1$(CCHSlot_1,$ $miniSlot_1) = (23, 6)$ and pair2 $(CCHSlot_2,\ miniSlot_2) = (24, 0)$. Through any of the two mini-slots new vehicles can send their association request. After getting successful reception by CH, the CH broadcasts ID of the new vehicle and the new vehicle again sends the "confirm" message to the entire cluster using its own mini-slots thereby CH can update network size and all vehicles of the cluster can get the new vehicle's status.

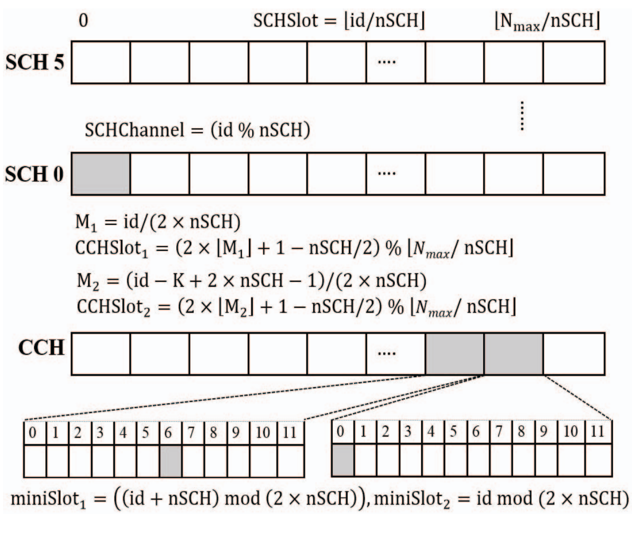


Fig. 2. TDMA frame structure of ETCM.

**Algorithm 1. Allocation of CCH mini-slots and SCH slot**

```
// id: vehicle ID from 0 to N_max
// nSCH: number of service channels
// N_max : maximum number of vehicles in a logical frame
// K: required for determining the position of mini-slot
// L: required for determining the position of mini-slot
// miniSlot: number of mini-slots in a CCH slot
// CCHSlot: slot number where CCH mini-slot contains
// SCHSlot: slot number of SCHs
// SCHch: channel number among the six SCHs

for id = 0 to N_max do
  K = id%(2 × nSCH)
  for i = 1 to 2 do
    if (i == 1 AND K < nSCH) OR
       (i == 2 AND K ≥ nSCH ) then
       miniSlot[i] = (id + nSCH)%(2 × nSCH)
    else
       miniSlot[i] = id%(2 × nSCH)
    end if
    if i == 1 then
      M[i] = id/(2 × nSCH)
    else
      if K < nSCH then
        M[i] = (id − K + 2 × nSCH − 1)/(2 × nSCH)
      else
        M[i] = (id − K + 3 × nSCH − 1)/(2 × nSCH)
      end if
    end if
    L = ⌊M[i]⌋ + 0.5
    if (i == 1 AND M[i] < L) OR
       (i == 2 AND M[i] ≤ L ) then
       CCHSlot[i] = (2 × ⌊M[i]⌋ − nSCH/2)%⌊N_max/nSCH⌋
    else
       CCHSlot[i] = (2 × ⌊M[i]⌋ + 1 − nSCH/2)%⌊N_max/
                     nSCH⌋
    end if
  end for
  SCHChannel = id% nSCH
  SCHSlot = ⌊id/nSCH⌋
end for
```

## *B. ETCM Default Slot Allocation*

In the ETCM, one logical frame (in 100ms duration) can contain any number of active vehicles ($N$), communicating either safety, non-safety or both, up to the predefined maximum number of vehicles ($N_{max}$) in a cluster. The TDMA logical frame of 100ms which guarantees that every vehicle in the cluster can send at least one safety/update messages to meet the safety/update messages requirements. The FCC defines the number of SCHs as six ($nSCH = 6$). We assign IDs of vehicles from 0 to $N_{max} - 1$ . The total number of slots in each logical frame is calculated as $nSlot = \left\lfloor \frac{N_{max}}{nSCH} \right\rfloor + 1$. In ETCM, $N_{max}$ is defined as $156$; we evaluated scenarios in Table I with Low, Medium and High density level. So, considering a highway in 300m radius communication range, on the 2 lanes highway makes 20, 40, and 80 vehicles cluster and 3 lanes highway makes 30, 60 and 120 vehicles cluster based on the three different density levels. We limited the maximum number of vehicles in the cluster. Based on the network settings, we can use maximum 156 vehicles in a cluster. $nSlot$ ($\lfloor N_{max}/\mathrm{nSCH} \rfloor$) $= 26$ slots are configured in one logical frame. The slot ID is assigned from 0 up to $\left\lfloor \frac{N_{max}}{nSCH} \right\rfloor$. All slots have fixed time duration of $t$, and are assigned based on the data rate and the maximum packet size.

