Effects of Time Slot Reservation in Cooperative ADHOC MAC for Vehicular Networks

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***Abstract*—Cooperative medium access control (MAC) protocols have been proposed for improving communication reliability and throughput in wireless networks. In a recent study, a cooperative MAC scheme called Cooperative ADHOC MAC (CAH-MAC) has been proposed to increase the network throughput by reducing the wastage of time slots under a static network scenario. Particularly, neighbor nodes cooperate to increase the transmission reliability by utilizing unreserved time slots for retransmission of failed packets. In this paper, we focus on a mobile networking scenario and study the effects of time slot reservation on the performance of CAH-MAC under highly dynamic vehicular environments. We find out that the introduction of time slot reservation results in cooperation collisions, degrading the system performance. To tackle this challenge, we present an enhanced CAH-MAC (eCAH-MAC) that is able to avoid cooperation collisions and thus efficiently utilize a time slot. In eCAH-MAC, the cooperative relay transmission phase is delayed, so that cooperation collisions can be avoided and time slots can be efficiently reserved. Through extensive simulations, we demonstrate that eCAH-MAC uses time slot more efficiently than CAH-MAC in direct and/or cooperative transmissions and in reserving time slots in the presence of relative mobility among nearby nodes.**

***Index Terms*—VANETs, medium access control, cooperative communication, time division multiple access (TDMA).**

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 an on-board unit (OBU) and one or more application units (AU) [1] for wireless communication, and a set of stationary units along the road called road side units (RSU). Although communication nodes (vehicles) are organized in an ad hoc manner to form a vehicular network, directly applying the existing communication protocols designed for tradition mobile ad hoc networks may not be reliable and efficient. Hence, development and operations of VANETs demand reliable and efficient communication protocols to support the wide range of applications.

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. Approaches such as the IEEE 802.11p [2] and distributed TDMA MAC protocols, namely ADHOC MAC [3] and VeMAC [4], have been proposed for the MAC layer in VANETs. However, these approaches are not free from packet dropping and throughput reduction due to a poor channel condition and can be inefficient in utilizing the available radio resources [5]. Cooperative MAC protocols have been recently proposed to enhance the reliability of communication links and mitigate wireless channel impairments. Cooperative ADHOC MAC (CAH-MAC) [5] is proposed for VANETs, in which a helper node performs cooperation utilizing an idle time slot to relay a packet that failed to reach the destination in a direct transmission. Using idle time slots for cooperative relay transmissions, the CAH-MAC protocol improves throughput of the VANET. However, such a cooperation scheme is useful only if the relative mobility among the nodes is negligible. In the presence of relative mobility among nodes, cooperation collisions occur between reservation packets from the nodes attempting to reserve the unreserved time slot and the cooperative relay transmissions. In this paper, we present a collision avoidance scheme for CAH-MAC, refereed to as enhanced CAH-MAC (eCAH-MAC). In eCAH-MAC, the destination node suspends the cooperative relay phase if there is any reservation attempt from a node seeking its own time slot. Cooperation is performed only if the destination node does not detect any reservation attempts in its one-hop transmission neighborhood.

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II. System Model

Consider a VANET with randomly distributed vehicles moving in along a one-way multi-lane road segment. All vehicles are identical with respect to their communication capabilities with transmission range r. Vehicles within the transmission range of a source node can successfully receive the transmitted packets with probability p, taking account of a possible poor channel condition. The probability p depends on channel characteristics and does not account for transmission errors due to collisions when multiple nodes within an interference range transmit simultaneously. The smaller the p value, the poorer the channel quality.

The channel access mechanism is based on distributed TDMA MAC protocols [3], [4], such that 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 (1PPS) signal [6] that a Global Positioning System (GPS) receiver gets every second. Nodes support broadcast, multicast, or point-to-point modes of communication. However, to evaluate the performance, we consider nodes communicating in a point-to-point mode only.

