Performance Analysis of Cooperative ADHOC MAC for Vehicular Networks

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***Abstract*—The paradigm of vehicular ad-hoc networks (VANETs) emerges as a promising approach to provide road safety, vehicle traffic management, and infotainment applications. Thus, it is important to develop a VANET medium access control (MAC) protocol that provides an efficient and reliable delivery of packets for diverse applications. Cooperative communication, on the other hand, can enhance the reliability of communication links in VANETs, thus mitigating wireless channel impairments due to a poor channel condition. Recently, a cooperative scheme for MAC in VANETs based on time-division multiple access, referred to as Cooperative ADHOC MAC (CAH-MAC), has been proposed [1]. CAH-MAC is an efficient protocol capable of increasing the network throughput by reducing the wastage of time slots. In CAH-MAC, neighboring nodes cooperate by utilizing the unreserved time slots, for retransmission of a packet which failed to reach its target receiver due to a poor channel condition. In this paper, we study the reliability of CAH-MAC in terms of packet transmission delay (PTD) and packet dropping rate (PDR). Through mathematical analysis and computer simulation, we show that CAH-MAC provides reliable communication by decreasing the PTD and PDR as compared with existing approaches.**

I. Introduction

Increasing road accidents and user demands for a drive-thru Internet connection have led to the evolution of intelligent transportation systems [2] and other applications that improve road safety, increase transportation efficiency, and provide on-board infotainment services. To make these applications possible, vehicles can be equipped with sensors and communication devices to form a communication network called vehicular ad-hoc network (VANET). In a VANET, a smart vehicle uses advance sensors for gathering information and wireless medium for exchanging the information with other vehicles. Such vehicles are equipped with an on-board unit (OBU) and/or one or multiple application units (AUs) [3]. An OBU is a device with a wireless networking interface which enables vehicles to communicate. AUs, on the other hand, are devices which run application(s) and make use of OBUs to exchange information with other vehicles. Vehicles communicate independently either with each other or with stationary wireless stations. These wireless stations are known as road side unit (RSU) and can be any equipment such as traffic lights, roadside monitors, and information traffic gateways which are connected to the Internet. Thus, VANETs will support both vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications.

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In addition to various obstacles due to unreliable wireless transmission medium, development and operation of VANETs have unique challenges when compared with other forms of wireless networks. High node mobility, dynamic topology changes with frequent link breakage, and strict delay constraints of high priority safety messages are some common challenges in VANETs. These issues must be considered in developing networking protocols for VANETs. Recently, the IEEE 802.11p [4] has been proposed for medium access control (MAC) in VANETs to address the aforementioned issues. However, in the IEEE 802.11p, even successful broadcast messages are left unacknowledged. Further, with the random channel access, it suffers from unbounded latency and broadcast storm [5], [6]. On the other hand, as high priority safety messages are short range, uncoordinated, and broadcast in nature [7], they have a strict delay requirement and demand a reliable broadcast service. Distributed time division multiple access (TDMA) based MAC protocols, namely the ADHOC MAC [5] and the VeMAC [8], are proposed to facilitate reliable broadcast and point-to-point (P2P) communication in VANETs. However, due to VANET dynamic topology, the 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 and the existing TDMA based MAC approaches are not free from packet dropping and throughput reduction due to a poor channel condition. Further, these approaches can be inefficient in utilizing the available radio resources.

Various techniques such as diversity and channel coding are effective to mitigate wireless channel impairments and to improve network throughput. An alternative approach is cooperative communication, which makes use of nearby nodes to improve transmission performance between a pair of source and destination ($s - d$) nodes via diversity gain. Existing works on link layer cooperation focus on cooperation in the IEEE 802.11 based networks [9]–[11] and/or infrastructure based TDMA networks [12]–[14]. Different from the existing works, here we consider distributed TDMA MAC for VANETs referred to as Cooperative ADHOC MAC (CAH-MAC) [1].

In CAH-MAC, all operations such as cluster formation, slot allocation, cooperation decision and cooperation itself are performed in a distributed manner. Also, the helper is not fixed and changes with channel condition and network topology. As each node has reserved a time slot to transmit its own packets, we propose cooperation in the unreserved time slots. In this way, relay transmission in cooperation does not stop direct transmission from neighboring nodes, and hence does not increase the waiting time of neighboring nodes to access the channel. In this paper, we study the reliability of CAH-MAC in terms of packet transmission delay (PTD) and packet dropping rate (PDR). The CAH-MAC allows a neighboring node to use an unreserved time slot to retransmit the packet that failed to reach the destination in the same frame. Since the packet is retransmitted earlier in CAH-MAC as compared with ADHOC MAC, packet transmission delay decreases. Consequently, for a given maximum retransmission limit, the packet dropping rate is significantly reduced in CAH-MAC as compared with ADHOC MAC in similar networking and channel conditions.