TABLE I. DENSITY LEVELS IN THE HIGHWAY (COMMUNICATION RANGE 300 METERS)

| Density Level | Number of Vehicles per Lane | Gap between Vehicles (m) | Number of Vehicles (2 lanes) | Number of Vehicles (3 lanes) |
|---|---|---|---|---|
| Low | 5 | 60 | 20 | 30 |
| Medium | 10 | 30 | 40 | 60 |
| High | 20 | 15 | 80 | 120 |

Similar to the SCHs, the time access on the CCH is also divided into $N_{max}/nSCH$ time slots of duration $t$. Each time slot on CCH is divided again into $nSCH \times 2 = 12$ mini-slots of duration $t/12$ ms, which are used to broadcast safety/update message. The main idea of the slot reservation schedule is that in each frame, each vehicle $id$ is used to allocate the time slot $SCHSlot = \lfloor id/nSCH \rfloor$ on the service channel $SCHChannel = (id \bmod nSCH)$. Moreover, each vehicle assigns two mini-slots in each logical frame based on the same $id$.

Every vehicle knows the frame and slot boundaries by the virtue of the synchronization. While the TC-MAC does not consider GI and IG, the proposed ETCM considers both: a GI at the beginning of each channel mini-slot and slot, and an IG at the beginning of each logical frame. Both intervals are used to enable the radio devices to complete switching, reduce synchronization inaccuracy and adjustment of frame duration. The channel switching is measured to be 40-80 $\mu sec$ [15]. In ETCM, the GI is defined as 50 $\mu sec$ and the IG 800 $\mu sec$, as shown in Fig. 3.

During the joining process of vehicles into the ETCM cluster, the CH provides vehicle IDs to the new entering vehicles and informs the updated number of active vehicles ($N$) to all cluster member vehicles. Due to frequent changing of network topology, the number $N$ may be changed dynamically, so the CH is in charge of updating $N$. Discovering of neighbor is not required at each individual vehicles; each vehicle broadcasts their status information, using two mini-slots in each logical frame (sync interval) to inform others.

In ETCM, there are two types of default SCH slot allocations: Balanced Allocation (BA) and Consecutive Allocation (CA). In the ETCM-BA, the CH assigns an ID to a newly joining vehicles in uniform manner from the available ID space, whereas in the ETCM-CA, the CH assigns an ID in a number from 12 to $N_{max} - 1$ of the available ID space. If all IDs are assigned in the range of 12~$N_{max} - 1$, then the CH assigns from 0 to 11, sequentially, as shown in Fig. 4. Algorithm 1 depicts the assignments of a pair of CCH mini-slots and a SCH slot based on the vehicle ID which is assigned by the CH. Uniqueness of the ID confirms that any two vehicles do not use the same mini-slot and slot. For example,

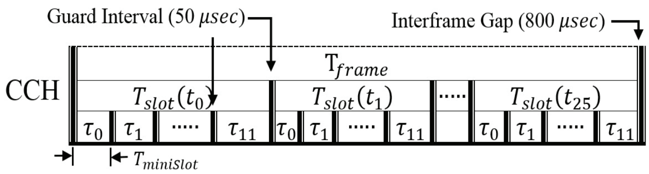


Fig. 3. GI and IG in the frame structure.