Each vehicle maintains sets of its one-hop and two-hop neighbors, namely one-hop set (OHS) and two-hop set (THS) respectively. One-hop and two-hop neighbors are those nodes which can be reached at maximum one and two hops in transmission distance respectively from a reference node. All nodes in the same THS can communicate with each other with a maximum of two hops. Formation of a THS stops simultaneous usage of a time slot by more than one node within the same interference range and thus avoids hidden node problem.

Nodes belonging to the same THS contend with each other to reserve a time slot. To contend for 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 reserves one time slot among the unreserved ones if available. Access collisions occur when multiple new nodes within the same interference range attempt to reserve the same time slot. A node successfully reserves a time slot if there is no access or cooperation collision. It then transmits a packet in its own time slot in every frame until it encounters a merging collision due to relative mobility. Merging collision occurs when nodes using the same time slot but belonging to different THSs approach each other, resulting in a transmission collision in the corresponding time slot [7]. A node, after suffering from a merging collision, releases its own time slot and attempts to reserve an unreserved time slot. Moreover, merging collisions may lead to access and/or cooperation collisions. In [7], it is shown that ADHOC MAC suffers from throughput reduction due to node mobility. To overcome the throughput reduction, VeMAC is proposed in [4]. 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.

In the sections that follow, we refer to a node seeking a time slot as a new node. To investigate the effects of the relative mobility among nodes, we introduce time slot reservation attempts from the new nodes. We define a parameter $\beta \in [0, 1]$, refereed to as a new node ratio, which is the fraction of new nodes in a THS. The larger the β value, the larger the number of nodes without their own time slots in a THS and the larger the number of unreserved time slots in the corresponding frame. A node attempts to reserve a time slot after it suffers from a merging collision, hence the presence of new nodes in a THS can be considered as a consequence of merging collisions, and consequently the relative mobility among the nodes. Direct and/or cooperative relay transmission are performed by only those nodes which have their own time slots for transmission. Here, with a focus on cooperation to improve transmission reliability, we consider a network where all nodes are perfectly synchronized in time. All operations such as reserving a time slot, synchronization among nodes, cooperation decision, and cooperative transmission are done in a distributed manner, making the scheme suitable for VANETs.

III. ENHANCED COOPERATIVE ADHOC MAC (eCAH-MAC)

In this section, we present the operations of eCAH-MAC based on CAH-MAC and a novel scheme to resolve the cooperation collisions. A node in its own time slot transmits a packet that consists of frame information, cooperation header, packet header (PH), payload data, and cyclic redundancy check (CRC). The packet header, payload data, and cyclic redundancy check are the same as in ADHOC MAC and VeMAC, whereas frame information is different. In addition, cooperation header is a new field that is introduced specifically for cooperation in CAH-MAC and eCAH-MAC.

A. Frame Information (FI)

The FI is a collection of ID fields (IDFs) of neighboring nodes and helps a node to maintain a neighbor-table which includes: (i) all of its one-hop neighbors, (ii) all of its two-hop neighbors, and (iii) the owner of each time slot in a frame. If there is no signal in a time slot, then a 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. Such a neighbor-table helps a node to identify an unreserved time slot in which it can transmit without causing any collision in its one-hop neighborhood. Note that a node updates its neighbor-table based on packets that it received successfully from new neighbors. These packets can be broadcast, unicast, or multicast packets. In addition to the neighborhood discovery and time slot reservation, the FI helps for transmission acknowledgement. For example, consider that node D does not include the ID of node S in the corresponding IDF of its FI. Upon receiving the FI from D, node S concludes a transmission failure between itself and node D, which is basically a negative acknowledgement. Similarly, inclusion of the node S ID in the FI of node D serves as an acknowledgement of a successful transmission from node S to node D.