This paper is organized as follows. Section II describes the system model and assumptions made to evaluate the performance of the CAH-MAC. The CAH-MAC protocol is described in Section III. Section IV presents performance analysis of CAH-MAC, which is verified in Section V with simulations. Finally, Section VI provides a summary of our contributions and identifies some issues for further investigation.

II. System Model

Consider a VANET consisting of N vehicles moving along a multi-lane road. Vehicles are distributed randomly. Let L be the number of lanes, each with width w_l, $l \in \{1, 2, 3, ..., L\}$. All vehicles move with negligible relative movements over an observation period. Hence, they are stationary with respect to each other, maintaining a fixed network topology. All vehicles are identical with respect to their communication capabilities with transmission range r. Therefore, vehicles with Euclidean distance more than r cannot communicate directly with each other. 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. The smaller the p value, the poorer the channel quality. The parameter p does not account for transmission errors due to the collision when multiple nodes within an interference range transmit simultaneously.

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. Accessing a time slot thus demands precise time synchronization among nodes. When a vehicle is equipped with a Global Positioning System (GPS) receiver, the one-pulse-per-second (1PPS) signal [15] that a GPS receiver gets every second can be use for the synchronization. Nodes support broadcast, multicast, or point-to-point modes of communication. However, to evaluate the performance of CAH-MAC, we consider nodes communicating in a point-to-point mode only. A helper node performs cooperation to retransmit an overheard packet from the source node.

Each vehicle maintains a list of its one-hop and two-hop neighbors. One-hop and two-hop nodes are those which can be reached at maximum one and two hops of transmission respectively from a reference node. Sets of these nodes are called one-hop set (OHS) and two-hop set (THS) respectively. All nodes in the same THS can communicate with each other with maximum two hops. Nodes form clusters of two-hop neighbors. Here a cluster refers to a group of nodes which are at a maximum two-hop transmission distance from each other. There is no cluster head, and a node can be a member of multiple clusters. Formation of a cluster stops simultaneous usage of a time slot by more than one node within the same interference range, thus avoids hidden and/or exposed node problems. 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 nodes within the same interference range attempt to reserve the same time slot. After successfully reserving a time slot, a node transmits a packet in its own time slot in every frame until it encounters a merging collision [5] due to relative mobility. Merging collision occurs when nodes using the same time slot but belonging to different clusters approach each other, resulting in a transmission collision in the corresponding time slot [16]. In [16], it is shown that ADHOC MAC suffers from throughput reduction due to node mobility. To overcome the throughput reduction, VeMAC is proposed in [8]. 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.

Here, with a focus on cooperation to improve transmission reliability, we consider a network where all nodes are perfectly synchronized and have already reserved their time slots. Hence, access collisions do not occur and cooperation is performed by only those nodes which have their own slots for transmission. Also, as relative mobility among nodes is negligible, merging collisions do not occur; hence a reserved time slot is always dedicated to its owner. All operations such as reserving a time slot, synchronization among nodes, cooperation decision, and cooperative transmission are done in a distributed manner, making it suitable for VANETs.

III. Cooperative ADHOC MAC

In this section, we review the operation of CAH-MAC as proposed in [1], including cooperation decision and helper selection. A node in its own time slot transmits a packet that consists of frame information, cooperation header, packet header, pay load data, and cyclic redundancy check (CRC). Fig. 1 shows the structure of a packet that a node transmits. The packet header, payload data, and CRC 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.

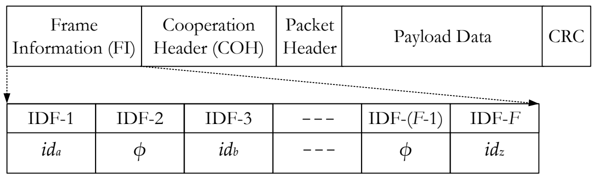

Fig. 1. Structure of a packet and a frame information field in CAH-MAC, where ϕ indicates an empty field.