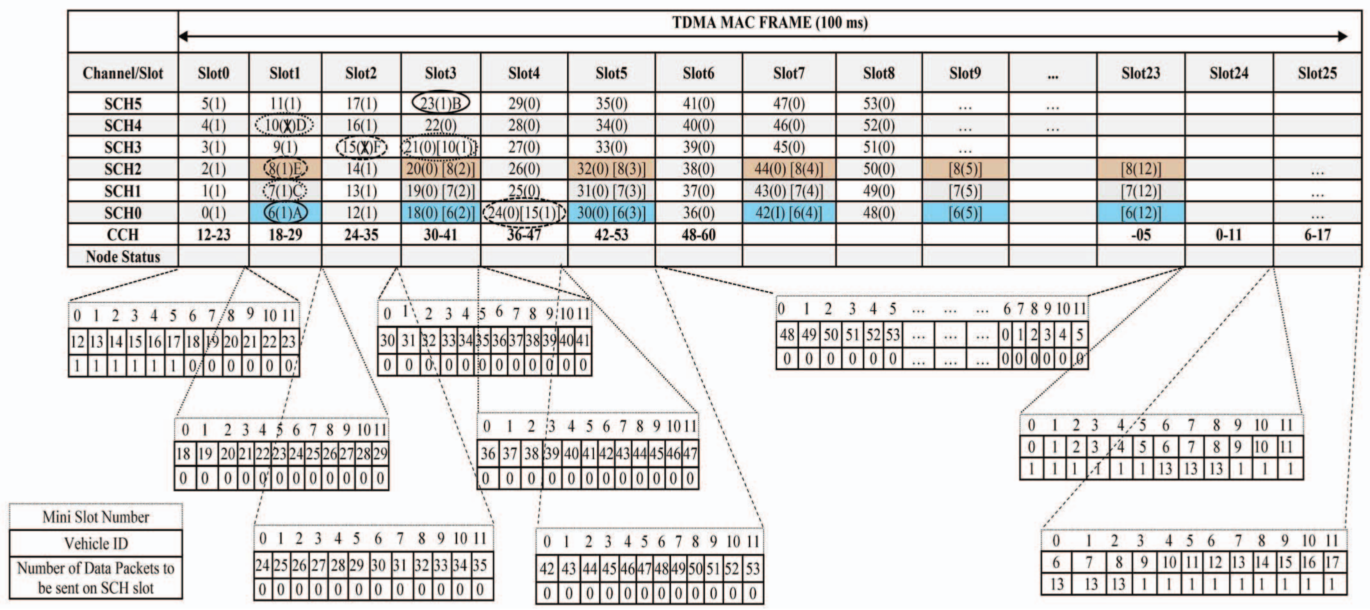


Fig. 4. TDMA map of ETCM protocol ($N$ = 54, $nSCH$ = 6, $nCCH$ =1.)

assume $N = 54$, $nSCH = 6$, $nCCH = 1$, $nSlot = 26$ and $N_{max}$ =156. A vehicle with ID 8 uses two CCH mini-slots in two consequtive slots. First CCH mini-slot is allocated at pair1 $(CCHSlot_1,\ miniSlot_1) = (24, 8)$ and second CCH mini-slot is allocated at pair2 $(CCHSlot_2,\ miniSlot_2) = (25, 2)$ for safety/update messages transmission. It also assigns one default SCH slot (Slot1) for non-safety messages transmission to the vehicles with ID 8.

## C. Non-safety Message Exchanges in ETCM

Before sending the non-safety messages, handshake messages are exchanged through the CCH mini-slots of the sender. For example, assume a vehicle $m$ wants to transmit non-safety messages to a vehicle $n$. By listening CCH, the vehicle $m$ gets the status information of the vehicle $n$, if the vehicle $n$ is available then the vehicle $m$ sends a handshake packet to $n$ using its own mini-slot. After completing the handshake procedure, $m$ can exchange non-safety message using either slot of $m$, slot of $n$ or both slots if available.

For illustrations, three different scenarios for different pair (A, B), (C, D), and (E, F) are shown in Fig 4. Assume we have two vehicles, A [ID 6, SCH slot $(SCHch, SCHSlot) = (0, 1)$ ] and B [ID 23, SCH slot $(SCHch, SCHSlot) = (5, 3)$]. Where $SCHch$ and $SCHSlot$ indicate SCH channel number and SCH slot number on this channel respectively. Since the vehicle A and the vehicle B are on different SCHs slots and also not consecutive slot numbers on the SCHs, both A and B can use their default slots without any problem. In next example, vehicle C [ID 7, SCH slot $(SCHch, SCHSlot) = (1, 1)$] and D [ID 10, SCH slot $(SCHch, SCHSlot) = (4, 1)$], cannot use the same slot on different SCHs channels by C and D. If vehicle C wants to send a packet to D by its default slot, vehicle D should skip its default slot, and try to reallocate an unused slot to transmit its own packet. In the case of pair (E, D), where E [ID 8, SCH slot $(SCHch, SCHSlot) = (2, 1)$] and F [ID 15, SCH slot $(SCHch, SCHSlot) = (3, 2)$], if both vehicles E and F want to use their default SCH slots, then vehicle F should tune with two consecutive SCH slots. For this reason, using two consecutive SCH slots creates missing of safety/update messages. Therefore, to solve the problem, F should skip its default SCH slot and reallocates an unused SCH slot to complete the process. In the ETCM-BA, the chances of these types of problem are less than the ETCM-CA. The skipping of the default SCH slot is applicable only for V2V communication, not for V2R communication.