B. Cooperation Among Neighboring Nodes

Denote S, D and H as the source, destination and helper nodes respectively. Cooperation decision and cooperative relay transmission are performed only if: (i) the direct transmission between source node S and destination node D fails, (ii) the helper node H successfully receives a packet from the source node S for cooperative relay transmission, (iii) the destination node D is reachable from the helper node H, and finally (iv)

there is an unreserved time slot available for cooperative relay transmission. If all the preceding conditions are satisfied, the helper node H offers cooperation to the source and destination $(s-d)$ pair, and the cooperative transmission is performed in one of the available unreserved time slots. Let the h^{th} slot of a frame be choosen for cooperation by node H. When the destination node D fails to receive a packet from source node S, it announces transmission failure through its FI. Upon deciding to cooperate, the helper node H transmits cooperation header (COH), in its packet, which includes information such as its intention to help and the time slot during which it will perform cooperative relay transmission. In the h^{th} time slot, after receiving a cooperation acknowledgement (C-ACK) from the destination node D, helper node H transmits the packet that node D failed to receive.

If there are multiple potential helper nodes, the one which first announces to help will relay the packet while all other potential helpers suspend their intention to help for the corresponding $s-d$ pair. Hence, helper H is the one which first offers cooperation in the frame and performs a cooperation for the $s-d$ pair. Collisions may occur at the destination node when two or more potential helpers, which are not in each other's OHS, offer cooperation at the same unreserved time slot. In order to avoid such collisions, C-ACK from the destination node is transmitted during the selected unreserved time slot. In C-ACK, the destination node puts the ID of node H and acceptance of cooperation. Transmission of C-ACK signal from the destination node forces other potential helper nodes to suspend their transmissions, thus avoiding any possible collision.

C. Cooperation Collision Avoidance

CAH-MAC suffers from cooperation collisions, when a reservation packet from a new node collides with C-ACK from the destination node and/or payload data from the helper node. One possible way to avoid cooperation collisions is to delay the cooperative relay transmission by some time interval, say α_1 time units. Duration of α_1 is long enough for a node to sense whether the channel is idle or busy, such as the distributed inter-frame space (DIFS) as in the IEEE 802.11 based MAC protocols [8]. Destination node D waits for α_1 time units and transmits C-ACK if the channel is idle during the waited time (i.e., if there is no transmission in that unreserved time slot), 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., $\alpha_1 = 0$. Helper node, after receiving its ID in the 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 cooperative relay transmission after the fixed duration from the start of a time slot, i.e., $\alpha = \alpha_1 + \alpha_2$ time units as in Fig. 1, where α_2 is the transmission time of a C-ACK plus the guard time.

A new node attempts to reserve the unreserved time slot by transmitting a packet in the same time slot. When the destination node detects the reservation packet(s) from the

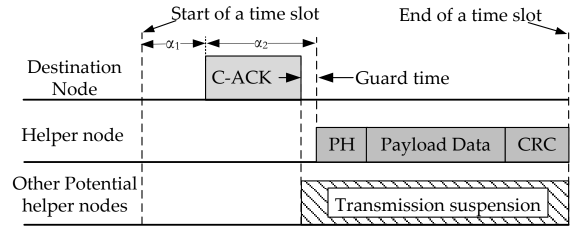

Fig. 1. Cooperative relay transmission in eCAH-MAC during an unreserved time slot.

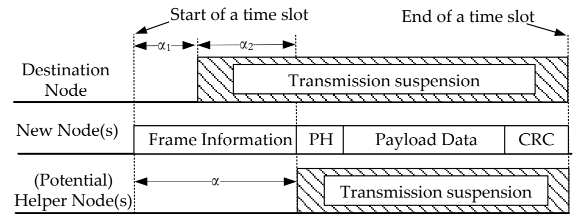

Fig. 2. Suspension of a cooperative relay transmission after the reservation packet(s) from the new node(s).

new node(s), it suspends the cooperation or transmission of the C-ACK. As the helper node does not receive any C-ACK, it also suspends cooperative relay transmission after α time units, from the start of a time slot as illustrated in Fig. 2. Delaying the cooperative relay transmission phase allows the destination node to detect the reservation packet from a new node and avoid a collision between C-ACK and the reservation packet. Such collision occurs only if a new node and the destination node are in each others' two-hop distance but not in the one-hop distance. In such a case, destination node does not sense the transmission of reservation packet from the new node and transmits C-ACK. Collisions occur when there is a simultaneous transmission from the destination and new nodes, at their common one-hop nodes.

