CAH-MAC: Cooperative ADHOC MAC for Vehicular Networks

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***Abstract*—Due to the rapid advancement in the wireless communication technology and automotive industries, the paradigm of vehicular ad-hoc networks (VANETs) emerges as a promising approach to provide road safety, vehicle traffic management, and infotainment applications. Cooperative communication, on the other hand, can enhance the reliability of communication links in VANETs, thus mitigating wireless channel impairments due to the user mobility. In this paper, we present a cooperative scheme for medium access control (MAC) in VANETs, referred to as Cooperative ADHOC MAC (CAH-MAC). In CAH-MAC, neighboring nodes cooperate by utilizing unreserved time slots, for retransmission of a packet which failed to reach the target receiver due to a poor channel condition. Through mathematical analysis and simulation, we show that our scheme increases the probability of successful packet transmission and hence the network throughput in various networking scenarios.**

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

I. INTRODUCTION

INCREASING road accidents, vehicle traffic congestions, and user demands for a drive-thru Internet connection have led to the evolution of intelligent transportation systems [1] 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 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) [2]. 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.

In addition to various obstacles due to unreliable wireless transmission medium, development and operation of VANETs have some 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 communication protocols for VANETs. Recently, the IEEE 802.11p [3] 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 [4], [5]. On the other hand, as high priority safety messages are short range, uncoordinated, and broadcast in nature[6], 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 [4] and the VeMAC [7], 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. They can introduce some overhead or require multiple antennas and/or transceivers. 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. The broadcast nature of a wireless transmission enables neighboring nodes to overhear the transmission of a packet from the source node to the destination. When the direct transmission between the $s-d$ pair suffers from a poor channel condition, the overheard packet can be relayed to the destination by a node or nodes which have good channel conditions with both $s-d$ nodes. This cooperative transmission with the help of neighboring node(s) can increase throughput of the entire network and/or reliability of a packet delivery. The node which helps to relay the packet to the destination is

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referred to as a helper node.

In this paper, we present a cooperation scheme for VANETs mainly focusing on the MAC layer, called cooperative ADHOC MAC (CAH-MAC). Existing works on link layer cooperation focus on cooperation in the IEEE 802.11 based networks and/or infrastructure based TDMA networks. Different from the existing works, here we consider a VANET using a distributed TDMA based MAC protocol. In the system, nodes reserve their time slots and nearby nodes form a cluster to share a time frame. For cooperation at the link layer, a helper node utilizes an idle time slot to relay a packet that failed to reach the destination in a direct transmission, without affecting the normal (non relay) transmissions. Using idle time slots for the cooperative relay transmissions, the proposed CAH-MAC protocol improves throughput of the VANET.

This paper is organized as follows. In Section II, related works on cooperative MAC protocols are discussed. Section III describes the system model and assumptions made for the protocol design. The CAH-MAC protocol is presented in Section IV. Section V presents throughput analysis of CAH-MAC, which is verified in Section VI with simulations. Finally, Section VII provides a summary of our contributions and identifies some issues for further investigation.

II. RELATED WORK ON COOPERATIVE MAC PROTOCOLS

Several cooperative MAC protocols have been proposed for the legacy IEEE 802.11 networks with distributed control [8]–[15] and for infrastructure TDMA based networks [16]–[18]. In [8] and [9], the cooperative MAC schemes (namely rDCF and CoopMAC respectively) exploit the multirate capabilities of the IEEE 802.11 networks. Helper nodes are chosen to shorten the transmission time of a packet. In [10], a similar cooperation scheme called CC-MAC is proposed for uplink transmission. The CC-MAC reduces occurrence of transmission bottleneck due to congestion in the vicinity of access points and allows the nodes to perform concurrent transmissions which further increase throughput. In all aforementioned studies, cooperation is performed based on previous transmission attempts. In [11], it is shown that cooperation based on historical transmissions does not work for a network where nodes are moving randomly with high dynamics. Changes in traffic load, channel condition, network topology are frequent and common in mobile ad hoc networks, hence historical transmission may not correctly reflect the present channel condition. In such a case, it is very likely that the source does not find helpers, or helpers fail to perform cooperation. This results in a delay in packet delivery and/or throughput reduction.

Motivated by issues with cooperation based on historical transmission, authors in [12]–[14] propose cooperative MAC protocols in which decision of cooperation and helper selection are made during the ongoing transmission. Cooperation decisions are made based on signal strength of control signal and/or information exchange among nodes. In [12], the CD-MAC is proposed to improve transmission reliability in which the source node searches for a helper to retransmit its packets if the destination sends the negative acknowledgement (NACK) or does not acknowledge (ACK) the reception. Similarly in [13], cooperation is enabled when vehicles missed broadcast packets from an RSU, such that helper nodes are selected to rebroadcast the packets, improving the overall throughput of a network and avoiding collision due to rebroadcast. In [14], Zhou et al. propose a cooperative MAC protocol, ADC-MAC, that is backward compatible with the IEEE 802.11.