A. Frame Information (FI)

The FI is a collection of ID fields (IDFs). The number of IDFs in an FI field is equal to F, i.e., the number of time slots per frame. Each IDF is dedicated to the corresponding time slot of a frame. The basic FI field structure is shown in Fig. 1. Destination node D, upon receiving a packet successfully from source node S in the s^{th} time slot, concludes that the s^{th} time slot belongs to S. Node D then puts the ID of node S in the s^{th} IDF of its FI. Hence by successfully receiving FIs from all of its one-hop neighbors, a node maintains 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 unreserved time slots are left empty in an FI field.

A node can 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 any packets 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 also helps for transmission acknowledgement. For example, consider that node D does not include the ID of node S in the IDF-S of its FI. Upon receiving FI from D, node S concludes a transmission failure between itself and D in the s^{th} time slot, which is basically a negative acknowledgement (NACK). Similarly, inclusion of the node S ID in the FI of node D serves as acknowledgement of a successful transmission from S to D.

B. Cooperation Among Neighboring Nodes

In the following, we discuss how a node decides and performs a cooperation. Denote S, D and H as the source, destination and helper nodes respectively. Cooperation decision and cooperative relay transmission are perform 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 available unreserved time slot for cooperative relay transmission.

If all the preceding conditions are satisfied, the helper node H offers cooperation to the source and destination, and the cooperative transmission is performed in one of the available unreserved time slots. Let the h^{th} slot of the frame be choosen for cooperation by node H. Fig. 2 shows necessary information exchanges for cooperation in the CAH-MAC. When the destination node D fails to receive a packet from source node S (in Fig. 2(a)), it announces transmission failure through its FI as shown in Fig. 2(b). Upon deciding to cooperate, the helper node H transmits its intention of cooperation using cooperation header (COH) as in Fig. 2(c). 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 (in Fig. 2(d)).

Once a node decides to cooperate, it transmits its decision via cooperation header (COH) in its packet as shown in Fig. 1. If there are multiple potential helper nodes, the one which first announces to help will relay the packet while all other potential helpers will not proceed with cooperation for the same packet. Hence, helper H is the one which first offers cooperation in the frame and performs a cooperation for the $s-d$ pair. The information included in the cooperation header are (i) its intention to cooperate, (ii) the index of time slot of the source during which transmission failure occurred, and (iii) the selected unreserved time slot in which the packet will be retransmitted from the helper to the destination. The information is embedded in the cooperation header and transmitted in the helper's time slot. Collisions may occurs 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 a collision, a cooperation acknowledgement (C-ACK) from the destination node is transmitted during the selected unreserved time slot. In C-ACK, the destination node puts the ID of the node H and acceptance of cooperation. Transmission of a C-ACK from the destination node forces other potential helper nodes to suspend their transmissions, thus avoiding any possible collision.

IV. Performance Analysis

In this section, we develop a mathematical model for the performance analysis of the CAH-MAC protocol. We will study the reliability of CAH-MAC in terms of packet transmission delay (PTD) and packet dropping rate (PDR) as compared with that of ADHOC MAC.

A. Vehicle Distribution

Vehicles are distributed randomly on the road with an exponentially distributed inter-vehicular distance over each lane. Let ρ_l, $l \in \{1, 2, 3, ..., L\}$, be the vehicle density of lane l in terms of the number of vehicles per unit length. Thus the counting of vehicles follows a Poisson process over a given length of road, such that the probability of finding m vehicles

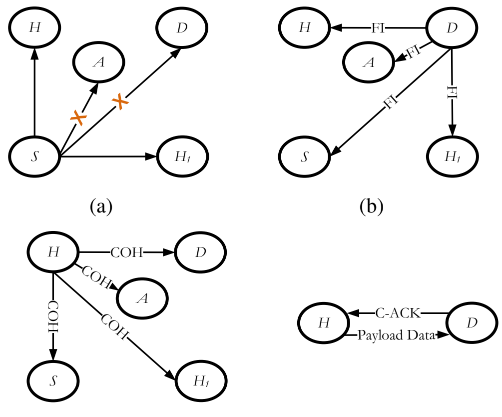

Fig. 2. Information exchanges in the CAH-MAC: (a) Phase 1: Source node transmits a packet to the destination; (b) Phase 2: Neighboring nodes detect transmission failure after examining the FI from the destination; (c) Phase 3: Helper node H, offers cooperation; (d) Phase 4: Helper node H, re-transmits the packet that failed to reach the destination after receiving a cooperation acknowledgement from the destination.

along a given length z of the road segment is given by

$$p(m,z) = \frac{(\rho z)^m e^{-\rho z}}{m!}, \qquad m = 0, 1, 2, ... \tag{1}$$

where $\rho = \sum_{l=1}^{L} \rho_l$.