Note that a helper node does not transmit the FI during cooperative relay transmission, i.e., the packet from a helper node consists of packet header (PH), payload data and CRC only. As each node has its own time slot in which it can transmit a complete packet, repeated transmission of the FI during cooperative relay transmission can be avoided. The absence of FI compensates for the delay time of cooperative relay transmission phase and does not affect the normal operations of CAH-MAC. In addition, new nodes transmit reservation packets without cooperation header as they are not eligible to perform cooperation.

IV. Performance Analysis

Extensive simulations are performed in MATLAB to evaluate the performance of eCAH-MAC in comparison with CAH-MAC and ADHOC MAC. Five hundreds nodes are distributed along a road segment following the Poisson distribution with different β values. A road segment with two lanes, each of $5\ m$ width, is considered. The vehicles density is kept at 30 vehicles/km in both lanes. For a fair comparison with the previous studies in [5], the total number of time slots per frame, F, is kept at 60 $time\ slots$ and the transmission range,

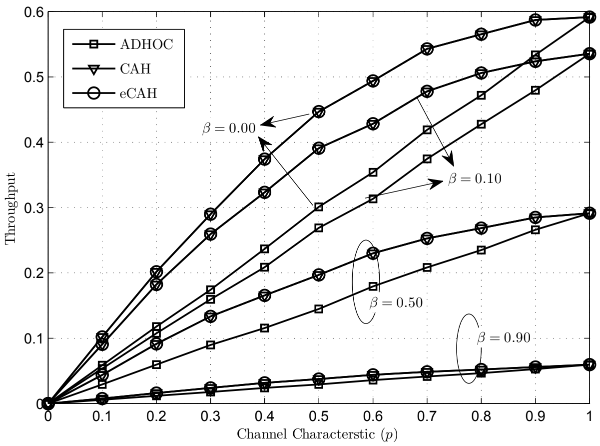

Fig. 3. Throughput comparison of ADHOC MAC, CAH-MAC and eCAH-MAC.

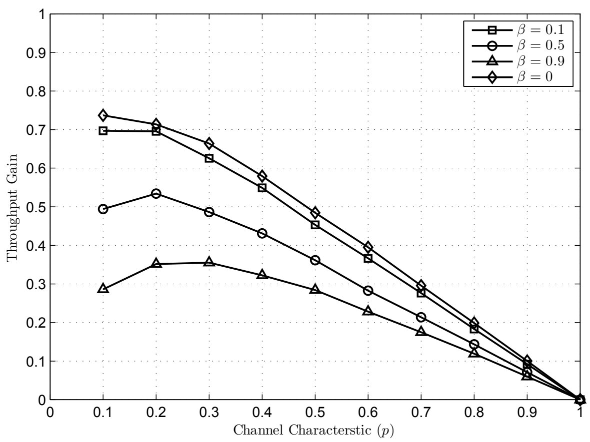

Fig. 4. Throughput gain of CAH-MAC and eCAH-MAC over ADHOC MAC.

r, is kept at 300 m. The value of p is varied to characterize different channel conditions. Each simulation result is obtained by averaging the results from 200,000 frames from a total of 40 different network topologies.

