Link-Layer Cooperation Based on Distributed TDMA MAC for Vehicular Networks

Sailesh Bharati, Weihua Zhuang, *Fellow, IEEE*, Lakshmi V. Thanayankizil, and Fan Bai, *Fellow, IEEE*

***Abstract*—Cooperative medium access control (MAC) protocols have been proposed for improving communication reliability and throughput in wireless networks. In our previous work, a cooperative MAC scheme called Cooperative ADHOC MAC (CAH-MAC) has been proposed to increase the network throughput under a static networking scenario for vehicular communications. In this paper, we study the effects of relative mobility among nodes and channel fading on the performance of CAH-MAC. In a dynamic networking environment, system performance degrades due to cooperation collisions. To tackle this challenge, we present an enhanced CAH-MAC (eCAH-MAC) scheme, which avoids cooperation collisions and efficiently utilizes cooperation opportunities without disrupting the time-slot reservation operations. Through mathematical analysis and computer simulations, we show that eCAH-MAC increases the effectiveness of node cooperation by increasing utilization of an unreserved time slot. Furthermore, we perform extensive simulations for realistic networking scenarios to investigate the probability of successful cooperative relay transmission and usage of unreserved time slots in eCAH-MAC, in comparison with existing approaches.**

***Index Terms*—Collision avoidance, cooperative communication, medium access control (MAC), time division multiple access (TDMA), Vehicular ad hoc networks (VANETs).**

I. INTRODUCTION

VEHICULAR ad hoc networks (VANETs) are expected to support a large spectrum of mobile distributed applications that range from collision warning and traffic alert dissemination (safety applications) to file-sharing and location-aware advertisements (infotainment). To support such diverse applications, a VANET consists of a set of vehicles, each equipped with one or more application units for running applications [2], an on-board unit for wireless communication, and a set of stationary units along the road called road-side units (RSUs). The development and operations of VANETs demand reliable and efficient communication protocols to support the wide range of applications. Although communication nodes (vehicles) are organized in an ad hoc manner to form a vehicular network, directly applying existing communication protocols designed for legacy mobile ad hoc networks may not be reliable and efficient.

The special characteristics of VANETs, such as the highly dynamic network topology (high node mobility with frequent link breakage) and stringent quality-of-service (QoS) requirements (for high priority delay sensitive safety messages) result in significant challenges in the design of an efficient medium access control (MAC) protocol. Although the IEEE 802.11p standard has been developed for MAC in VANETs [3], the protocol does not acknowledge any successful broadcast messages. Furthermore, with the random channel access, it suffers from unbounded latency and broadcast storm [4], [5]. On the other hand, high priority safety messages are short ranged, uncoordinated, and broadcast in nature [6]. They have a strict delay requirement and demand a reliable broadcast service. Distributed time division multiple access based MAC protocols, abbreviated as D-TDMA MAC, such as ADHOC MAC [4] and VeMAC [7], are proposed to facilitate reliable broadcast and point-to-point (P2P) communication in VANETs. Under a perfect channel condition, VeMAC has a smaller probability of transmission collisions and satisfies the strict QoS requirements as compared to the IEEE 802.11p standard [8]. However, due to VANET dynamic topology, the D-TDMA MAC protocols may lead to wastage of time slots. The wastage occurs when there are not enough nodes in a neighborhood to use all the time slots of a frame. In addition, upon a transmission failure, the source node has to wait until the next frame for retransmission even if the channel is idle during unreserved time slots. Hence, both the IEEE 802.11p standard and the existing D-TDMA MAC approaches are not free from packet dropping and throughput reduction due to a poor channel condition. Furthermore, these approaches can be inefficient in utilizing the available radio resources.

Link-layer cooperation among nearby nodes enhances the reliability of communication links and mitigates wireless channel impairments. In [9]–[11], a cooperation scheme for TDMA MAC is presented for infrastructure based wireless networks. In such networks, communication links are established between a central controller (or access point) and mobile nodes. Cooperation is performed by dedicated (fixed) helper nodes and coordinated by the controller. In [10], dedicated time slots are allocated for helper nodes, even if cooperation is not required. Hence, these schemes cannot be applied directly in VANETs. Differ-

---

Manuscript received November 5, 2015; revised April 15, 2016 and August 4, 2016; accepted November 1, 2016. Date of publication December 1, 2016; date of current version July 14, 2017. This work was supported in part by research grants from the Natural Sciences and Engineering Research Council of Canada and in part by General Motors Canada. This paper was presented in part at the IEEE International Communications Conference, Budapest, Hungary, June 2013 [1].

S. Bharati and W. Zhuang are with the Broadband Communication Research Laboratory, Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada (e-mail: sbharati@uwaterloo.ca; wzhuang@uwaterloo.ca).

L. V. Thanayankizil and F. Bai are with the Electrical and Controls Integration Laboratory, General Motors Global R&D, Warren, MI 48090 USA (e-mail: lakshmi.thanayankizil@gm.com; fan.bai@gm.com).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TVT.2016.2634545

ent from the existing works, when VANETs use D-TDMA, all operations such as cluster formation, slot allocation, and cooperation decisions must be performed in a distributed manner. In [12]–[17], node cooperation schemes with distributed cooperation decisions are presented. In [12], helper nodes perform dynamic cooperative retransmission to transmit packets to the target receivers during the source node's time slot. In the absence of helper nodes, the source node retransmits the same packet. On the other hand, in [13], helper nodes use their own time slots to relay the failed packets. Application of such cooperative retransmission to VANETs is not straightforward as each node with a time slot must broadcast its neighborhood information to its nearby nodes in every frame, in order to continue using its time slot in the next frame. In [14] and [15], cooperative retransmission for multihop communication is achieved using idle time slots. It requires acknowledgement (ACK) from the target relay node during the source node's time slot. Potential helper nodes participate in cooperation if they have the packet and do not receive ACK from the relay node. Such a scheme requires a large (and may be variable) time-slot duration in order to accommodate ACKs during the source node's time slot, which is not desirable as it adds communication overhead. When the number of vehicles with respect to the number of time slots per frame is high, there are not enough unused time slots to perform node cooperation. In [16], the cognitive radio technique to access the unlicensed channel is applied to perform opportunistic node cooperation, when the vehicle density is high. However, such a technique requires the knowledge of channel state information of the unlicensed channel at the cost of additional overhead in terms of signaling. To exploit benefits of node cooperation for D-TDMA MAC, cooperative ADHOC MAC (CAH-MAC) is proposed for VANETs [17]. In CAH-MAC, upon detecting a transmission failure between a source node and the destination node (an s–d pair), a helper node offers cooperation to relay the packet to the destination node during an unreserved time slot. As unreserved time slots are used, the nodes use their own time slots to broadcast their neighborhood information. Also, throughput improvement is achieved due to the usage of idle time slots that are wasted in the absence of node cooperation [17]. In addition, as the packet is retransmitted by a helper node, transmission delay and packet dropping rate are reduced [18]. However, CAH-MAC is only useful if the unreserved time slots selected for node cooperation are not selected for time-slot reservations. Conflicts occur, in the form of cooperation collisions, if the selected unreserved time slot is chosen by a node seeking a time slot. Thus, cooperation opportunities and time-slot reservation attempts fail, and disruption in D-TDMA MAC's operations occurs due to cooperation collisions. To tackle this problem, the existing node cooperation scheme must be improvised to avoid cooperation collisions, thus efficiently utilizing unreserved time slots for either cooperative relay transmissions (CRTs) or time-slot reservations.

In this paper, we study the impact of node cooperation in the operations of D-TDMA MAC. We present an improvised CAH-MAC with a collision avoidance scheme, referred to as enhanced CAH-MAC (eCAH-MAC). In eCAH-MAC, CRT is suspended if there is (are) any transmission attempt(s) from the one-hop node(s) of the destination and/or helper nodes, avoiding cooperation collision. CRT is performed only if the destination and helper nodes do not detect any potential transmissions in their one-hop neighborhood. Through mathematical analysis and simulations, we show that the proposed collision avoidance scheme increases the utilization of unreserved time slots by either allowing them to be reserved by nodes seeking their own time slots or using them to perform CRTs, without disrupting the D-TDMA MAC's normal operations. Furthermore, through extensive simulations we study the performance of eCAH-MAC over a practical channel model and relative node mobility. A real highway is replicated using PTV VISSIM [19], a microscopic multimodal traffic flow simulator, to generate vehicle mobility traces. Such mobility traces are used to simulate and evaluate the performance of the newly proposed eCAH-MAC, in comparison with CAH-MAC and ADHOC MAC.

The rest of this paper is organized as follows. Section II describes the system model and assumptions made for the protocol design. The enhanced CAH-MAC protocol is presented in Section III. Section IV presents performance analysis of eCAH-MAC in terms of efficient utilization of unreserved time slots, which is numerically validated in Section V with simulations. Furthermore, performance of eCAH-MAC in the presence of vehicle mobility over a practical channel model is presented in Section VI. Finally, Section VII provides a summary of our contributions and concludes this research.

II. SYSTEM MODEL

Consider a VANET consisting of $\aleph$ vehicles moving along a one-way multilane road. Vehicles are distributed randomly along the road and moving with the same average speed. Vehicles separated by more than the distance R, referred to as transmission range, cannot communicate with each other, taking account of a possible poor channel condition. Vehicles form sets of neighboring nodes that are in their one-hop and two-hop distance, referred to as one-hop set (OHS) and two-hop set (THS), respectively, based on information exchanged between nodes within their transmission range R. In the following, necessary assumptions, in terms of the network configuration and protocol layers, for tractability in establishing the analytical framework are discussed. As various symbols are used in this paper, summary of important symbols are given in Table I.