In V2R communication, the RSU communicates with one or more vehicles. Both RSU and the other vehicles use their default SCH slot to exchange non-safety messages. In the case of empty SCH slot reallocation, the V2R gets higher priority than V2V communication, because, most DSRC services are expected to be offered by the RSU [16].

## D. Reallocation of unused ETCM Slot

In reallocations of unused slots, vehicles monitor SCH slot status of other vehicles through the status information carried in CCH mini-slots. If the vehicle does not have any non-safety packets for transmission using default SCH slot, it gives the *"unused"* status information to other vehicles through the safety/update messages. Oppositely, if it has more non-safety messages, it can negotiate with another vehicle's unused default SCH slot after listening the status information. Those vehicles using even number position SCH slots can use only empty SCH slots at even position. Minimum two cycle is required to implement the reallocation of unused slot. The basic sequence is shown in Fig. 5. Assume, three vehicles X, Y, and Z belong to the even number position SCH slot and require 2, 3 and 0 SCH slots, respectively. At the first cycle, vehicles X and Y broadcast update messages containing information about their required slot to all neighbor vehicles. Since, the vehicle Z does not have any non-safety messages to use its default SCH slot, it can provide its own slot to others.

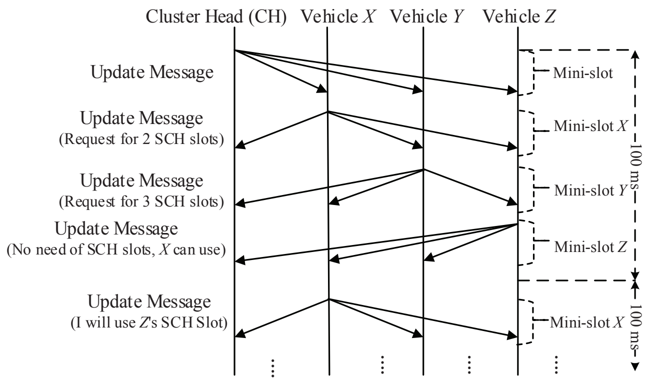


Fig. 5. Sequence Diagram for reallocating of SCH slot

Both vehicle X and Y request for the SCH slot but vehicle Z has only one slot.

In ETCM, the Shortest Job First (SJF) algorithm is used to give the prioritization to reallocate the empty SCH slots. In SJF algorithm, vehicles with smaller number of SCH slot usages are prioritized over vehicles that require more SCH slots. If two or more vehicles have requested for the same number of SCH slot, then the priority will be given to a vehicle with the smaller ID among the requesting vehicles for reallocating of unused SCH slots. Thus, according to SJF, the vehicle X gets the permission from Z to use the upcoming SCH slot of vehicle Z at the second cycle.

For example, vehicle ID 1 with default SCH slot position at the slot0 can use slot2, slot4... slot24, in any SCHs slots except its own CCH slot. Similarly, the vehicles using odd slots can only access the odd number position SCHs slots only. As shown in Fig.4, when vehicle with ID 6 has many non-safety packets while vehicles 18, 30, 42 do not have any packet. The vehicle 6 that listens the status information of vehicles 18, 30, 42 from the CCH mini-slots, and broadcasts required SCH slot information through update message to all vehicles. The three vehicles then apply SJF algorithm to make the priority among requested vehicles. At the next cycle, they give confirmation through their mini-slots regarding default SCHs slots. Also vehicle 6 broadcasts along with reallocating information to the receiver. It makes the receiver to tune to SCH slots of vehicles 18, 30, 42 … and to prevent access of those slots from others. If any vehicle does not get any empty SCH slot, it has to wait for the next MAC frame to transmit non-safety message. In Fig. 3, if vehicles with ID 6, 7, and 8 need more SCH slots; the vehicle 6 will get the vehicle 18's SCH slot, similarly vehicles 7 will get the vehicle 19's SCH slot, and so on.