All of the existing cooperative MAC protocols are based on the IEEE 802.11 and force neighboring nodes to stop their own transmissions during the cooperative transmission for an $s-d$ pair. Nodes in the vicinity of the helper along with the $s-d$ pair should back-off their transmissions until the ongoing transmission finishes. In addition, the interference area increases with the introduction of helpers, which further increases the probability of hidden and exposed node problems. In [16]–[18], cooperation in TDMA MAC is presented for infrastructure based wireless networks. In such networks, a communication link is established between a central controller (or access point) and mobile nodes. Cooperation is thus performed by dedicated (fixed) helper nodes and coordinated by the controller. In [17], time slots for source nodes and for helpers are fixed even if cooperation is not required. Hence these protocols cannot be applied directly in VANETs.

Different from the existing works, here we consider TDMA MAC for VANETs. 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.

III. SYSTEM MODEL

This section describes the system model under consideration and the framework to evaluate performance of the proposed CAH-MAC protocol. Necessary assumptions are made regarding network topology, mobility, protocol layers, and node distribution.

A. Network Topology and Channel Model

Consider a VANET consisting of 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. 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.

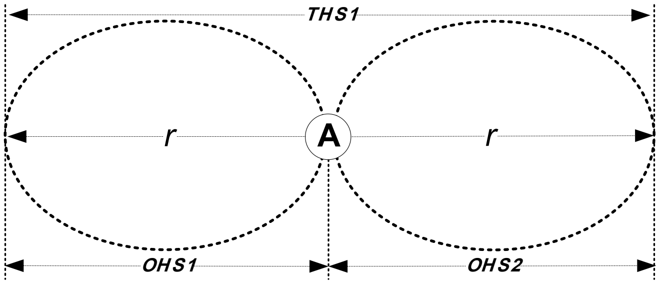

Fig. 1. Illustration of a two-hop set, where an ellipse represents an OHS such that all nodes inside one ellipse can directly communicate with each other, with node A as a reference.

B. Neighboring Nodes

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. For example in Fig. 1, node A is a member of two OHSs namely OHS 1 and OHS 2. In addition, it is also a member of two-hop set, THS 1. Node A can communicate directly with any nodes in its OHSs i.e., nodes in OHS 1 and OHS 2. Similarly, all nodes in the same THS can communicate with each other with maximum two hops.

C. Channel Access

The channel access mechanism is based on distributed TDMA scheme as in ADHOC MAC [4] and VeMAC[7], 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. 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 [19] that a GPS receiver gets every second can be use for the synchronization. If the GPS signal is lost, a GPS receiver's local oscillator can be used for a short duration and a distributed synchronization scheme can be used for a longer duration, to synchronize nodes [20]. Details of such synchronization schemes are out of the scope of this paper. 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.

Nodes form clusters of two-hop neighbors. Here a cluster refers to a group of nodes which are at 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 THS stops simultaneous usage of a time slot by more than one node within the same interference range and thus avoids the 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 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 [4] 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 [21]. In [21], 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.

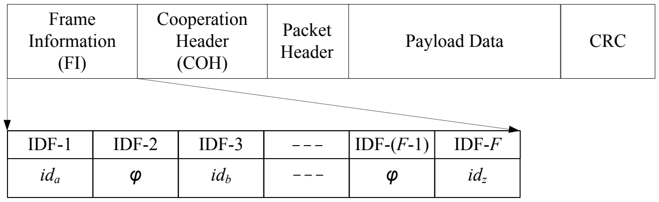

Fig. 2. Structure of a packet and a frame information field in CAH-MAC, where ϕ indicates an empty field.

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.

IV. PROTOCOL DESCRIPTION

In this section, we discuss the detail operation of CAH-MAC, 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. 2 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. In the following, we describe the structure and purposes of the signalling fields, namely the frame information and cooperation header.

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. 2. Temporary (or short) identifier [4], [7], which is shorter ($1-2$ bytes) than the size of a MAC address, can be used as an ID of a node. Such a short ID can be selected randomly by a node and changed if there is a conflict [4]. Use of such a short ID reduces the size of the FI in a packet and, hence, reduces the MAC overhead.

Destination node D, upon receiving a packet successfully from the 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. By successfully receiving a packet from node S, node D knows (a) the existence of node S as its one-hop neighbor, (b) node S is the owner of the s^{th} time slot, and finally (c) all the one-hop neighbors of node S and their corresponding time slots. 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 as illustrated in Fig. 2 for IDF-2.