A. Channel Model

As the Nakagami-m channel model represents small-scale fading in vehicular communication and reflects a realistic driving environment [20], we consider a generalized Nakagami-m channel with correlated amplitudes. For the Nakagami-m channel, the probability density function of the received power by a node at distance r, in meters, from a transmitting node, denoted as γ_r, follows a gamma distribution and is given by [21]

$$f_{\gamma_r}(x) = \left(\frac{m}{\bar{\gamma}_r}\right)^m \frac{x^{m-1}}{\Gamma(m)} e^{\left(-m\frac{x}{\bar{\gamma}_r}\right)} \tag{1}$$

where $\Gamma(\cdot)$ is the gamma function, $\bar{\gamma}_r = \frac{P_t C}{r^\alpha}$ is the average received power at distance r from the transmitting node, P_t

TABLE I
SUMMARY OF IMPORTANT SYMBOLS

Symbol	Description
$\aleph$	The number of vehicles in the network
E_1	Event that an unreserved time slot is not selected by contending nodes
E_2	Event that an unreserved time slot is selected by only one contending node
F	The number of time slots per frame
G_r	Antenna gain of a receiver
G_t	Antenna gain of a transmitter
N_C	The number of contending nodes in a reference two-hop neighborhood
N_T	The number of nodes in a reference two-hop neighborhood
P_t	Transmission power
R	Transmission range of a node
U	The number of unreserved time slots in a frame
α	Path-loss exponent
β	The sum of time durations to sense the channel, transmit a cooperative ACK, and the guard time
β_1	The time duration during which a destination node sense the channel before CRT
β_2	The transmission time of a cooperative ACK plus the guard time
$\gamma_r\,(\bar{\gamma}_r)$	The (average) received power by a node which is at r meters from a transmitter
γ_{th}	Threshold received power level
ϵ_A	The utilization of an unreserved time slot in ADHOC MAC
ϵ_C	The utilization of an unreserved time slot in CAH-MAC
ϵ_E	The utilization of an unreserved time slot in eCAH-MAC
η	The ratio of the number of reserved time slots in a frame to the total number of time slots per frame
ρ	The vehicle density of a road segment
τ	The time duration between two time instances of received signal's amplitude
ϱ	The amplitude correlation coefficient of a received signal
θ	The slope value of effective velocity
f_c	The carrier frequency of signals
f_d	The average Doppler spread
m	The shape parameter of the Nakagami-m channel
o	The offset value of effective velocity
v_{eff}	The effective velocity between a receiver and a transmitter
v_r	The velocity of a receiver
v_t	The velocity of a transmitter

is the transmission power, α is the path-loss exponent, $C = G_t G_r (\frac{c}{4\pi f_c})^2$ is a constant, G_t and G_r are antenna gains at the transmitter and receiver, respectively, $f_c = 5.9$ GHz is the carrier frequency, $c = 3 \times 10^8$ m/s is the speed of light, and m is a distance-dependent shape parameter of the Nakagami-m channel, which is given as [22]

$$m = \begin{cases} 3, & r \leq 50 \\ 1.5, & 50 < r \leq 100 \\ 1, & r > 100. \end{cases} \tag{2}$$

In order to successfully decode a packet within the transmission range R from a source node, the instantaneous received power at the target destination node must be equal to or greater than a threshold received power, denoted as γ_{th}. All vehicles have the same P_t and γ_{th} values.

In the system under consideration, vehicles are moving in a one-way road with the same average speed. In [23], it is shown that when vehicles move relatively in a similar speed, the autocorrelation function can be approximated by Jake's model [24]. Furthermore, in [25], such approximation is validated with simulation in vehicular environment. Hence, the amplitude correlation coefficient of a signal received, denoted as ϱ, at two different time instants, separated by τ time units, can be realized by Jake's model and is given by [26]

$$\varrho = J_0^2(2\pi f_d \tau) \tag{3}$$

where $J_0(\cdot)$ is the zeroth-order Bessel function of the first kind and f_d is the average Doppler spread. The nature of a time-varying channel greatly depends on the normalized fading rates, which is the product of the average Doppler spread and sample time, i.e., $f_d\tau$ [27]. The average Doppler spread, f_d, of the time-variant vehicle-to-vehicle channel, on the other hand, depends on the effective speed, $v_{\text{eff}} = \sqrt{v_r^2 + v_t^2}$, where v_r and v_t are the velocities of receiver and transmitter, respectively. Moreover, f_d also depends on the driving environment where the receiver and transmitter are traveling, such as highway, rural and suburban environments. As mobile and stationary scatterers, such as foliage, pedestrians, and passing vehicles, are unavoidable, the presence of such scatterers greatly affect the Doppler spread [28] and eventually the channel variations. In [29], Cheng *et al.* present an experiment at 5.9 GHz and derive a close-form expression of Doppler spread in terms of the effective velocity and environment-dependent parameters and is given as

$$f_d = \frac{\theta}{\lambda\sqrt{2}} v_{\text{eff}} + o \tag{4}$$

where θ and o are environment-dependent parameters, referred to as slope and offset, respectively, whose values are given in Table IV for different environments.

B. Channel Access Mechanism

The channel access mechanism is based on distributed TDMA MAC protocols [4], [7], where the channel time is partitioned into frames and each frame is further partitioned into time slots. Each time slot is of a constant time interval and each frame consists of a fixed number of time slots, denoted by F. Each vehicle is capable of detecting the start time of a frame and, consequently, the start time of a time slot based on the one-pulse-per-second signal [30] that a global positioning system receiver gets every second. Nodes support broadcast, multicast, or P2P modes of communication. However, for the protocol performance evaluation, we consider nodes communicating in a P2P mode only.

C. Reservation, Retention, and Release of Time Slots

At the beginning of each time frame, a node prepares to transmit in its own time slot, if it already has a reserved time slot, or selects a time slot to perform reservation attempt based on its neighboring sets, otherwise. Nodes belonging to the same THS contend with each other to reserve a time slot. To reserve a time slot, a node first listens to the channel over the period of F consecutive time slots (not necessarily in the same frame), then attempts to reserve one time slot among the unreserved ones, if available. A node reserves a time slot by transmitting its frame information (FI) that consists of neighborhood information and time-slot usage information (to be discussed). Collisions occur when multiple THS nodes, i.e., nodes that are within each others' two-hop transmission distance, transmit during the same time slot. The node successfully reserves a time slot if there is no collision and all the OHS member nodes have successfully received the FI.

We focus on the control channel, which is used to broadcast safety messages and control information among one-hop neighbors and for negotiation between a pair of nodes for P2P communication. With a focus on cooperation to improve transmission efficiency, we consider a network where vehicles have information to transmit, targeting specific destination nodes in each frame. Thus, a node accesses the channel once in every frame in its own time slot and transmits a packet that may consist of FI, packet header (PH), payload data, and cyclic redundancy check (CRC), and makes cooperation decisions (as discussed in [17]). The FI is a collection of ID fields (IDFs) of neighboring nodes and helps a node to maintain neighborhood information that includes:

1) all of its one-hop neighbors;
2) all of its two-hop neighbors;
3) the owner of each time slot in a frame.

A node announces time-slot ownerships among its one-hop neighbors if it successfully received the packet in the previous frame. If there is no signal in a time slot or a node fails to receive a packet transmitted during the time slot, the node considers it as an unreserved time slot. In such a case, corresponding IDFs of the unreserved time slots are left empty in the FI. Hence, successful reception of FIs helps a node to extract its neighborhood information, such as IDs of the one-hop neighboring nodes and their corresponding time slots. Also, FI can be used to detect transmission failures due to poor channel conditions and transmission collisions. A node releases or continues using its time slot based on the FIs received from its OHS neighbors. A node releases its time slot if it fails to detect its ID in FIs received from at least one of its OHS member nodes. To avoid unnecessary loss of time slots, a node does not use FI from any new one-hop node that is not in its OHS. However, upon receiving FI from new one-hop nodes, the node updates its OHS. Hence, in the network, there are nodes with and/or without their own time slots. In this paper, nodes without (with) their own time slots and seeking for one are referred to as contending (resident) nodes, as they contend for time slots in (continue to be a resident of) the corresponding two-hop neighborhood.

Due to channel fading and relative mobility, a node can fail to reserve or retain a time slot; hence, contending nodes remain as contending nodes or resident nodes become contending nodes, respectively, in the next frame. Access collisions occur when two or more contending nodes in the same two-hop neighborhood try to reserve the same unreserved time slot. Furthermore, in the presence of contending nodes, cooperation collisions may occur during unreserved time slots among reservation packets from contending nodes and CRTs.[1] Hence, with the introduction of node cooperation, cooperation collisions occur in D-TDMA MAC between reservation attempt(s) from a contending node(s) and CRT [either cooperative ACK (C-ACK) from a destination node or relayed packet from a helper node or both]. Under such a situation, both CRT and time-slot reservation fail and contending nodes have to wait longer to acquire time slots. On the other hand, most of the time only resident nodes get an opportunity to access the channel for direct and/or CRT. Furthermore, cooperation collisions occur when CRT is performed during a time slot belonging to an existing user. For instance, if a helper node chooses an unreserved time slot to help an s–d pair, collision occurs when a node, which owns the selected unreserved time slot, enters the region where the s–d pair and helper node reside. Under such a case, conflict arises between transmission from newly joined node and scheduled CRT.