## IV. Performance Evaluation

### A. *Simulation Configuration*

To analyze and compare the performances of the IEEE 1609.4, TC-MAC and the proposed ETCM protocol with the same operational conditions, a series of simulations were conducted using ns-3 simulator [17]. For VANETs mobility, we used the modules [18] which is based on Intelligent Driver Model (IDM) and the MOBIL lane change model. We assume that all vehicles are using single RF transceiver. The simulation parameters of the network are listed in Table II.

TABLE II. Simulation Parameters

| Parameter | Value |
|---|---|
| Data rate of each channel | 6Mbps |
| Number of CCH ($nSCH$) | 1 |
| Number of SCHs ($nCCH$) | 6 |
| Safety/update Packet Size (MAC payload size) | 200 bytes |
| Non-safety Packet Size (MAC payload size) | 1200 bytes |
| Transmission Power | 5.4 dBm |
| SINR Threshold | 7 dB |
| Transmission Range | 300 m |
| Frame Size | 100 ms |
| Simulation time | 100 s |
| IEEE 1609.4 WAVE [1] | |
| CCHI | 50 ms |
| SCHI | 50 ms |
| TC-MAC [7] [8] | |
| Mini Slot Size | 0.268 ms |
| SCH Slot Size | 1.6 ms |
| Total Number of SCH Slot in a Frame | 372 slots |
| Guard Interval (GI) | N/A |
| Inter Frame Gap (IG) | N/A |
| ETCM | |
| Mini Slot Size | 0.268 ms |
| SCH Slot Size | 3.76 ms |
| Non-safety Packet Size (MAC payload size) | 900 bytes |
| Total Number of SCH Slot in a Frame | 156 slots |
| Guard Interval (GI) | 50 $\mu$s |
| Inter Frame Gap (IG) | 800 $\mu$s |

The frame size is 100 ms for all protocols. In the IEEE 1609.4, all vehicles must tune to the CCH for safety messages during CCHI (50 ms), but vehicles can optionally switch to SCHs to exchange non-safety messages during SCHI (50 ms). In the ETCM scheme, all vehicles must monitor the CCH during the frame interval except its own SCH slot time and reallocated SCH slot times. In order to maximize the packet delivery ratio of safety/update messages, the ETCM allocates two mini-slots for each vehicle to transmit safety/update message in two consecutive slots in each sync interval (logical frame).

In the simulations, all vehicles are in one cluster (i.e., considered one hop range of each other). Each vehicle can be at random position, and it can be a source or a destination. As predefined data rates of CCH and SCHs [19], we use 6 Mbps as the lowest data rate for safety and non-safety applications. The safety/update messages have the bounded delay of 100 ms latency. So, when a vehicle generates a safety/update packet, the safety packet should be delivered within 100 ms, otherwise this safety packet is dropped.

### B. *Packet Delivery Ratio (PDR)*

The packet delivery ratio of safety messages is shown in Fig. 6. Each vehicle randomly generates the safety/update messages with constant packet interval rate of 10 packets/second. In the case of TC-MAC and ETCM, it is assumed that all vehicles in the cluster are engaged in communication during their default SCH time slot. So, if a vehicle is always active on its own SCH slot, this vehicle will miss all the safety/update messages from vehicles that have their mini-slots in the CCH at the same slot. In this condition TC-MAC provides better performance when the number of vehicles increase, because the ratio of the vehicles that switch from CCH to the SCHs from the total active vehicles reduces. However, the ETCM achieves substantial improvement over all protocols by successfully delivering the safety packets to