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, formation of a THS cluster, 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*

Cooperation is always performed through a one-hop neighbor of the source and destination nodes. Since the channel condition may remain the same during the unused time slot as that during the source node's time slot, retransmission by the source node during the unused time slot is not likely to be helpful and will waste the transmission opportunity. On the other hand, cooperative relay transmission of a packet, through an independent channel (i.e., between the helper and destination) during an unreserved time slot provides transmission diversity and, hence, improves transmission reliability even if the channel condition between an $s-d$ pair is poor [22]. In the following, we discuss how a node decides and performs cooperation. Let $\mathcal{F}=\{1,2,3,...,F\}$ be the set of time slots in a frame. Consider $\mathcal{O}_x$ and $\mathcal{T}_x$ as the OHS and THS of a node x. Let $\mathcal{R}_x$ be a set of all time slots which belongs to the THS of node x, i.e., any time slot $t \in \mathcal{R}_x$ is reserved from the perspective of node x. Consider S and D as the source and destination nodes with the s^{th} and d^{th} time slots respectively and node H as the helper node. Cooperation decision and cooperative relay transmission are performed only if all the following conditions are satisfied:

1) **The direct transmission fails**: Cooperation is trigged when the direct transmission between the source and the destination fails. Upon a transmission failure, node D does not acknowledge the transmission from node S, such that $S \notin \mathcal{O}_D$. Potential helper nodes have the transmission failure information after receiving the FI from node D.
2) **The helper successfully receives a packet for retransmission**: A node can potentially offer cooperation only if it receives the packet successfully from the source node S during the s^{th} time slot.
3) **The destination is reachable**: Node H can relay a packet that node D failed to received from node S, if node D is within its transmission range. Hence both source node S and destination node D must be listed as one-hop neighbors in node H's neighbor-table, i.e., $S, D \in \mathcal{O}_H$.
4) **There is an available time slot**: Helper node H, when conditions $1)-3)$ are satisfied, can offer and perform cooperation if there exists at least one unreserved time slot $h \in \mathcal{F}$ during which it can transmit. The transmission from H in time slot h shall not cause any collision at its one-hop neighbors, i.e. $\forall h \notin \mathcal{R}_H$.

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 time slot h. 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. Fig. 3 shows necessary information exchanges for cooperation in the CAH-MAC. When the destination node D fails to receive a packet from the sender node S (in Fig. 3(a)), it announces transmission failure through its FI as shown in Fig. 3(b). Upon deciding to cooperate, the helper node H transmits its intention of cooperation using cooperation header (COH) as in Fig. 3(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. 3(d)). Next, we discuss the cooperation header that a helper node uses to offer cooperation and C-ACK that a destination node uses to avoid collision during cooperative relay transmission.

C. *Cooperation Header and Cooperation Acknowledgement*

Once a node decides to cooperate, it transmits its decision via cooperation header in its packet. The following information is included in the cooperation header:

- its intention to cooperate,
- the index of time slot of the source during which transmission failure occurred, and
- the index of the selected unreserved time slot in which the packet will be retransmitted from the helper to the destination.

The aforementioned information is embedded in the cooperation header and transmitted in the helper's time slot.

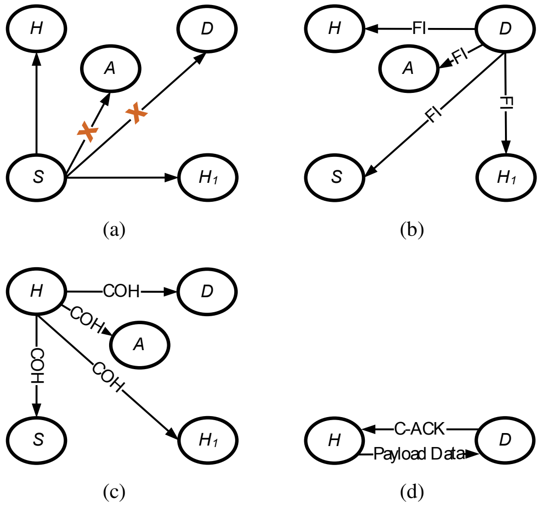

Fig. 3. Information exchanges in the CAH-MAC: (a) Phase 1: Source node transmits a packet to the destination; (b) Phase 2: Neighboring nodes detect transmission failure after examining the FI from the destination; (c) Phase 3: Helper node H, offers cooperation; (d) Phase 4: Helper node H, re-transmits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

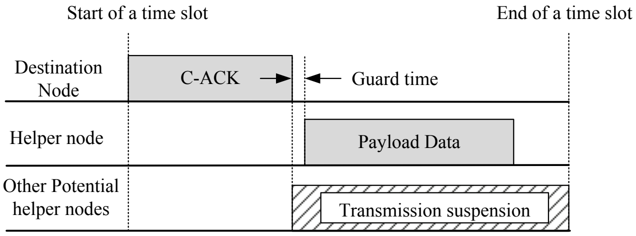

Fig. 4. Cooperative relay transmission during an unreserved time slot.