A merging collision occurs when resident nodes using the same time slot but belonging to different THSs approach each other, resulting in a transmission collision in the corresponding time slot [31]. A resident node, after suffering from a merging collision, releases its own time slot and attempts to reserve an unreserved time slot. Moreover, merging collisions result in an increase in the number of contending nodes, which likely lead to an increase in the rate of access and/or cooperation collisions. In [31], it is shown that ADHOC MAC suffers from throughput reduction due to node mobility. To overcome the throughput reduction, VeMAC is proposed in [7]. In VeMAC, time slots are separated into three disjoint groups, dedicated to vehicles moving in opposite directions and to RSUs, respectively. Separation of the time slots into three disjoint groups alleviates throughput reduction due to node mobility.

A node releases its time slot if it suffers from transmission failure or transmission collision. Upon releasing its time slot, the node seeks a new one. Also, a node that is without a time slot prior to joining the network seeks a time slot after it joins the network. Furthermore, due to the relative mobility, a node may enter a new THS where its neighboring nodes are not aware of its arrival. If the node owns an unreserved time slot, with respect to the new THS, it keeps on using it as there will not be any conflict. However, a collision occurs if the unreserved time slot is selected to perform CRT. With a focus on analyzing the performance of node cooperation, we consider that a node continues using its time slot in the next frame, if it successfully delivers its packet to all the nodes in its OHS in the current frame. Otherwise, it releases the time slot, becomes a contending node, and seeks for a time slot in the next frame. Hence, by the end of each frame, a resident node may lose its time slot and/or a contending node may successfully reserve one. Consequently, a frame consists of reserved and unreserved time slots at the beginning of the next frame. The number of reserved (or unreserved) time slots depends on channel quality, relative mobility, and other networking scenarios.

III. ENHANCED NODE COOPERATION

The cooperation decisions can lead to cooperation collisions resulting in the failure in time-slot reservation and CRT. Hence, in this section, we present the approach in the eCAH-MAC scheme to avoid cooperation collisions. In eCAH-MAC, we propose to use different types of packet structure to resolve coop-

---

[1] In CAH-MAC [17], i.e., node cooperation enabled D-TDMA MAC, a destination node initiates CRT by transmitting cooperation ACK (C-ACK) to a target helper node. When the helper node detects the C-ACK, it transmits a packet with payload data to the destination node following reception of C-ACK.

eration collisions. In the following, we present different packet types and a novel collision avoidance scheme for eCAH-MAC.

A. Types of Packet Structure

A resident node transmits a packet in order to exchange its FI and payload data to the nearby nodes during its own time slot. The resident node must deliver the FI to all nodes in its OHS, to continue using its time slot in the next frame, and payload data to the target destination. Furthermore, a resident node may transmit a packet during an unreserved time slot to perform CRT. In such a case, the resident node must deliver the payload data to the target destination(s). On the other hand, a contending node transmits a packet during an unreserved time slot to reserve the time slot for accessing the channel. Thus, the contending node must deliver its FI to all the nodes in its OHS, during the selected unreserved time slot, to successfully reserve the time slot. Hence, it is not necessary to transmit the same information, with the same packet structure or fields, for the aforementioned scenarios. Based on the operations, we define three type of packets that a node can transmit during a time slot, as described below.

1) General (*Type-G*) packet consisting of FI, PH, payload data, and CRC, which is transmitted by a resident node to exchange messages to its nearby nodes. A node transmits Type-G packet only during its own time slot to deliver its FI to the OHS nodes and payload data to the target destination(s). Furthermore, the packet may have a cooperation header if the transmitting node decides to help an s–d pair that failed to exchange a packet during the source node's time slot [17].
2) Reservation (*Type-R*) packet consisting of FI, PH, and CRC, which is transmitted by contending nodes to perform time-slot reservation. A node first reserves a time slot to access the channel using a Type-R packet (without payload data), then starts to transmit a Type-G packet to exchange payload data with its one-hop neighbor node(s) during the acquired time slot.
3) Cooperation (*Type-C*) packet consisting of a PH, payload data, and CRC, which is transmitted by a helper node to perform CRT. As the helper node has its own time slot to transmit Type-G packets, it is not necessary to transmit its FI during CRT.

In addition to these three types of packet, C-ACK is transmitted by a destination node to start the CRT phase, which consists of the ID of the helper node, as described in [17]. In the following, advantages of using different packet types in eCAH-MAC are discussed.

B. Cooperation Collision Avoidance

In CAH-MAC[17], cooperation decisions, such as selection of helper nodes and unreserved time slots, to perform CRT are performed in a distributed manner. If there are multiple potential helper nodes, the one which first announces to help will relay the packet, while all other potential helper nodes suspend their intention to help for the corresponding s–d pair. Furthermore, an unreserved time slot, among all the available ones, is selected randomly by a potential helper node to perform CRT. A cooperation collision occurs if the unreserved time slot selected for CRT is accessed by a contending node. One possible way to avoid cooperation collisions is to delay the CRT by some time interval, say β_1 time units. The duration of β_1 units must be long enough for a node to sense whether the channel is idle or busy, such as the distributed interframe space in the IEEE 802.11 based MAC protocols [32]. During the selected unreserved time slot, the destination node waits for β_1 time units and then transmits C-ACK if the channel is idle during the waiting time, which is illustrated in Fig. 1. Note that in CAH-MAC, the destination node transmits C-ACK as soon as the unreserved time slot starts, i.e., $\beta_1 = 0$. The helper node, after receiving its ID in C-ACK from the destination node, transmits a payload data from the source after a guard time. Since the length of C-ACK (in bits) and guard time are constant, the helper node always performs CRT after the fixed duration from the start of a time slot, i.e., $\beta = \beta_1 + \beta_2$ time units as in Fig. 1, where β_2 time units correspond to the transmission time of C-ACK plus the guard time.

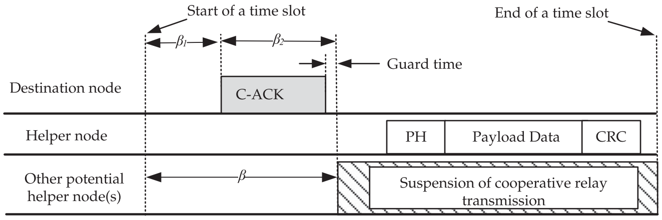


Fig. 1. CRT in eCAH-MAC during an unreserved time slot.

A helper node transmits a Type-C packet to perform CRT. As each node has its own normal time slot in which it transmits a complete packet with FI, repeated transmission of a copy of the same FI during CRT is unnecessary. The absence of FI compensates for the delayed time of CRT phase and does not affect the normal operation of D-TDMA and node cooperation. Hence, the transmission of C-ACK and a Type-C packet helps to avoid collision among helper or destination nodes and contending nodes during the CRT.

A contending node may access the unreserved time selected for cooperation. When the destination node detects transmission(s) from the contending node(s), it suspends the cooperation or transmission of the C-ACK. As the helper node does not receive C-ACK, it also suspends CRT. The helper node makes a decision to suspend CRT after β time units from the start of a time slot. A collision occurs if a contending node and the destination node are in each others' two-hop distance but not in one-hop distance. In such a case, the destination node does not sense the transmission from the contending node and transmits C-ACK, resulting in a transmission collision at their common one-hop nodes and/or helper node. To avoid such a collision, both the helper and destination nodes must suspend the CRT. One possible way to force both the destination and helper nodes to suspend cooperation is by using energy-burst or channel jamming signal, also known as black–burst [33]. Black–burst has been used in wireless networks to inform neighboring nodes about the channel usage and to avoid transmission collisions

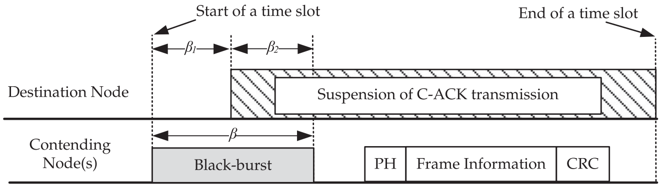


Fig. 2. Suspension of a CRT by the destination node in the presence of the contending node(s) in its one-hop distance.

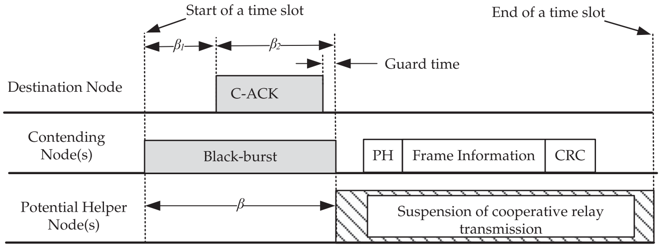


Fig. 3. Suspension of a CRT by the helper node after failing to receive C-ACK.

by forcing neighboring nodes to delay or suspend their transmissions [34], [35]. In eCAH-MAC, a contending node uses black–bursts to inform destination and/or helper nodes about its intention to perform reservation attempt followed by the transmission of a Type-R packet. The contending node transmits a black–burst of β time units. If the destination node is in the one-hop neighborhood of the contending node, it suspends the CRT after finding the channel busy. On the other hand, if the destination node finds an idle channel, it transmits C-ACK. The transmitted C-ACK collides with the black–burst at helper node's receiver and helper node suspends CRT. After transmitting a black–burst, a contending node transmits a Type-R packet to reserve the corresponding time slot. The suspension of CRT is illustrated in Figs. 2 and 3. Delaying the CRT phase and the use of a black–burst by contending node allow the destination and/or helper nodes to detect time-slot reservation attempts from contending nodes, to avoid cooperation collisions. Access collisions occur if two or more contending nodes transmit black–burst signals and their corresponding Type-R packets during the same unreserved time slot.