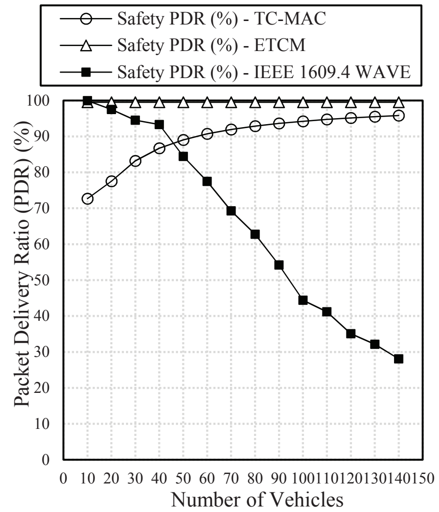


Fig. 6. Packet Delivery Ratio (PDR) of the safety messages

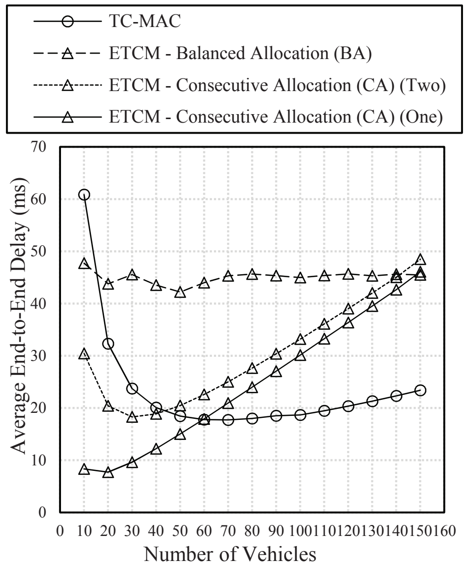


Fig. 7. Average End-to-End Delay of the safety messages

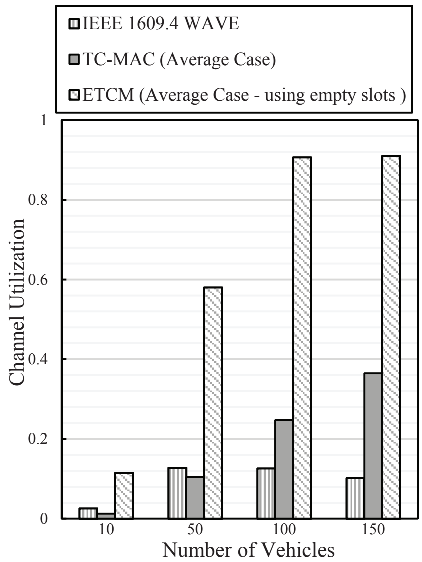


Fig. 8. Channel Utilization of the SCHs

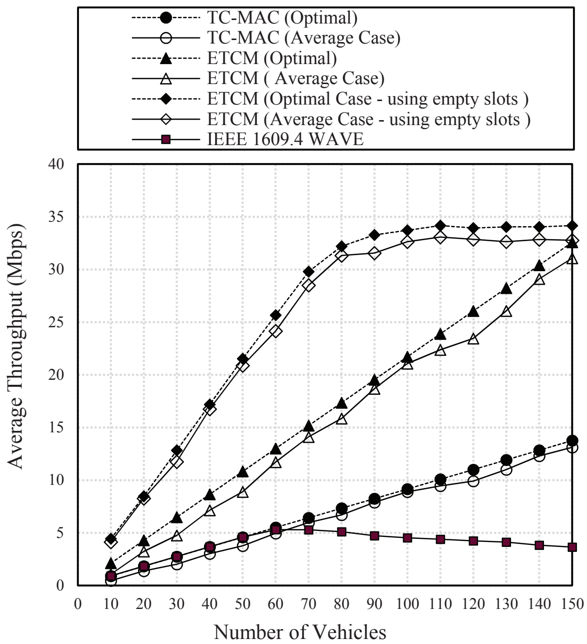


Fig. 9. Average Throughput of the non-safety message

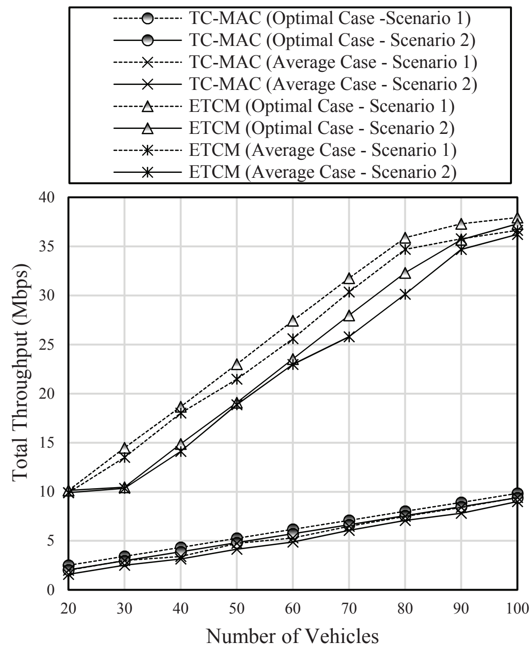


Fig. 10. Total Throughput of the safety and non-safety message

around 99% to the intended recipients using two mini-slots in consecutive of the sender vehicles. Even at high traffic load, it can still maintain the highest packet delivery ratio. The IEEE 1609.4 WAVE loses large number of safety/update packets at higher traffic load, since all generated safety packets could not be transmitted within the CCHI (50 ms) because of increased collisions.