Other potential helpers (which can offer cooperation and are in the OHS of helper node) suspend their intentions, once they receive cooperation decision from the helper H. Hence, helper node H is the one which first offers cooperation and performs cooperation for the $s-d$ pair. Such a suspension of cooperation intention avoids collision among potential helpers during cooperative relay transmission. However, 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, a cooperation acknowledgement (C-ACK) from the destination node is transmitted during the selected unreserved time slot, which is illustrated in Fig. 4. In C-ACK, the destination node puts the ID of the first potential helper which offered cooperation to accept cooperation. Transmission of a C-ACK from the destination node forces other potential helpers to suspend their transmissions, thus avoiding any possible collision. The helper node retransmits the packet that failed to reach the destination in the direct transmission from the source node.

The size of a short ID is always enough to be shared among the nodes that are sharing a frame. Hence, the size of an index of a time slot is comparable with the size of a short ID. Consequently, the size of a cooperation header is negligible as compared to the size of FI (and obviously the size a time slot), which has a space for F IDs. Generally, the F value is set large enough to guarantee a time slot for each node. In addition, cooperation acknowledgement (C-ACK) and cooperative transmission are performed in an unreserved time slot. Hence, cooperation can be performed at the cost of negligible overhead as compared to a time slot which would be wasted in absence of cooperation. It is to be noted that, in the proposed CAH-MAC, only one helper performs the cooperative relay transmission for a failed $s-d$ direct transmission. Potential helpers, which can offer cooperation to the failed $s-d$ direct transmission, suspend their cooperation intentions once they receive cooperation decision from the helper node. Hence, a potential helper offers cooperation to only those failed $s-d$ direct transmissions which are not offered with cooperation, but not to every failed $s-d$ direct transmissions. This reduces the size of COH and hence the communication overhead due to cooperation.

V. THROUGHPUT ANALYSIS OF CAH-MAC

In this section, we develop a mathematical model for performance evaluation of the proposed CAH-MAC protocol. Throughput is taken as a metric to compare the performance of CAH-MAC with ADHOC MAC.

A. Node 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 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 [23], 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. Distribution of the Neighboring Node Numbers

Let N_T be the number of nodes in a given THS, including all nodes within distance of r units both in backward and forward directions of the reference node (including itself). Fig. 1 illustrate that nodes in the given THS distributed along the road segment of length $2r$ units. As the counting of nodes follows a Poisson distribution, the probability mass function (pmf) of N_T can be obtained by substituting $z = 2r$ in (1), given by,

$$\Pr\{N_T = n\} = \frac{(2\rho r)^n e^{-2\rho r}}{n!}, \qquad n = 0, 1, 2, ... \tag{2}$$

A node cannot access time slots that are being used by its THS members. Thus for stable performance, F must be

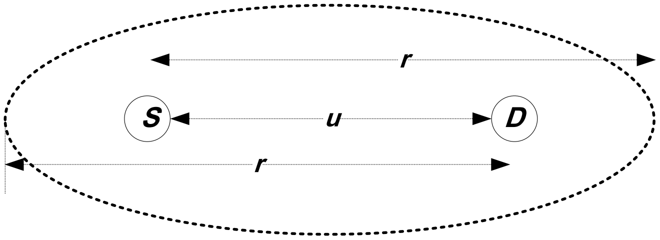

Fig. 5. Illustration of the common coverage road segment of an $s-d$ pair.

large enough so that each node located within a road segment of $2r$ units gets a unique time slot. Hence, we should have $F > E[N_T] = 2\rho r$ to achieve stable performance of the MAC protocol.

Next, consider the number of nodes which are at maximum one hop from both the source and the destination, denoted by N_o. Fig. 5 illustrates the road segment where such nodes are distributed. In Fig. 5, nodes which are in OHS of both source and destination are distributed along the road segment of length $2r - u$ units, where u $(\leq r)$ is the distance between the source and destination nodes. If u is uniformly distributed within $[0, r]$, the average distance between the source and destination is $0.5r$. Consequently, common OHS nodes are distributed along length of $1.5r$ units on average. The probability mass function of N_o can be obtained by substituting $z = 1.5r$ in (1), given by

$$\Pr\{N_o = v\} = \frac{(1.5\rho r)^v e^{-1.5\rho r}}{v!}, \qquad v = 0, 1, 2, \ldots . \tag{3}$$

C. Types of Time Slots and their Distributions

In a given THS, out of the total F time slots in a frame, each time slot is one of following types:

- ***Unreserved***: Time slots which are not yet reserved by any node are unreserved time slots. Any time slots other than unreserved in a frame are reserved time slots. Let random variable U represent the number of unreserved time slots in a frame.
- ***Successful***: The reserved time slots during which data packets are successfully delivered to the destination are regarded as successful time slots. Let random variable X represent the number of successful time slots in a frame. Hence, given $U = j$, we have $0 \leq X \leq F - j$.
- ***Failed***: Time slots other than unreserved and successful belong to failed time slots.