Fig. 3 shows that the throughput is inversely proportional to the new node ratio (β) for a given channel condition. The throughput is defined as the fraction of successful time slots over the total number of time slots per frame. Successful time slots include only those time slots during which a source successfully delivers a packet to the target destination directly or through a helper. Note that direct and cooperative rely transmissions are performed by those nodes which have their own time slot to transmits the corresponding FIs. The value of β is changed to vary the number of new nodes in a THS or the number of reserved (or unreserved) time slots in a frame. Hence, the larger β value means, the fewer number of reserved time slots used for direct and/or cooperative relay transmissions. Fig. 4 shows the effect of the new node ratio, β, on the throughput gain of CAH-MAC and eCAH-MAC over ADHOC MAC for the different p values. The throughput gain decreases with an increase in the β value. For example, the throughput gain, at $p = 0.2$, is almost 50% less for $\beta = 0.9$ than that when $\beta = 0$. This is due to the presence of new nodes transmitting the reservation packets during unreserved time slots, resulting in the suspension of cooperative relay transmissions in eCAH-MAC or cooperation collisions in CAH-MAC. In CAH-MAC, cooperation collisions occur when a helper and a new node simultaneously perform cooperative relay transmission and time slot reservation, whereas in eCAH-MAC the destination node suspends the cooperative relay transmission phase when it detects a reservation packet(s) from the new node(s). Hence, the throughput and throughput gain are the same for CAH-MAC and eCAH-MAC. On the other hand, the number successful time slot reservations in eCAH-MAC is higher than in CAH-MAC as shown in Fig. 5.

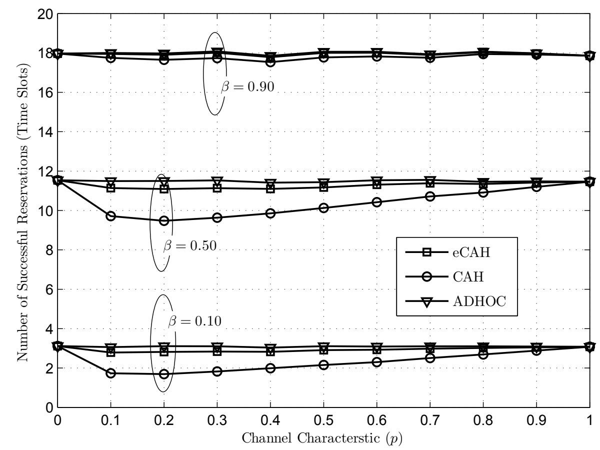

Fig. 5. The number of successful time slot reservations per frame in ADHOC MAC, CAH-MAC and eCAH-MAC.

At a large β value, due to the presence of a large number of new nodes, a higher number of reservation attempts are performed and, consequently, a higher number of time slots are reserved. Fig. 5 shows that the number of time slots reserved per frame. With an increase in cooperation gain in CAH-MAC and eCAH-MAC, the number of cooperation collisions increases and a fewer number of new nodes successfully reserve time slots as compared to that of ADHOC MAC. For example, in Fig. 4 for $\beta = 0.5$, the throughput gain increases as the p value increases from 0 to 0.2 and decreases as the p value further increases, as a result the number successful time slot reservation changes accordingly, as shown in Fig. 5. As the cooperation gain increases, the number of successful time slot reservations decreases in CAH-MAC due to an increase in the number of cooperation collisions. The higher number of successful time slot reservations in eCAH-MAC, as compared to CAH-MAC, is due to the suspension of cooperative relay transmission to avoid cooperation collision and to allow the new nodes to access the unreserved time slots. It can be seen from Fig. 5 that the number of successful time slot reservations in eCAH-MAC is significantly higher than that of CAH-MAC and slightly less than that of ADHOC MAC. Note that the difference between the numbers of reserved time slots in eCAH-MAC and ADHOC MAC is due to cooperation collisions between a destination node and a new node that are not in one-hop transmission range of each other. In such a case, the destination node does not detect the reservation packet

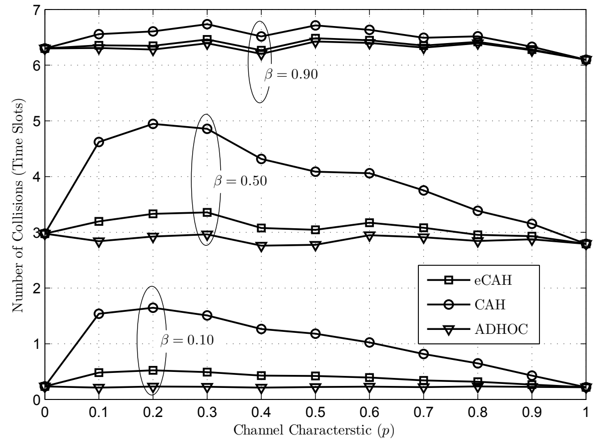

Fig. 6. The number of collision time slots per frame in ADHOC MAC, CAH-MAC and eCAH-MAC.

from the new node and both nodes perform simultaneous transmission. Collisions occur at the one-hop neighbors of both destination and the new nodes.