To summarize, the use of three packet types, use of black–bursts to reserve a time slot, and suspension and/or delay of CRT phase allow to avoid cooperation collision and, thus, efficiently use unreserved time slots either to perform CRTs or time-slot reservations. In Section IV, we derive a close-form expression for the utilization of an unreserved time slot in eCAH-MAC.

IV. UTILIZATION OF AN UNRESERVED TIME SLOT

Reserved time slots are used in a similar manner in cooperation enabled transmission to that without cooperation. However, with node cooperation enabled, unreserved time slots, if used, are used for either time-slot reservations or CRTs. Hence, the performance of node cooperation in eCAH-MAC must be evaluated based on how efficiently it utilizes unreserved time slots in comparison with that of D-TDMA MAC, such as ADHOC MAC. The objective of such analysis is to study the effectiveness of node cooperation in utilizing unreserved time slots, without affecting the normal operations of D-TDMA MAC. Specifically, we intend to study how an unreserved time slot is utilized in the presence of node cooperation. For tractable analysis, following assumptions are made.

1) A packet is transmitted only once by the source and/or the helper nodes.
2) Cases where a failed direct transmission does not find a helper node and/or unreserved time slot to perform cooperation are ignored. Details of node cooperation and its performance due to the existence of potential helper nodes and unreserved time slots are presented in [17]. In this study, we focus on how node cooperation affects time-slot reservation, which is one of the important operations in D-TDMA MAC.
3) With a focus on impact of node cooperation in the operation of D-TDMA MAC, only the unreserved time slots chosen to perform CRTs are considered. Time slots that are not chosen for cooperation will not be affected by node cooperation, hence we ignored those cases in the following.
4) We define a parameter $\eta \in (0, 1]$, referred to as reserved ratio, which is the ratio of the number of reserved time slots in a frame to the total number of time slots per frame, F. The η (or $1-\eta$) value reflects the number of reserved (or unreserved) time slots and depends on channel quality, relative mobility, and other networking aspects. At the beginning of a time frame, ηF time slots are allowed to be reserved. Accordingly, at least $(1-\eta)F$ time slots are unreserved time slots and are left for contending nodes to perform reservation attempts.

To derive a close-form expression for the utilization of unreserved time slots, we consider the following events that can occur during an unreserved time slot selected for CRT.

1) $Event\ 1$ (E_1): None of the contending nodes in the THS of both the helper and destination nodes sharing a common frame attempts to access the unreserved time slot;
2) $Event\ 2$ (E_2): Only one contending node in the THS of both the helper and destination nodes sharing a common frame transmits its reservation packet during the selected unreserved time slot.

Next, we derive necessary probability distribution functions required to obtain the probability of the aforementioned events.

A. Distribution of Node Number

At a given instance, the vehicles are distributed randomly following an exponential distribution. Hence, the probability mass function (pmf) of the number of nodes sharing the same frame, also referred to as THS nodes and denoted as N_T, is given as [17]

$$\Pr\{N_T = n_t\} = \frac{(2\rho R)^{n_t} e^{-2\rho R}}{n_t!}, \qquad n_t = 0, 1, 2, ... \qquad (5)$$

where ρ is vehicle density in terms of the number of vehicles per unit length of the road segment. For a time slot to be called as reserved (or unreserved) or for a frame to exist, there must be at least one node in the corresponding THS, i.e., $N_T \geq 1$. Let N_C denote the number of contending nodes in a THS. Contending node exists if $N_T > \eta F$, such that ηF nodes have their own time slots and the remaining are contending nodes seeking their own time slots. Thus, given the reserved ratio, η, the number of contending nodes in a THS can be written as

$$N_C = \begin{cases} 0, & N_T \leq \eta F \\ N_T - \eta F, & N_T > \eta F. \end{cases} \tag{6}$$

Hence, from (5) and (6), the pmf of N_C can be written as

$$\Pr\{N_C = n_c\} = \begin{cases} \sum_{n_t=0}^{\eta F} \dfrac{(2\rho R)^{n_t} e^{-2\rho R}}{n_t!}, & \text{if } n_c = 0 \\ \frac{(2\rho R)^{\eta F + n_c} e^{-2\rho R}}{(\eta F + n_c)!}, & n_c > 0. \end{cases} \tag{7}$$

Let U denote the number of unreserved time slots in a frame. We have

$$U = \begin{cases} F - N_T, & N_T < \eta F \\ F - \eta F, & N_T \geq \eta F. \end{cases} \tag{8}$$

Note, a contending node, if exists ($N_C > 0$ or $N_T > \eta F$), attempts to transmit a packet during an unreserved time slot. Among $F - \eta F$ available unreserved time slots in a frame, a contending node selects one randomly. Thus, a contending node chooses a given unreserved time slot with probability $\frac{1}{F-\eta F}$. Consequently, the probability that a contending node does not choose the given unreserved time slot is $\frac{F-\eta F-1}{F-\eta F}$. Furthermore, if a THS does not contain any contending nodes, i.e., if $N_C = 0$ or $N_T \leq \eta F$, unreserved time slots are not selected to perform reservation attempts. Based on these probability values, next we will derive the probability of occurrence of $Events$ 1 and 2, and use them to derive the required close-form expressions.

B. Probability of $Event$ 1

A contending node performs reservation during an unreserved time slot. Hence, an unreserved time slot remains idle, i.e., $Event\ E_1$ occurs, if none of the contending nodes in the corresponding THS attempt to access it. Based on discussion in the Section IV-A, given $N_C = n_c$ and $N_T = n_t$, the probability of $Event\ E_1$ occurrences can be written as

$$\Pr\{E_1 | N_C = n_c, N_T = n_t\} = \begin{cases} 1, & n_t \leq \eta F \\ \left(\frac{F-\eta F-1}{F-\eta F}\right)^{n_c}, & n_t > \eta F. \end{cases} \tag{9}$$

Consequently, from (6) and (9), we have

$$\Pr\{E_1 | N_C = n_c\} = \begin{cases} 1, & n_c = 0 \\ \left(\frac{F-\eta F-1}{F-\eta F}\right)^{n_c}, & n_c > 0. \end{cases} \tag{10}$$

From (7) and (10), the probability that an unreserved time slot is not selected by contending nodes, i.e., the probability of $Event$ 1 occurrences, can be written as

$$\Pr\{E_1\} = \sum_{n_t=0}^{\eta F} \frac{(2\rho R)^{n_t} e^{-2\rho R}}{n_t!} + a^{-\eta F} e^{-2\rho R} \left(e^b - \sum_{n_c=0}^{\eta F} \frac{b^{n_c}}{n_c!}\right) \tag{11}$$

where $a = \frac{F-\eta F-1}{F-\eta F}$ and $b = 2\rho R a$.

C. Probability of $Event$ 2

$Event\ E_2$ occurs if only one contending node attempts to access the unreserved time slot selected for node cooperation. Hence, given $N_C = n_c$ and $N_T = n_t$, the probability of $Event\ E_2$ occurrences can be written as in (12), shown at the bottom of this page.

Consequently, from (6) and (12), the probability of $Event\ E_2$ occurrences given $N_C = n_c$ can be written as in (13), shown at the bottom of this page. From (7) and (13), the probability that an unreserved time slot is selected by only one contending node, i.e., the probability of $Event$ 2 occurrences, can be written as

$$\Pr\{E_2\} = \left(\frac{1-a}{a^{\eta F+1}}\right) e^{-2\rho R} \times \left[(b - \eta F)e^b + \sum_{n_c=0}^{\eta F-1} (\eta F - n_c) \frac{b^{n_c}}{n_c!}\right]. \tag{14}$$

D. Close-Form Expressions for Time-Slot Utilization

In ADHOC MAC, as cooperation is not enabled, a successful time-slot reservation guarantees the efficient utilization of the unreserved time slot. With cooperation enabled transmission, in addition to successful time-slot reservation, successful CRT further guarantees the efficient utilization of unreserved time slots. In the following, we use the probabilities of event occurrences from the previous subsections to derive the utilization of an unreserved time slot for ADHOC MAC, CAH-MAC, and eCAH-MAC.

In ADHOC MAC, an unreserved time slot is referred to as efficiently utilized if only one contending node chooses it to

---

$$\Pr\{E_2 | N_C = n_c, N_T = n_t\} = \begin{cases} 0, & n_t \leq \eta F \\ n_c \left(\frac{1}{F-\eta F}\right)\left(\frac{F-\eta F-1}{F-\eta F}\right)^{n_c-1}, & n_t > \eta F \end{cases} \tag{12}$$

$$\Pr\{E_2 | N_C = n_c\} = \begin{cases} 0, & n_c = 0 \\ n_c \left(\frac{1}{F-\eta F}\right)\left(\frac{F-\eta F-1}{F-\eta F}\right)^{n_c-1}, & n_c > 0 \end{cases} \tag{13}$$

TABLE II
PARAMETERS USED IN SIMULATION

Parameter	Value
Path-loss exponent (α)	2,3, and 4
Antenna gains at receiver and transmitter nodes (G_r and G_t)	0 dB
Transmission power (P_t)	20 mW
Threshold received power (γ_{th})	95 dBm
Transmission range (R)	100 m
Number of time slots per frame (F)	50
Time-slot duration	1 ms
Simulation time	120 s

perform reservation. In other cases, i.e., if it remains unused or more than one contending nodes transmit their reservation packets, the unreserved time slot is wasted. Hence, the utilization of an unreserved time slot in ADHOC MAC, denoted as ϵ_A, can be written as

$$\epsilon_A = \Pr\{E_2\}. \tag{15}$$

On the other hand, in CAH-MAC, an unreserved time slot selected for cooperation is considered to be efficiently utilized if none of the contending nodes choose it to perform reservation. A cooperation (access) collision occurs if at least one contending node chooses to reserve the unreserved time slot selected to perform CRT. Hence, the utilization of an unreserved time slot in CAH-MAC, denoted as ϵ_C, can be written as