Note that in cooperation enable transmission, for each failed direct transmission, an unreserved time slot is used for the relay transmission if conditions in Section IV-B are satisfied. With cooperation, the corresponding time slot is considered a successful time slot if a packet is successfully delivered to the destination through the helper, and a failed time slot otherwise.

One way to evaluate the MAC protocol is by its ability to handle channel errors. In TDMA based MAC, the number of successful time slots per frame is an indication of this ability. If a MAC protocol is more robust in reliable packet delivery in a relatively poor channel condition, it can achieve a higher number of successful time slots in a frame. A time slot is successful only if the transmitted packet does not collide with packets from other nodes in the THS and successfully reaches the target receiver. Let p_s denote the probability of successful transmission during a reserved time slot. As channel condition (characterized by p) and transmission collision are independent of each other, p_s is given by

$$p_s = (1 - p_c)p \tag{4}$$

where p_c is the probability of transmission collisions in a given time slot. Collisions can be merging collisions [4] and are 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. Hence $p_c = 0$ and $p_s = p$. Given $U = j$, X follows a binomial distribution with parameters $(F - j, p_s)$ and its conditional pmf is given by

$$\Pr\{X = i | U = j\} = \binom{F-j}{i} p_s^i (1 - p_s)^{F-j-i}, \quad i = 0, 1, 2, ..., F - j. \tag{5}$$

Consequently, the expected value of X given $U = j$ is

$$E[X | U = j] = (F - j)p_s. \tag{6}$$

In a frame, out of F available time slots, only N_T time slots are reserved by members of the corresponding THS. Hence we have

$$U = \begin{cases} 0, & \text{if } N_T \geq F \\ F - N_T, & \text{if } 1 \leq N_T < F. \end{cases} \tag{7}$$

Note that in (7), for a time slot to be called as reserved (or unreserved) or for a frame to exists, there must be at least one node in the corresponding THS, i.e., $N_T \geq 1$. If a frame exists, unreserved time slots are leftover time slots after all members of the THS finish their reservations. Hence, if a frame exists, $0 \leq U \leq F - 1$. On the other hand, if there are more than F members in a THS, there will be no unreserved time slot in the corresponding frame, i.e., $U = 0$. Hence, from (2) and (7), the pmf of U is given by

$$\Pr\{U = j\} = \begin{cases} 1 - \sum_{i=1}^{F-1} \frac{(2\rho r)^i e^{-2\rho r}}{i!}, & \text{for } j = 0 \\ \frac{(2\rho r)^{F-j} e^{-2\rho r}}{(F-j)!}, & \text{for } 0 < j \leq F - 1. \end{cases} \tag{8}$$

From (6) and (8), the expected number of successful time slots, $E[X]$ can be written as

$$\begin{aligned} E[X] =& p_s \sum_{j=1}^{F-1} (F - j) \frac{(2\rho r)^{F-j} e^{-2\rho r}}{(F-j)!} \\ &+ p_s F \left(1 - \sum_{j=1}^{F-1} \frac{(2\rho r)^j e^{-2\rho r}}{j!} \right). \end{aligned} \tag{9}$$

D. Cooperation Enabled Transmission

If a transmission failure occurs, cooperation may be triggered. Based on the operation procedure discussed in Section IV, cooperation gets triggered if all of the following events occur:

- *Event 1* (E_1): There is at least one potential helper. 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 2* (E_2): There exists at least one unreserved time slot in which a potential helper node can transmits without causing any collision in its OHS neighborhood.

Event E_1 depends on the channel conditions between the source node and common one-hop neighbors of an $s-d$ pair. On the other hand, from (7) and (8), event E_2 depends on the number of THS members of the helper node for the given F value. Hence, events E_1 and E_2 are independent of each other. The probability of cooperation decision for each failed direct transmission, p_{coop}, is given by

$$p_{coop} = \Pr\{E_1\}\Pr\{E_2\}. \tag{10}$$

In the following, we derive a close form expression of the probabilities of events E_1 and E_2 respectively.