Note that (1) is an approximation for tractable analytical framework, considering a vehicle as a point in a line representing a roadway. In reality, the inter-vehicular distance follows a shifted negative exponential distribution, such that a minimum safety distance (MSD) is always maintained by two adjacent vehicles in a lane to avoid any vehicle collision between them.

B. Direct Transmission

Let p_s denote the probability of successful transmission during a time slot. As channel condition (characterized by p) and transmission collision are independent of each other, p_s is given by

$$p_s = (1 - p_c)p \tag{2}$$

where p_c is the probability of transmission collisions in a given time slot. Collisions can be merging collisions [5] due to relative mobility between nodes. Since nodes are relatively stationary with respect to each other in the system model under consideration, there are no collisions among packets transmitted by different nodes, i.e, $p_c = 0$ and $p_s = p$.

C. Cooperative Relay Transmission

If a transmission failure occurs, cooperation may be triggered. Based on the criteria explained in Section III-B, upon a transmission failure between an $s-d$ pair, cooperation gets triggered if all of the following events occur:

1) Event E_1: There exits at least one potential helper which can help an $s-d$ pair to relay the packet that failed to reach the destination. Potential helpers are those nodes which are in the same OHS of the source and the destination. In addition, potential helpers must have successfully received the packet that failed to reach the destination. *Event* E_1 occurs if there is at least one potential helper. The probability of *Event* E_1 occurrences can be written as in (3).

2) Event E_2: There exists at least one unreserved time slot in which a potential helper can transmit without causing any collision in its OHS neighborhood. For nodes belonging to the same THS, an unreserved time slot for one node is unreserved for all of them. Hence, a potential helper can help an $s-d$ pair if there exists at least one unreserved time slot in the frame belonging to the corresponding THS. *Event* E_2 occurs if there exists at least one unreserved time slot in the frame, which is being shared by the source, the destination, and the potential helpers. The probability of *Event* E_2 occurrences is given by

$$\Pr\{E_2\} = \sum_{j=1}^{F-1} \frac{(2\rho r)^j e^{-2\rho r}}{j!}. \tag{4}$$

Events E_1 and E_2 are independent of each other. Hence, the probability of cooperation decision for each failed direct transmission, p_{coop}, is given by

$$p_{coop} = \Pr\{E_1\}\Pr\{E_2\}. \tag{5}$$

With the introduction of cooperation, transmission is successful either direct or cooperative relay transmission is successful. Hence, the probability of a successful transmission with cooperation, p_s^{coop}, is given by

$$p_s^{coop} = p_s + p_s(1 - p_s)p_{coop}. \tag{6}$$

D. Packet Transmission Delay

Upon transmission failure, a source attempts retransmission of a packet until it successfully reaches the destination. In this work, the packet transmission delay (PTD) is defined as the number of frames that is required to successfully transmit a packet to the destination. Since in the system model under consideration, the probability of successful transmission during a time slot depends only on channel characteristics, the number of retransmission attempts is independent of collision probability and follows a geometric distribution [17], [18]. Let random variables M and M_{coop} represent PTD of ADHOC MAC and CAH-MAC respectively. Hence, the probability mass function (pmf) of M with parameter p_s, is given by

$$\Pr\{M = i\} = (1 - p_s)^{i-1} p_s, \quad i = 1, 2, 3, ... \tag{7}$$

Similarly, the pmf of M_{coop} with parameter p_s^{coop} is given as

$$\Pr\{M_{coop} = i\} = (1 - p_s^{coop})^{i-1} p_s^{coop}, \quad i = 1, 2, 3, ... \tag{8}$$

Consequently, the expected values of M and M_{coop} are

$$E[M] = \frac{1}{p_s}, \; E[M_{coop}] = \frac{1}{p_s^{coop}} \tag{9}$$

respectively.