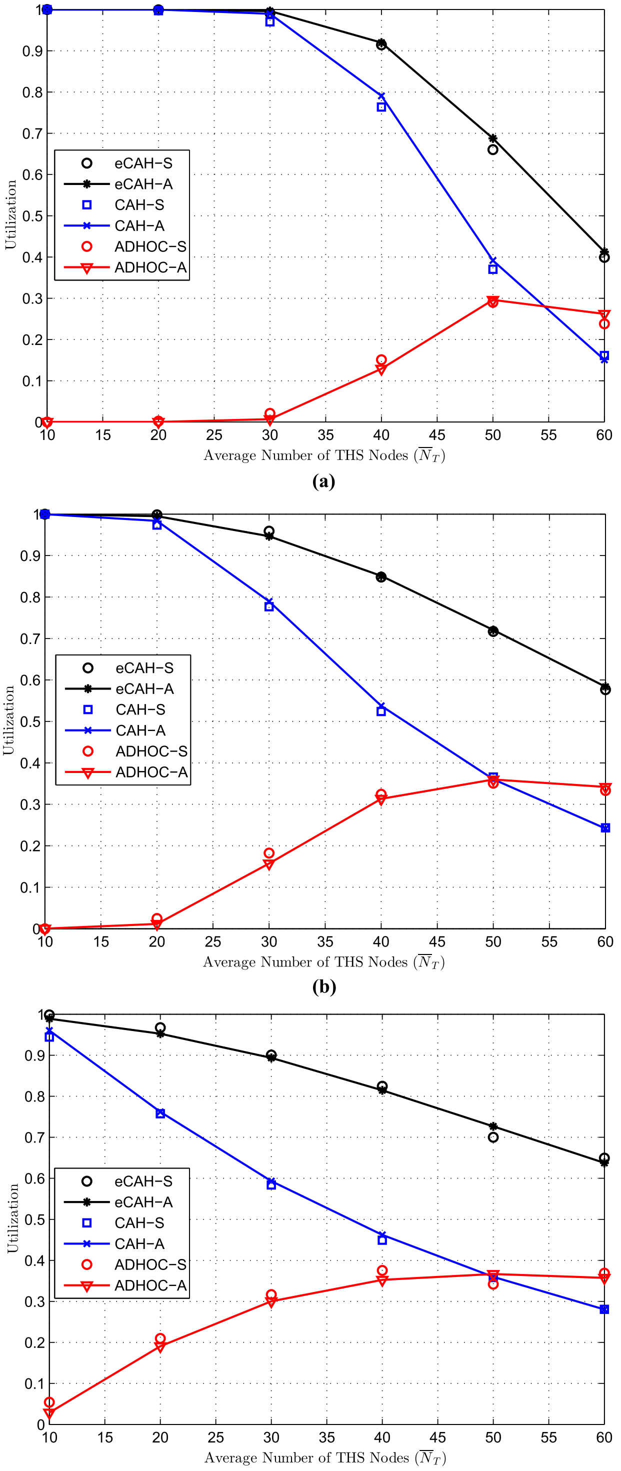
$$\epsilon_C = \Pr\{E_1\}. \tag{16}$$

Finally, in eCAH-MAC, an unreserved time slot selected for cooperation is considered to be efficiently utilized if it is used to perform either CRT, if none of the contending node chooses it, or reservation attempt is performed by only one contending node. Hence, the utilization of an unreserved time slot in eCAH-MAC, denoted as ϵ_E, is given by

$$\epsilon_E = \Pr\{E_1\} + \Pr\{E_2\}. \tag{17}$$

V. NUMERICAL RESULTS

In this section, we present numerical results obtained from simulations to analyze the performance of eCAH-MAC. Simulations are performed in MATLAB with parameters given in Table II. Vehicles are distributed following the Poisson distribution along a road segment of length 10 km with three lanes.[2] Furthermore, free-flow node mobility as in [36] is considered, such that at the beginning of simulation vehicles choose their speed following a truncated normal distribution,[3] with mean velocity 100 km/h, standard deviation of velocity 20 km/h, maximum velocity 130 km/h, and minimum velocity 90 km/h. Vehicles then move with the same speed value throughout the simulation. Moreover, vehicles exiting from one end of the road segment re-enter from the other end. To avoid any unrealistic loss of time slot, a vehicle that is at a distance r from one end of the road segment can communicate with vehicles which are at a distance $R - r$ from the other end, such that vehicles do not break their communication even after exiting from one end of



(a)

(b)

(c)

Fig. 4. Comparison of utilization of unreserved time slots in eCAH-MAC, CAH-MAC, and ADHOC MAC with (a) $\eta = 0.80$, (b) $\eta = 0.50$, and (c) $\eta = 0.20$.

---

[2] A line represents a lane that is 5 m away from its adjacent lane(s). Vehicles are represented by points on the lines representing lanes.

[3] Velocities that are more than maximum velocity and less than minimum velocity are ignored while drawing speed of a vehicle. Moreover, maximum and minimum velocities are kept the same as the default VISSIM parameters, to make it consistent with the simulation setup in the next section.

TABLE III
VISSIM SIMULATION PARAMETERS

Car following (Wiedemann99)				**Lane changing**			**Vehicle characteristics**			
Parameter	***Value***	***Parameter***	***Value***	***Parameter***	***Lane changer***	***Trailing vehicle***	***Parameter***	***Car***	***HGV***	***Bus***
CC0	1.5 m	CC1	0.90 m	Maximum deceleration	-4 m/s^2	-3 m/s^2	Average length	4.44 m	11.54 m	11.54 m
CC2	4.0 m	CC3	-8.0	$-1 m/s^2$ per distance	200 m	200 m	Width	1.5 m	2.5 m	2.5
CC4	-0.35	CC5	0.35	Accepted deceleration	-1 m/s^2	-0.50 m/s^2	Percentage of the total # vehicles	80%	15%	5%
CC6	11.44	CC7	0.25 m/s^2	**Simulation time**: 5 minutes			Desire speed dist. (Km/h)	U(90,130)	U(85,120)	U(85,120)
CC8	3.5 m/s^2	CC9	1.50 m/s^2	Units in meter and second are denoted by m and s, respectively. Furthermore, default VISSIM parameters such as maximum/desired acceleration and deceleration functions for cars, HGVs and buses are used as described in [19].						

the road segment and entering from the other end. Utilization of eCAH-MAC, CAH-AMC, and ADHOC MAC is obtained and compared for several η values to validate the close-form expressions for time-slot utilization derived in Section IV.

Fig. 4 compares the utilization with $\eta = 0.8,\ 0.5$, and 0.2, respectively. It can be seen that the analytical results match well with simulation results, thus validating the close-form expressions for utilization of unreserved time slots selected for CRT. For a given average number of two-hop nodes, denoted by $\overline{N}_T = 2\rho R$, the larger the η value, the higher the utilization of unreserved time slot. This is obvious as a larger η value results in a lesser number of contending nodes, i.e., a lesser number of reservation attempts, and consequently, a lesser number of cooperation collisions. However, for a larger $\overline{N}_T$ values, the utilization decreases with an increase in η values, for eCAH-MAC and ADHOC MAC. This is because the lesser the η value, the larger the number of contending nodes and unreserved time slots, which results in successful time-slot reservation and increases the utilization. As the average number of THS nodes increases, the utilization decreases in cooperation enabled transmission. As the $\overline{N}_T$ value increases, the average number of contending nodes increases, increasing the number of reservation attempts. Such reservation attempts improve the performance of ADHOC MAC and eCAH-MAC (as unreserved time slots are used for reservations). However, in CAH-MAC, it decreases the performance due to cooperation collisions. When the average number of THS nodes is high, CAH-MAC performs worst among all the D-TDMA MAC (e.g., $\overline{N}_T > 50$ in both the cases). This is because at a high $\overline{N}_T$ value, reservation attempts by a contending node during an unreserved time slot will fail due to CRT. Thus, it reduces the utilization value as both time slot access and CRT fail.

VI. SIMULATION RESULTS

Computer simulations with a practical channel model and vehicle mobility traces are conducted to evaluate the performance of eCAH-MAC and compare it with that of CAH-MAC and ADHOC MAC. To simulate mobility among nodes, we use a well-known vehicle traffic simulator PTV VISSIM [19] and MATLAB. Real road networks are replicated in VISSIM to generate vehicle traces. We consider a road network based on a segment of Highway 401 of the province of Ontario in Canada. To keep vehicles in the simulation, a ring of highway segment, of length approximately 4 km with three lanes, is formed, such that the vehicles keep moving in the ring throughout the simulation. Road segments, speed limits, and other traffic rules are defined based on realistic observations. Vehicles such as cars, heavy goods vehicles (HGVs), and buses are included. Vehicles follow the Wiedemann99 Car Following Model [37] to follow the headway traffic. Based on these models, appropriate decisions are made to perform lane changes, left or right turns, and to follow the vehicle in front.

At the start of simulations, vehicles are injected to the road networks with rate 2100, 2400, and 7200 vehicle per hour. After the injection period of 5 min, the vehicle injection is stopped and the number of vehicles in the network, i.e., $\aleph$, becomes 364, 496, and 622, respectively, for each vehicle injection rates. The generated vehicles are allowed to move according to the corresponding traffic rules and road network parameters. To reduce any transient state effects, vehicle traces are not recorded for a warm-up period of 5 min (after the injection period). When the warm-up period ends, vehicle traces are recorded at the interval of 0.1 s till the end of simulation. The simulation time is the time interval between the end of the warm-up period and the end of simulation, i.e., actual start of simulation is considered only after the end of the warm-up period. The generated vehicle traces consist of vehicle positions and speeds at a given time. Such vehicle traces are used to simulate the performance of eCAH-MAC, which is compared with that of CAH-MAC and ADHOC MAC. The VISSIM simulation parameters are given in Table III.