Fig. 6 shows the number of time slots per frame that experience both access and cooperation (if applicable) collisions in ADHOC MAC, CAH-MAC, and eCAH-MAC. In ADHOC MAC only access collisions occur, whereas in CAH-MAC and eCAH-MAC both cooperation and access collisions occur. The number of access collisions depends on the number of new nodes in the THS and the number of unreserved time slots in a frame [4]. Cooperation collisions, on the other hand, depend on the probability of cooperation decision for each failed direct transmission, i.e., the existence of a helper and an unreserved time slot for the cooperation [5], in addition to the number of new nodes in the THS and the number of unreserved time slots in the frame. The difference between the numbers of collision time slots in ADHOC MAC and eCAH-MAC/CAH-MAC is the number of time slots with cooperation collisions. In eCAH-MAC, as the destination node detects a potential reservation packet from a new node before transmitting C-ACK, the number of cooperation collisions is reduced from that in CAH-MAC.

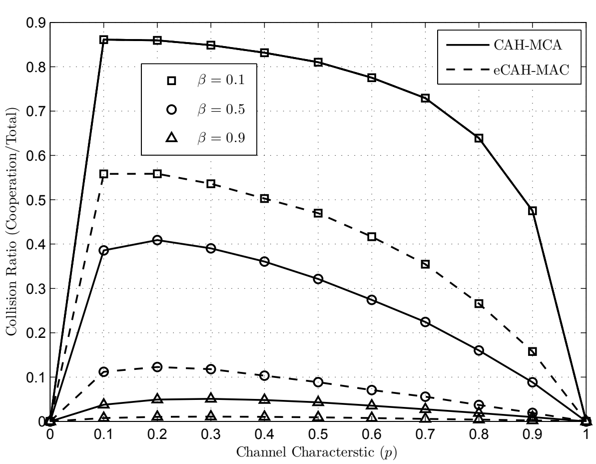

Fig. 7. The fraction of cooperation collisions over total collisions per frame in CAH-MAC and eCAH-MAC.

Fig. 7 shows the cooperation collisions rate, i.e., the fraction of cooperation collisions over the total number of collision in a frame. The cooperation collision rate reaches its peak when the cooperation gain reaches its peak, as in Fig. 4, for the given β value. This is due to an increase in the probability of cooperation during an unreserved time slot [5]. The gap between collision rates of CAH-MAC and eCAH-MAC is high when the collision rate is at its peak. On the other hand, as the channel quality further improves, the probability of successful direct transmission increases, reducing the needs for cooperation [5], which reduces the number of the cooperation collisions and the gap between the collision rates. At two extreme channel conditions, i.e., $p = 0$ and 1, AHDOC MAC and CAH-MAC perform equally as no cooperation is trigged [5]. Hence, eCAH-MAC also behaves in the same way as ADHOC MAC and CAH-MAC in the two extreme channel condition and performs equally as in Figs. 3-5.

V. Conclusion

In this paper, we present a collision avoidance scheme for the CAH-MAC protocol, refereed to as enhanced Cooperative ADHOC MAC (eCAH-MAC). The eCAH-MAC uses available bandwidth resource efficiently in the presence of time slot reservation attempts, which is a consequence of the relative mobility among vehicles, improving the performance of cooperation at the MAC layer protocol of vehicular networks. Through extensive simulations, we observe that eCAH-MAC is capable to avoid cooperation collisions by delaying a cooperative relay transmission phase, which allows more new nodes to efficiently reserve unused time slots.

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