1) Existence of Potential Helpers (Event 1): The number of common OHS neighbors of an $s-d$ pair, which receive a packet from the source, follows a binomial distribution. These common OHS neighbors are potential helpers. Let random variable Y denote the number of potential helpers for a given failed packet transmission. Given the number of common nodes in the S and D's OHSs $N_o = k$, a potential helper does not exist if $k \leq 2$, as $s-d$ pair cannot be the helper. If $3 \leq k \leq F$, up to $k-2$ nodes can act as a helper if they successfully receive the packet from the source. Finally if $k > F$, only $F-2$ nodes which have reserved a time slot in a frame can act as a helper. A node, which does not own a time slot cannot transmit its cooperation header, hence it cannot perform cooperation. Therefore, given $N_o = k$, the pmf of Y is given in (11).

Event 1 occurs, when at least one common OHS neighbor of the $s-d$ pair successfully receives the packet from the sender, i.e., $Y > 0$. Given $N_o = k$, the probability of *Event 1* occurrences is

$$\Pr\{E_1 | N_o = k\} = 1 - \Pr\{Y = 0 | N_o = k\}. \tag{12}$$

From (3), (11), and (12), the probability of *Event 1* occurrences can be derived as

$$\Pr\{E_1\} = \sum_{k=3}^{F} \left(1-(1-p_s)^{k-2}\right) \frac{(1.5\rho r)^k e^{-1.5\rho r}}{k!} + \left(1-(1-p_s)^{F-2}\right)\left(1 - \sum_{k=0}^{F} \frac{(1.5\rho r)^k e^{-1.5\rho r}}{k!}\right). \tag{13}$$

2) Existence of Unreserved Time Slots (Event 2): 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 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. From (8), we have

$$\Pr\{E_2\} = \Pr\{U > 0\} = \sum_{j=1}^{F-1} \frac{(2\rho r)^j e^{-2\rho r}}{j!}. \tag{14}$$

From (10), (13), and (14), the probability of cooperation, p_{coop}, can be calculated.

E. Benefit of Cooperation

Note that just triggering a cooperation does not guarantee a successful retransmission. Cooperation is beneficial only if the transmission from the helper to the destination is successful. 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 as

$$p_s^{coop} = p_s + p_s(1-p_s)p_{coop}. \tag{15}$$

With the cooperation, the expected number of successful time slots in a frame as in (9) changes to

$$E[X_{coop}] = p_s^{coop} \sum_{j=1}^{F-1} (F-j) \frac{(2\rho r)^{F-j} e^{-2\rho r}}{(F-j)!} + p_s^{coop} F \left(1 - \sum_{j=1}^{F-1} \frac{(2\rho r)^j e^{-2\rho r}}{j!}\right) \tag{16}$$

where X_{coop} is a random variable representing the number of successful time slots in a frame with cooperation enabled transmissions.

F. Throughput Analysis

Throughput is defined as the fraction of successful time slots over the total number of time slots per frame, F. Let σ and σ_{coop} denote the throughput of ADHOC MAC and CAH-MAC respectively. We have

$$\sigma = \frac{E[X]}{F}, \qquad \sigma_{coop} = \frac{E[X_{coop}]}{F}. \tag{17}$$

The normalized throughput gain achieved by cooperation is given by

$$\sigma_{gain} = \frac{\sigma_{coop} - \sigma}{\sigma}. \tag{18}$$

In the next section, we present numerical results to validate the throughput analysis and to evaluate performance gain by cooperation.

VI. ANALYTICAL AND SIMULATION RESULTS

Simulations were performed in MATLAB. A road segment with two lanes each of $5m$ width was considered, i.e., $L = 2$ and $w_l = 5m$. Five hundreds nodes were distributed along a road segment following the Poisson distribution. Vehicles densities, ρ_l (vehicles/km), were kept equal in both lanes, hence $\rho = L\rho_l$. Each simulation result was obtained by simulating $200,000$ frames from 40 different network topologies. The value of p was varied to characterize different channel conditions. Throughput and throughput gain of CAH-MAC were obtained in comparison with ADHOC MAC for several different scenarios.