E. Packet Dropping Rate

In a communication system, a packet is dropped by a source node from its buffer memory, when it fails to deliver the packet to the destination within the predefine time limit. In our system, we consider this time limit in terms of the number

$$\Pr\{E_1\} = \sum_{k=3}^{F} \left(1-(1-p_s)^{k-2}\right) \frac{(1.5\rho r)^k e^{-1.5\rho r}}{k!} + \left(1-(1-p_s)^{F-2}\right) \left(1 - \sum_{k=0}^{F} \frac{(1.5\rho r)^k e^{-1.5\rho r}}{k!}\right) \quad (3)$$

of frames. Let M_{max} denote the maximum number of frames that a source node attempts to transmits a packet, referred as the maximum transmission limit. Hence, for a given M_{max} value, the packet dropping rate (PDR) of ADHOC MAC is given by

$$PDR = 1 - \sum_{i=1}^{M_{max}} (1-p_s)^{i-1} p_s. \quad (10)$$

With the cooperation, PDR as in (10) changes to

$$PDR_{coop} = 1 - \sum_{i=1}^{M_{max}} (1-p_s^{coop})^{i-1} p_s^{coop} \quad (11)$$

where PDR_{coop} is the packet dropping rate of CAH-MAC.

In the next section, we present numerical results to validate the performance analysis of CAH-MAC.

V. Analytical and Simulation Results

Computer simulations are performed in MATLAB. A road segment with two lanes, each of 5 m width, is considered, i.e., $L = 2$ and $w_l = 5$ m. Vehicles density, ρ_l, is kept 0.05 vehicle/m in both lanes, hence $\rho = L\rho_l = 0.1$ vehicle/m. For the fair comparison, the total number of time slots per frame is kept 60, i.e., $F = 60$ time slots/frame. Transmission range, r, is varied to change the number of THS members sharing a frame, and consequently, the number of unreserved time slots in a frame. The value of p is varied to characterize different channel conditions. The PTD and PDR of CAH-MAC are obtained and compared with ADHOC MAC for different scenarios.

Fig. 3 compares the PTD of CAH-MAC with that of ADHOC MAC. Figs. 4-6 compare the PDR of CAH-MAC with that of ADHOC MAC for different M_{max} values. It is observed that, at two extreme channel condition (i.e., $p = 0$ and 1), both protocols perform equally. When $p = 0$, all transmissions fail due to channel errors; thus there are no potential helpers and cooperation will not be trigged (i.e., $p_{coop} = 0$), resulting in PTD to be infinite and PDR to be 1 for both protocols. On the other hand, at $p = 1$, all packets reach to the destination directly from the source. Thus cooperation is not needed, resulting in PTD to be 1 and PDR to be 0 for both protocols. The advantage of cooperation starts as p increases from zero, such that a source node can get potential helpers upon a transmission failure.

Fig. 3 shows that PTD of CAH-MAC is almost reduced by 40% at a poor channel condition (for $p \leq 0.25$) as compared with that of ADHOC MAC when $r = 200$. However, for the case $r = 300$, reduction in PTD is only about 20%. This is due to the fact that, the advantage of cooperation can be achieved when there are a moderate number of THS members as compared with F. In such a case, there are potential helpers and sufficient unreserved time slots to perform cooperative relay transmission. When $r = 300$, the average number of THS nodes sharing a frame is almost equal to the total available time slots. i.e., ($2\rho r = 60$), hence few unreserved time slots. The smaller the number of unreserved time slots or the larger the number of THS members, the smaller the p_{coop} value, which decreases the cooperation gain. Hence, a less number of unreserved time slots for the cooperative relay transmission results in a higher PTD for $r = 200$. As p increases, the delay improvement starts to decrease. The probability of a successful direct transmission increases with the improvement in the channel condition (i.e., $p \geq 0.85$), the gap between PTD values for both protocols decreases as the channel condition deteriorates.

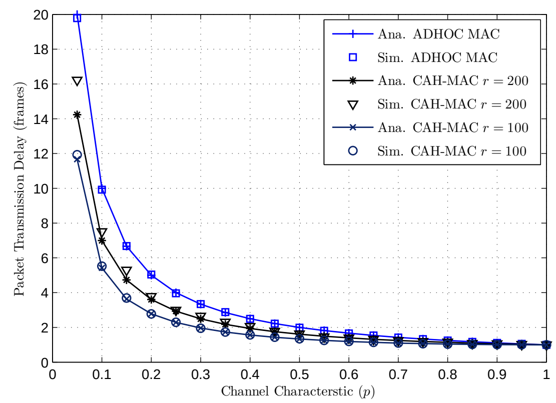

Fig. 3. Packet transmission delay of ADHOC MAC and CAH-MAC.