To realize a practical channel, autocorrelated Nakagami-m envelope sequences are generated based on [38], such that the generated sequence follows the rank statistics of the reference

TABLE IV
PARAMETERS FOR DOPPLER SPREAD IN DIFFERENT DRIVING ENVIRONMENTS [29]

Parameter	Rural	Highway	Suburban
Offset (o)	0.500	0.200	11.20
Slope (θ)	0.420	0.414	0.428

Rayleigh sequence that is generated based on the Jake model [24]. Correlation coefficient is generated as in (3) and (4), with slope and offset for highway environment as in Table IV. Other simulation parameters are given in Table II.

Fig. 5 shows the fractions of resident and contending nodes, and reserved and unreserved time slots in a THS sharing a common frame, for various channel conditions. As the channel degrades, a large number of nodes lose their time slots and become contending nodes. Consequently, more time slots are left unreserved in the corresponding frame. Also, Fig. 5(c) shows the frame-by-frame status of time slots, during a stable state after the initial transitions. At the beginning of the simulation, all nodes in the network try to access the channel, which results in collision. In the steady state, for a given networking scenario, the fractions of reserved (unreserved) time slot remains constant at each time frame.

To study the effects of node cooperation on the operations of D-TDMA MAC, the performance of eCAH-MAC is evaluated based on how efficiently an unreserved time slot selected for CRT is used. To do so, we ignore unreserved time slots during which 1) two or more contending nodes perform reservation attempts, and 2) CRT is not scheduled for a given failed direct transmission. In such events, irrespective of the presence of node cooperation, reservation attempts are unsuccessful due to access collisions or not affected by node cooperation, respectively. If a cooperation is scheduled during an unreserved time slot, one of the following events occur.

1) A helper node successfully relays the packet to the destination node, i.e., a successful CRT.
2) A helper node fails to relay the packet to the destination node due to channel errors.
3) CRT collides or gets suspended due to the reservation attempt from a contending node that is in one-hop neighborhood from either destination node or helper node or both.

Fig. 6 shows the probabilities of such events. As the number of nodes in the network increases or the channel quality degrades (when α value increases), the probability of successful CRT decreases. This is primarily due to an increase in the number of cooperation collisions in eCAH-MAC or suspension of CRTs, as a large number of nodes lose their time slots due to channel errors. Similarly, with an increase in the number of nodes in the network, for a given F value, the number of contending node increases. The larger the contending nodes, the higher the probability of reservation attempt(s) during an unreserved time slot. Thus, such phenomenon forces helper and/or destination nodes to suspend the scheduled CRTs in eCAH-MAC or results in cooperation collisions in CAH-MAC, decreasing the probability of successful cooperative relay transmission. In CAH-MAC, cooperation collisions occur when a helper node and a contending node simultaneously perform CRT and time-slot reservation, respectively. On the other hand, in eCAH-MAC to tackle the similar situation, the destination node suspends the

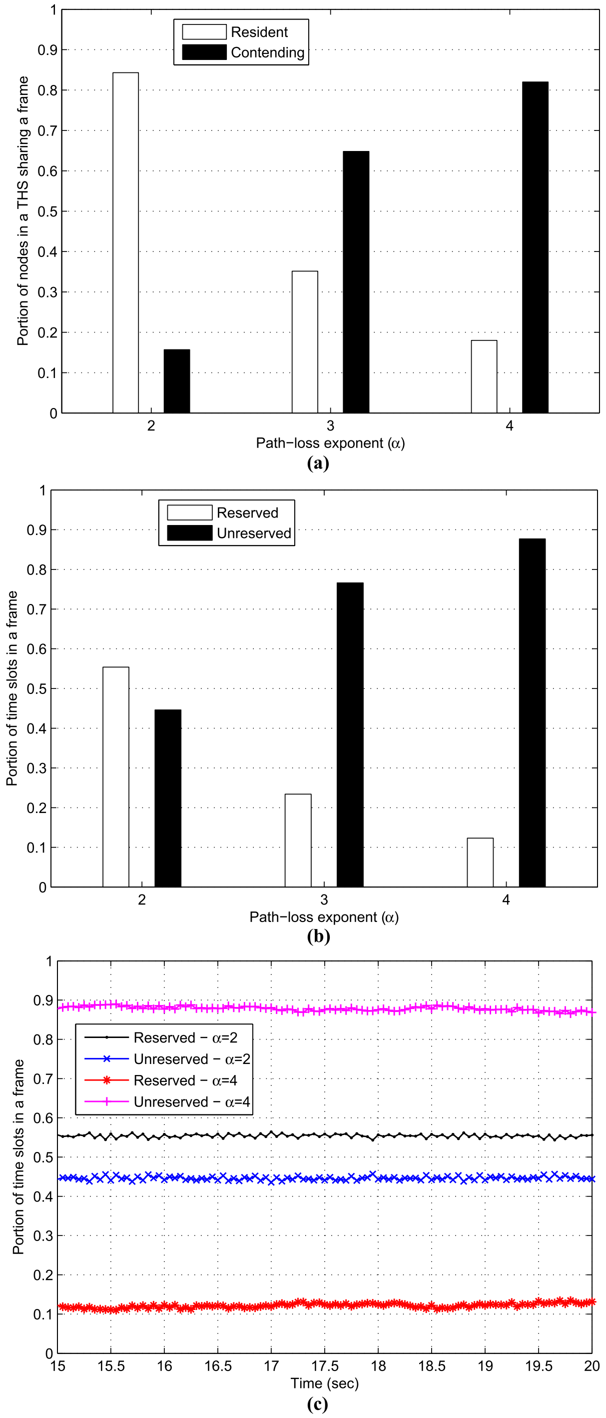


Fig. 5. Status of two-hop member nodes and time slots of the corresponding frame with $\aleph = 622$ over various channel conditions: (a) portion of the number of resident and contending nodes in a THS per frame; (b) portion of reserved and unreserved time slots in a THS per frame; and (c) portion of reserved and unreserved time slots in a THS per frame observed between consecutive frames in a steady state.

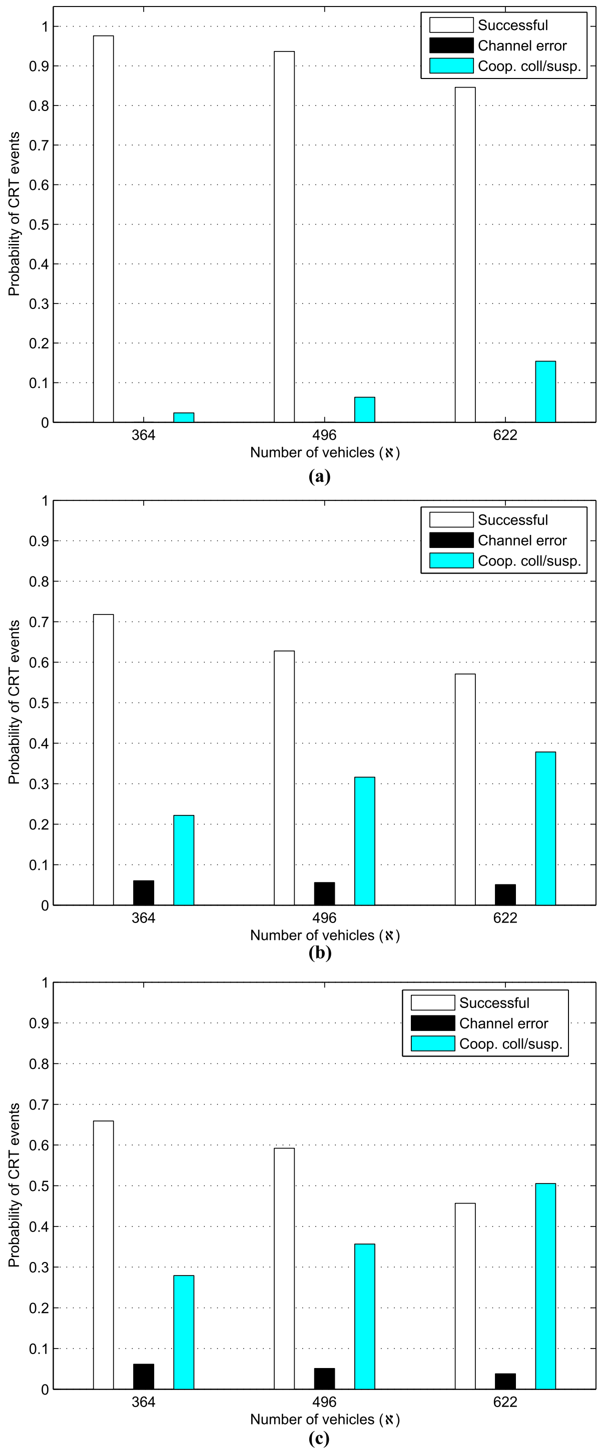


Fig. 6. Probability of events during CRT, such as successful CRT (Successful), failed CRT due to a poor channel condition (Channel error), and failed CRT due to cooperation collision in CAH-MAC or suspension of CRT to avoid cooperation collision in eCAH-MAC (Coop. coll/susp.), with (a) $\alpha = 2$, (b) $\alpha = 3$, and (c) $\alpha = 4$.