First, we study the effect of the exponentially distributed inter-vehicular distance assumption on validity of the analysis in Section V. Fig. 6 shows that the throughput with minimum safety distance, d_0, between adjacent vehicles in a lane, and

$$\Pr\{Y=a|N_o=k\}=\begin{cases}1, & \text{for } a=0 \text{ if } k\le 2\\ \binom{k-2}{a}p_s^a(1-p_s)^{k-a-2}, & \text{for } 0\le a\le k-2 \text{ if } 3\le k\le F\\ \binom{F-2}{a}p_s^a(1-p_s)^{F-a-2}, & \text{for } 0\le a\le F-2 \text{ if } k>F\end{cases} \tag{11}$$

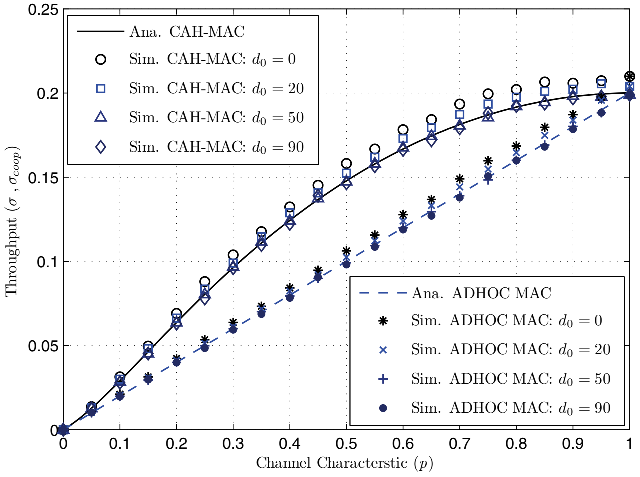

Fig. 6. Throughput comparison of network topology with and without a minimum separation distance (d_0) for $\rho_l = 10$ vehicles/km, $r = 300$ m, and $F = 60$ time slots.

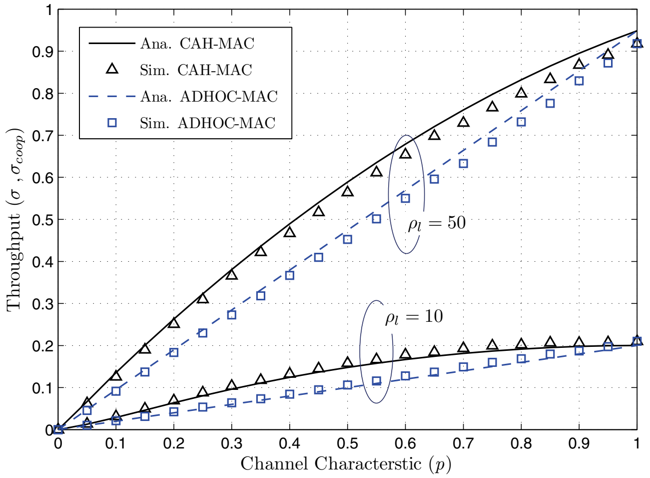

Fig. 7. Throughput comparison of ADHOC MAC and CAH-MAC with $r = 300$ m, and $F = 60$ time slots.

the analytical results with $d_0 = 0$. It is observed that the analytical results match well with the simulation results for both scenarios with and without cooperation. The effect of non-zero d_0 values on the throughput is not significant. As a result, in the following, we present numerical results under assumption $d_0 = 0$.

Figs. 7–9 compare the throughput of CAH-MAC with that of ADHOC MAC. It is observed that with an introduction of cooperation, throughput of CAH-MAC is in general higher than that of ADHOC MAC. However at two extreme channel conditions, i.e., $p = 0$ and 1, both protocols perform equally as expected. When $p = 0$, all transmissions fail due to channel errors; thus there are no potential helpers. On the other hand, at $p = 1$, all packets reach to the destination directly from the source; thus cooperation is not needed. The advantage of cooperation starts as p increases from zero, such that a source node can get potential helpers upon a transmission failure. Figs. 10–11 show the throughput gain of CAH-MAC over ADHOC MAC. Note that, at $p = 0$, both protocols have a zero throughput. On the other hand, at $p = 1$, the throughput of both protocols are equal, resulting in no throughput gain. All the simulation results match well with the analytical results.

Fig. 7 shows that the throughputs are proportional to the vehicle density per lane (ρ_l) values. The smaller density value means a smaller number of THS members on average. This tends to increase the number of unreserved time slots in a frame, which has a negative effect on the throughput. In ADHOC MAC, unreserved time slots are left unused, while in CAH-MAC the introduction of cooperation reduces transmission failure probability by utilizing unreserved time slots. Fig. 8 shows that the throughput increases with an increase in the transmission range r. For the given vehicle density, increasing the transmission range also increases the number of THS members, leading to more efficient utilization of available time slots in each frame. Fig. 9 shows the effect of the frame size F on the throughput. For the given vehicle density and transmission range, the throughput decreases with an increase in F. For the relatively small average number of THS members, an increase in F increases the number of unreserved time slots and hence decreases the throughput. Figs. 7–9 show the increase in throughput of CAH-MAC over