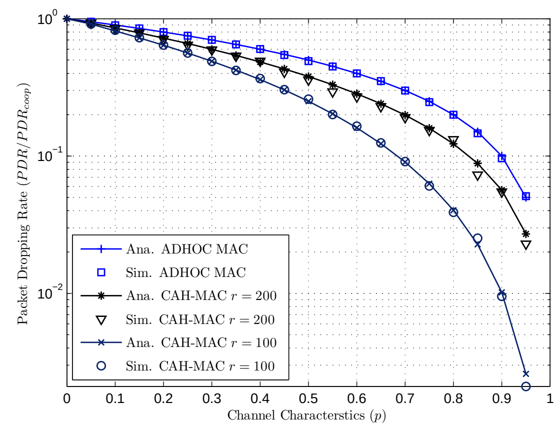

Fig. 4. Packet Dropping Rate of ADHOC MAC and CAH-MAC with $M_{max} = 1$ frame.

Figs. 4-6 show PDR for both protocols at various M_{max} values. It is observed that the PDR of CAH-MAC is always less than that of ADHOC MAC for a given channel condition. However, the gap between the PDR values for CAH-MAC and ADHOC MAC increases as the channel gets better in a similar networking condition. Also, the gap increases with the probability of cooperative relay transmission p_{coop}. Hence, the gap between two protocols when $r = 200$ is higher than that

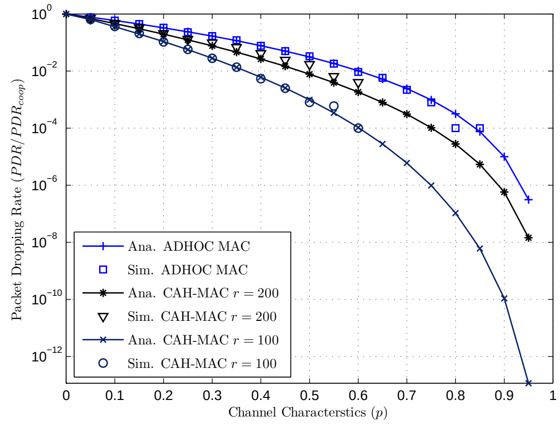

Fig. 5. Packet Dropping Rate of ADHOC MAC and CAH-MAC with $M_{max} = 5$ frames.

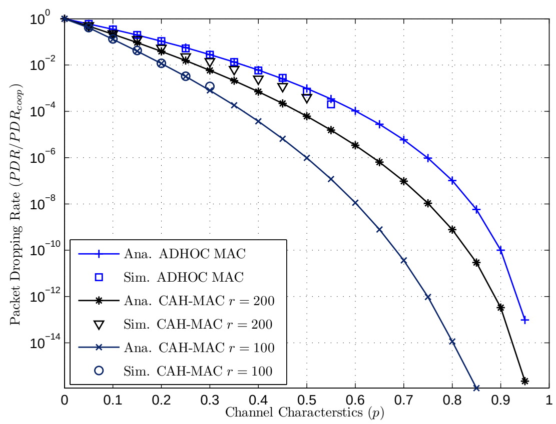

Fig. 6. Packet Dropping Rate of ADHOC MAC and CAH-MAC with $M_{max} = 10$ frames.

when $r = 300$. For the same channel condition, the larger the M_{max} value, the larger the gap between the PDR values of two protocols. Upon a transmission failure, in CAH-MAC, the helper node retransmits a packet in an unreserved time slot. Hence, with a larger M_{max}, a node in CAH-MAC gets more retransmission attempts than that of ADHOC MAC. This increases the probability of successful packet delivery to the destination within M_{max} frames, preventing it from being dropped from the buffer memory.

VI. Conclusion

In this paper, we study the reliability of cooperative ADHOC MAC protocol (CAH-MAC) for VANETs based on ADHOC MAC. In CAH-MAC, upon detecting a transmission failure between an $s - d$ pair, a neighboring node offers cooperation to relay the packet to the destination during an unreserved time slot. As a packet is retransmitted by a helper node, delay improvement is achieved and chances of packet being dropped decrease. We derive a close-form expression for the packet transmission delay and packet dropping rate of the CAH-MAC protocol, which are verified using simulations. Our analysis shows that the CAH-MAC protocol achieves lower packet delay and packet dropping rate than that of the ADHOC MAC under a similar networking condition. Numerical results demonstrate that CAH-MAC performs better in the presence of a moderate number of nodes in a two-hop neighborhood as compared with the total number of time slots available in a frame. Also, the packet dropping rate is smaller for a larger maximum retransmission limit value.

In this work, we have not considered relative mobility among nodes. Effects of dynamic network topology changes due to the relative mobility and a more realistic link model (other than the unit disk model) on the performance of CAH-MAC need further investigation.

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