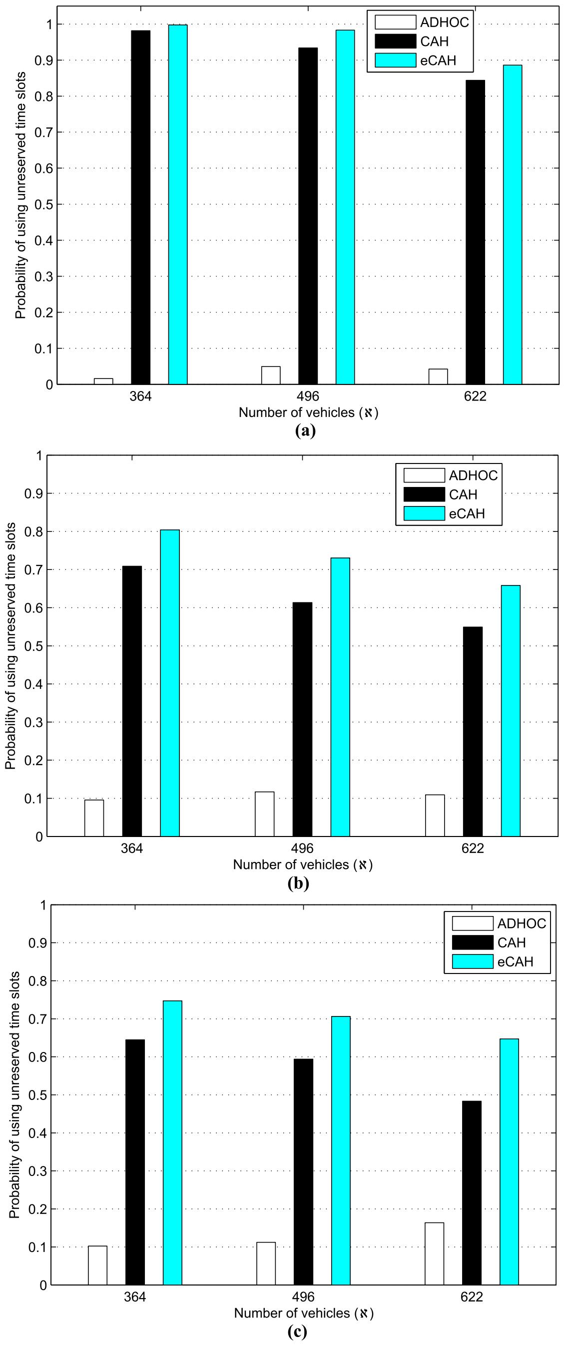


Fig. 7. Probability of successful usage of unreserved time slots in ADHOC MAC, CAH-MAC, and eCAH-MAC, with (a) $\alpha = 2$, (b) $\alpha = 3$, and (c) $\alpha = 4$.

CRT phase when it detects a reservation packet(s) from the contending node(s).

Furthermore, we study the effectiveness of node cooperation in efficiently using the idle time slots that are selected for node cooperation. Fig. 7 shows the probability of using an unreserved time slot in ADHOC MAC, CAH-MAC, and eCAH-MAC. As the number of nodes increases in the network, the average distance between neighboring nodes decreases. As a result, the capability of a contending node to successfully transmit its reservation packet to all of its OHS nodes due to a poor channel condition decreases. Furthermore, in CAH-MAC, the ongoing CRTs may lead to cooperation collisions, wasting time slot. On the other hand, CRT is suspended in eCAH-MAC, allowing contending nodes to perform reservation attempts. Hence, eCAH-MAC uses an unreserved time slot better than CAH-MAC and ADHOC MAC.

VII. CONCLUSION

Node cooperation for D-TDMA MAC, such as CAH-MAC, suffers from cooperation collisions, thus disrupting the normal operations of the D-TDMA MAC. In this paper, we present a collision avoidance scheme for the CAH-MAC protocol, referred to as enhanced Cooperative ADHOC MAC (eCAH-MAC), for vehicular communication network. In eCAH-MAC, the CRT phase is delayed, so that cooperation collisions can be avoided. It uses available bandwidth resource efficiently in the presence of time-slot reservation attempts, which is a consequence of vehicular network dynamics, improving the performance of node cooperation at the MAC layer protocol. Our analysis shows that effectiveness of node cooperation decreases with an increase in the number of nodes mainly due to increase in the number of reservation attempts. However, as contending nodes are allowed to reserve time slot despite the scheduling of CRT, eCAH-MAC does not disrupt the normal operations of the D-TDMA MAC. Furthermore, we consider a realistic channel model and vehicle traces to perform extensive simulations. We demonstrate the efficiency and robustness of eCAH-MAC in the presence dynamic networking environment. Through mathematical analysis and simulations, we observe that eCAH-MAC is capable of avoiding cooperation collisions by suspending a CRT phase, which allows more contending nodes to efficiently reserve unused time slots.

In this paper, node cooperation for broadcast service to tackle a poor channel condition is considered. The node cooperation mechanism to enhance the reliability of broadcast service in VANETs needs further investigation in order to successfully deploy the safety applications.

REFERENCES

[1] S. Bharati, L. Thanayankizil, F. Bai, and W. Zhuang, “Effects of time slot reservation in cooperative ADHOC MAC for vehicular networks,” in *Proc. IEEE Int. Commun. Conf.*, Jun. 2013, pp. 6371–6375.

[2] H. Moustafa and Y. Zhang, *Vehicular Networks: Techniques, Standards, and Applications*. Boston, MA, USA: Auerbach, 2009.

[3] *IEEE Standard for Information Technology–Local and Metropolitan Area Networks–Specific Requirements–Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments*, IEEE Std 802.11p-2010 (Amendment to IEEE Std 802.11-2007 as amended by IEEE Std 802.11k-2008, IEEE Std 802.11r-2008, IEEE Std 802.11y-2008, IEEE Std 802.11n-2009, and IEEE Std 802.11w-2009), Jul. 2010, pp. 1–51.

[4] F. Borgonovo, A. Capone, M. Cesana, and L. Fratta, “ADHOC MAC: New MAC architecture for ad hoc networks providing efficient and reliable point-to-point and broadcast services,” *Wireless Netw.*, vol. 10, pp. 359–366, 2004.

[5] M. Hassan, H. Vu, and T. Sakurai, “Performance analysis of the IEEE 802.11 MAC protocol for DSRC safety applications,” *IEEE Trans. Veh. Technol.*, vol. 60, no. 8, pp. 3882–3896, Oct. 2011.

[6] D. Jiang, V. Taliwal, A. Meier, W. Holfelder, and R. Herrtwich, “Design of 5.9 GHz DSRC-based vehicular safety communication,” *IEEE Wireless Commun.*, vol. 13, no. 5, pp. 36–43, Oct. 2006.

[7] H. Omar, W. Zhuang, and L. Li, “VeMAC: A TDMA-based MAC protocol for reliable broadcast in VANETs,” *IEEE Trans. Mobile Comput.*, vol. 12, no. 9, pp. 1724–1736, Sep. 2013.

[8] H. Omar, W. Zhuang, A. Abdrabou, and L. Li, “Performance evaluation of VeMAC supporting safety applications in vehicular networks,” *IEEE Trans. Emerg. Topics Comput.*, vol. 1, no. 1, pp. 69–83, Jun. 2013.

[9] A. Sadek, K. Liu, and A. Ephremides, “Collaborative multiple-access protocols for wireless networks,” in *Proc. IEEE Int. Commun. Conf.*, Jun. 2006, pp. 4495–4500.

[10] G. Yuan, M. Peng, and W. Wang, “Opportunistic user cooperative relaying in TDMA-based wireless networks,” *Wireless Commun. Mobile Comput.*, vol. 10, no. 7, pp. 972–985, Jul. 2010.

[11] Z. Yang, Y.-D. Yao, X. Li, and D. Zheng, “A TDMA-based MAC protocol with cooperative diversity,” *IEEE Commun. Lett.*, vol. 14, no. 6, pp. 542–544, Jun. 2010.

[12] J.-K. Lee, H.-J. Noh, and J. Lim, “Dynamic cooperative retransmission scheme for TDMA systems,” *IEEE Commun. Lett.*, vol. 16, no. 12, pp. 2000–2003, Dec. 2012.

[13] Z. Chen, Z. Liu, J. Han, S. Hu, and Y. Lu, “Co-DDTMA: Cooperative distributed TDMA for vehicular networks,” *Int. J. Future Gen. Commun. Netw.*, vol. 9, no. 2, pp. 143–154, 2016.

[14] X. Liu, C. Chen, A. Huang, and Q. Zhou, “A new TDMA-based cooperative MAC scheme,” in *Proc. Int. Conf. Telecommun.*, Apr. 2015, pp. 48–53.

[15] J.-K. Lee, H.-J. Noh, and J. Lim, “TDMA-based cooperative MAC protocol for multi-hop relaying networks,” *IEEE Commun. Lett.*, vol. 18, no. 3, pp. 435–438, Mar. 2014.

[16] F. Peng, G. Zhang, X. Huang, X. Ye, and M. Wu, “A novel TDMA-MAC protocol for VANET using cooperative and opportunistic transmissions,” in *Proc. IEEE Veh. Technol. Conf. Fall*, Sep. 2015, pp. 1–2.

[17] S. Bharati and W. Zhuang, “CAH-MAC: Cooperative ADHOC MAC for vehicular networks,” *IEEE J. Sel. Areas Commun.*, vol. 31, no. 9, pp. 470–479, Sep. 2013.

[18] S. Bharati and W. Zhuang, “Performance analysis of cooperative ADHOC MAC for vehicular networks,” in *Proc. IEEE Global Telecommun. Conf.*, Dec. 2012, pp. 5482–5487.