### *C. Average End-to-End Delay*

Fig. 7 shows the average end-to-end delay of the safety messages. We observe that in TC-MAC, at lower number of vehicles, the average end-to-end delay is higher than the proposed ETCM. The ETCM-BA assigns pair of mini-slots to the new entering vehicles in uniform manner, while the ETCM-CA assigns pair of mini-slots from first mini-slot of the first slot to the last in sequential manner. At ETCM-CA we measure two types of average end-to-end delays: i) the end-to-end delay of two safety packets which are sent by each vehicle through the first and second mini-slots, and ii) the end-to-end delay of one safety packet which is received by the vehicles at the first time from the two safety packets through the first and second mini-slots.

### *D. Channel Utilization*

The channel utilization of the six SCHs as shown in Fig. 8. Both TC-MAC and ETCM use the average case which applies random pair selection where some of the pairs have the same time slot number in the SCHs, while the others not.

In the case of IEEE 1609.4 WAVE, because of the 50% utilization of the SCHs as well as packet collision when traffic density is high, the channel utilization is lower than others. As far as TC-MAC is concerned, its access mechanism is free of access collision, but it only uses default SCH slot as well as some pair of vehicles are engaged in communication on the SCHs has the same time slot number. Therefore, each frame has many empty SCH slots which are wasted. However, in ETCM, using default SCHs slots as well as re-allocation of unused slots, gives much better performance than others.

### *E. Throughput*

In Fig. 9, we can see that the different throughputs of optimal cases, where every pair of vehicles on the SCHs has a different time slot number, and average case, random pairs, of non-safety messages using TC-MAC and ETCM. In both cases, ETCM provides better performance than TC-MAC and IEEE 1609.4 WAVE. By implementing the dynamic reallocation of unused slot, the ETCM provides much higher throughput than the other protocols.

Fig. 10 shows the comparison of total throughput (both safety and non-safety throughput) between the TC-MAC and the Enhanced TDMA MAC. Two different scenario is observed by considering both optimal and average case. In Senario1, number of broadcasting vehicles are 50, RSU-to-Vehicles are 10, and Vehicle-to-Vehicle Nodes are 10, 20… 90 for non-safety message transmission. In case of Senario2, the number of broadcasting vehicles are 50, RSU-to-Vehicle Nodes are 20 and Vehicle-to-Vehicle Nodes are 0, 10, 20 …80 for non-safety message transmission. The number of currently active vehicles is 100 for both scenarios. In all cases the proposed Enhanced MAC shows much improved performance than TC-MAC.

## V. Conclusions and Future work

In this paper, we proposed an enhanced TDMA cluster-based MAC (ETCM) which provides i) enhanced performance with collision-free channel access and reliable time-critical safety message deliveries based on an enhanced logical frame structure that allocates two mini-slots for each vehicle in each 100ms sync interval, ii) enhanced service channel utilization with dynamic reallocation of unused slots, and iii) increased fairness among vehicles by balanced slot allocations.

The proposed ETCM protocol has been analyzed with a series of simulations using ns-3 network simulator. The simulation results show that the packet delivery ratio of safety messages was greatly enhanced with 99% delivery, and the throughput (channel utilization) was greatly improved from 10Mbps (in TC-MAC) to 25~30 Mbps (in ETCM) 7 channels (1 CCH and 6 SCHs) of 6 Mbps for a cluster of 100 vehicles. As future work, we will extend the research to VANET multi-rate and multihop wireless environment.

## Acknowledgment

This research was supported by Yeungnam University research grant in 2015. This research was also supported in part by the fellowship grants for higher education and research in information and communication technology program funded by the Ministry Posts, Telecommunication and Information Technology, Bangladesh under Grant (Stipends/Scholarships: 3-2801-0001-5963). Dr. Young-Tak Kim is the corresponding author.

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