[19] [Online]. Available: http://vision-traffic.ptvgroup.com/en-us/products/ptv-vissim/

[20] L. Cheng, B. Henty, D. Stancil, F. Bai, and P. Mudalige, “Mobile vehicle-to-vehicle narrow-band channel measurement and characterization of the 5.9 GHz dedicated short range communication (DSRC) frequency band,” *IEEE J. Sel. Areas Commun.*, vol. 25, no. 8, pp. 1501–1516, Oct. 2007.

[21] M. K. Simon and M.-S. Alouini, *Digital Communication Over Fading Channels*. 2nd ed. New York, NY, USA: Wiley, 2005.

[22] M. Torrent-Moreno, S. Corroy, F. Schmidt-Eisenlohr, and H. Hartenstein, “IEEE 802.11-based one-hop broadcast communications: Understanding transmission success and failure under different radio propagation environments,” in *Proc. ACM Int. Symp. Modeling Anal. Simul. Wireless Mobile Syst.*, 2006, pp. 98–77.

[23] G. M. T. Abdalla, M. A. Abu-Rgheff, and S.-M. Senouci, “An adaptive channel model for VBLAST in vehicular networks,” *EURASIP J. Wireless Commun. Netw.*, vol. 11, 2009.

[24] W. C. Jakes and D. C. Cox, Eds., *Microwave Mobile Communications*. New York, NY, USA: Wiley, 1994.

[25] S. Lin, Y. Li, Y. Li, B. Ai, and Z. Zhong, “Finite-state Markov channel modeling for vehicle-to-infrastructure communications,” in *Proc. IEEE Int. Symp. Wireless Veh. Commun.*, Sep. 2014, pp. 1–5.

[26] F. Lopez-Martinez, D. Morales-Jimenez, E. Martos-Naya, and J. Paris, “On the bivariate Nakagami-m cumulative distribution function: Closed-form expression and applications,” *IEEE Trans. Commun.*, vol. 61, no. 4, pp. 1404–1414, Apr. 2013.

[27] C. Pimentel, T. Falk, and L. Lisboa, “Finite-state Markov modeling of correlated Rician-fading channels,” *IEEE Trans. Veh. Technol.*, vol. 53, no. 5, pp. 1491–1501, Sep. 2004.

[28] A. Borhani and M. Patzold, “Correlation and spectral properties of vehicle-to-vehicle channels in the presence of moving scatterers,” *IEEE Trans. Veh. Technol.*, vol. 62, no. 9, pp. 4228–4239, Nov. 2013.

[29] L. Cheng, B. Henty, F. Bai, and D. Stancil, “Doppler spread and coherence time of rural and highway vehicle-to-vehicle channels at 5.9 GHz,” in *Proc. IEEE Global Telecommun. Conf.*, Nov. 2008, pp. 1–6.

[30] W. Ding, J. Wang, Y. Li, P. Mumford, and C. Rizos, “Time synchronization error and calibration in integrated GPS/INS systems,” *ETRI J.*, vol. 30, no. 1, pp. 59–67, Feb. 2008.

[31] F. Borgonovo, L. Campelli, M. Cesana, and L. Fratta, “Impact of user mobility on the broadcast service efficiency of the ADHOC MAC protocol,” in *Proc. IEEE Veh. Technol. Conf. Spring*, Jun. 2005.

[32] M. Rubinstein, I. Moraes, M. Campista, L. Costa, and O. Duarte, “A survey on wireless ad hoc networks,” *Mobile Wireless Commun. Netw.*, vol. 211, pp. 1–33, Jan. 2006.

[33] G. Korkmaz, E. Ekici, and F. Ozguner, “Black-burst-based multihop broadcast protocols for vehicular networks,” *IEEE Trans. Veh. Technol.*, vol. 56, no. 5, pp. 3159–3167, Sep. 2007.

[34] N. Wisitpongphan, O. Tonguz, J. Parikh, P. Mudalige, F. Bai, and V. Sadekar, “Broadcast storm mitigation techniques in vehicular ad hoc networks,” *IEEE Wireless Commun.*, vol. 14, no. 6, pp. 84–94, Dec. 2007.

[35] N. Wisitpongphan, F. Bai, P. Mudalige, V. Sadekar, and O. Tonguz, "Routing in sparse vehicular ad hoc wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 8, pp. 1538–1556, Oct. 2007.

[36] M. J. Khabbaz, W. F. Fawaz, and C. M. Assi, "A simple free-flow traffic model for vehicular intermittently connected networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 3, pp. 1312–1326, Sep. 2012.

[37] R. Wiedemann, *Simulation des Strassenverkehrsflusses*. Karlsruhe, Germany: Schriftenreihe des Instituts fr Verkehrswesen der Universitt Karlsruhe, 1974.

[38] J. Filho, M. Yacoub, and G. Fraidenraich, "A simple accurate method for generating autocorrelated Nakagami-m envelope sequences," *IEEE Commun. Lett.*, vol. 11, no. 3, pp. 231–233, Mar. 2007.

Sailesh Bharati received the B.Eng. degree in electronics and communication engineering from Tribhuvan University, Kirtipur, Nepal, in 2005, the M.Eng. degree in information and communications technologies from the Asian Institute of Technology, Khlong Nung, Thailand, in 2008, and the Ph.D. degree in electrical and computer engineering from the University of Waterloo, Waterloo, ON, Canada, in 2016.

He is currently a Postdoctoral Fellow with the Department of Electrical and Computer Engineering, University of Waterloo. His current research interests include design and analysis of systems and protocols for vehicular networks.

Dr. Bharati is a corecipient of the Best Paper Award from the IEEE Global Telecommunications Conference 2012.

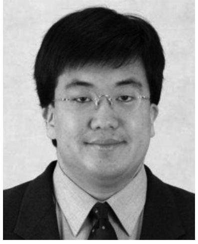
Weihua Zhuang (M'93–SM'01–F'08) has been with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada, since 1993, where she is currently a Professor and a Tier I Canada Research Chair in wireless communication networks. Her current research focuses on resource allocation and QoS provisioning in wireless networks, and on smart grid.

Prof. Zhuang is a Fellow of the Canadian Academy of Engineering, a Fellow of the Engineering Institute of Canada, and an elected member in the Board of Governors and VP Publications of the IEEE Vehicular Technology Society. She was the Editor-in-Chief of the IEEE Transactions on Vehicular Technology (2007–2013), and the TPC Co-Chair of the IEEE Vehicular Technology Conference Fall 2016. She is a corecipient of several best paper awards from the IEEE and ACM conferences.

Lakshmi V. Thanayankizil received the B.S. degree in electrical engineering from the University of Calicut, Malappuram, India, and the M.S.E.E. and Ph.D. degrees in electrical engineering from Georgia Institute of Technology, Atlanta, GA, USA, in 2011.

She has been a Senior Systems Engineer with the Core Technologies Group, General Motors Corporation, Warren, MI, USA, since September 2011. She has also held industry positions at IBM Research Lab and Crash Avoidance Metric Partnership (CAMP) working on Wi-Fi and DSRC. She has been an active member of several industry standard bodies including Wi-Fi Alliance, IEEE 802.11p, and Industry Consortiums like CAMP. She is the Vice-Chair of the DSRC Marketing Group, Wi-FI Alliance.

Dr. Thanayankizil has received two IEEE best paper awards and the NSF scholarship for her research work. She serves as TPC Co-Chairs for a number of academic research conferences including the IEEE Vehicular Technology Conference, the IEEE Global Telecommunications Conference, the IEEE Military Communications Conference, the International Symposium on Wireless Personal Multimedia Communications, the International Workshop on VehiculAr Inter-NETworking, Systems, and Applications. She is also a Reviewer for the IEEE Transactions on Vehicular Technology, the IEEE Transactions on Communications and the IEEE Transactions on Mobile Computing.



Fan Bai (M'05–SM'15–F'16) received the B.S. degree in automation engineering from Tsinghua University, Beijing, China, in 1999, and the M.S.E.E. and Ph.D. degrees in electrical engineering from the University of Southern California, Los Angeles, CA, USA, in 2005.

He has been a Staff Researcher with the Electrical and Control Systems Laboratory, Research & Development and Planning, General Motors Corporation, Warren, MI, USA, since September 2005. His current research interests include the discovery of fundamental principles and the analysis and design of protocols/systems for next-generation vehicular networks, for safety, telematics, and infotainment applications.

Dr. Bai received the Charles L. McCuen Special Achievement Award from General Motors Corporation in recognition of his accomplishment in the area of vehicle-to-vehicle communications for drive assistance and safety. He was featured as "ITS People" in 2014 by the IEEE ITS Magazine for his technical contributions to vehicular networks and intelligent transportation systems. He serves as the TPC Co-Chairs for the IEEE International Symposium on Wireless Vehicular Communications 2007, the IEEE International Workshop on Mobile Vehicular Networks 2008, ACM International Workshop on VehiculAr Inter-NETworking, Systems, and Applications (ACM VANET) 2011, and ACM VANET 2012, among other leading roles in academic and industry technical conferences. He is an Associate Editor of the IEEE Transactions on Vehicular Technology and the IEEE Transactions on Mobile Computing, and he also serves as the Guest Editor for the IEEE Wireless Communication Magazine, the IEEE Vehicular Technology Magazine, and Elsevier *Ad-Hoc Networks Journal*. He is also serving as a Ph.D. supervisory committee member at Carnegie Mellon University, Pittsburgh, PA, USA, the University of Illinois—Urban Champaign, Champaign, and the University of Southern California, Los Angeles. He is a Distinguished Lecturer of the IEEE.