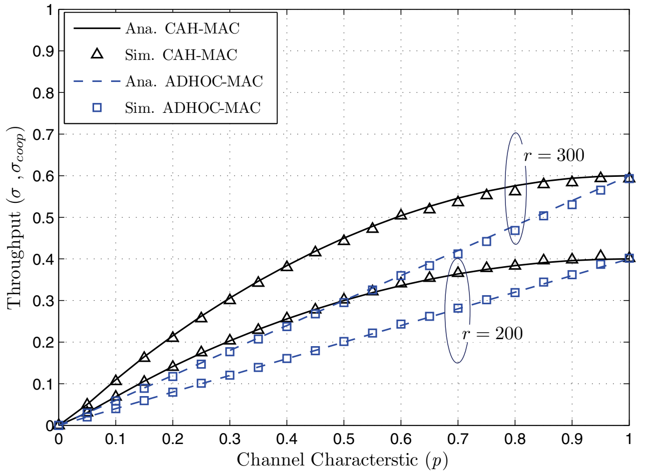

Fig. 8. Throughput comparison of ADHOC MAC and CAH-MAC with $\rho_l = 30$ vehicles/km, and $F = 60$ time slots.

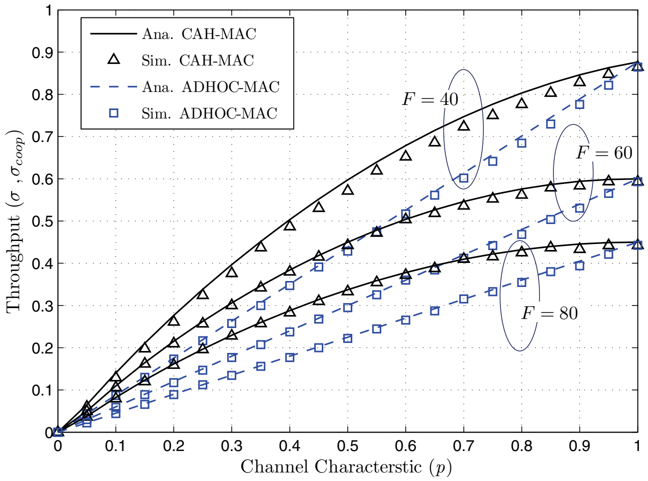

Fig. 9. Throughput comparison of ADHOC MAC and CAH-MAC with $\rho_l = 30$ vehicles/km, and $r = 300$ m.

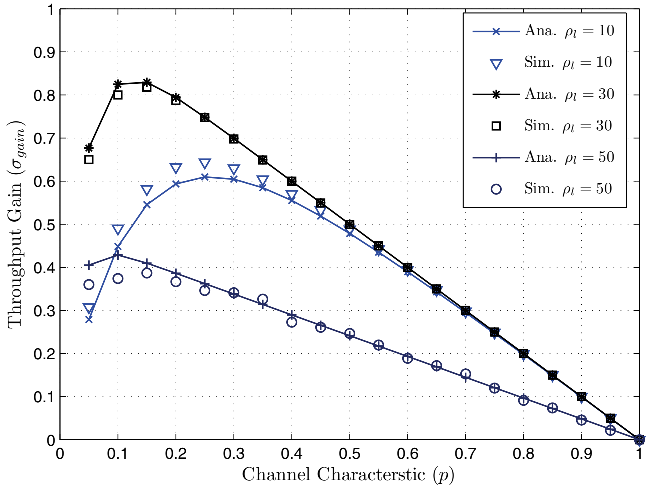

Fig. 10. Throughput gain of CAH MAC over ADHOC MAC with $F = 60$ time slots, and $r = 300$ m.

ADHOC MAC for the same p under the similar networking environments. In general, the throughput improvement by cooperation increases as the channel quality improves from a very poor condition (i.e., a very small p value). The better channel quality increases the probability of successful relay transmission. On the other hand, as the channel quality further improves, the probability of successful direct transmission increases, reducing the needs for cooperation and leading to a smaller cooperation gain in the throughput.

Fig. 10 depicts the throughput gain of CAH-MAC over ADHOC MAC versus the channel parameter p for different vehicle density values. As ρ_l increases from 10 to 30 vehicles/km, the throughput gain increases with p. This is due to the fact that, with an increase in the node density, the population of potential helpers increases and ultimately increases the probability of *Event 1* as defined in Section V. However, with a further increase in the number of nodes, the number of unreserved time slots decreases. This reduces the cooperation gain as there are less time slots available for cooperation, i.e., decreasing the probability of *Event 2* as defined in Section V. Hence, the throughput gain decreases when ρ_l is further increased from 30 to 50 vehicles/km. Fig. 11 shows the throughput gain of CAH-MAC over ADHOC MAC in several scenarios. With an increase in ρ and r, the number of helpers increases, which ultimately increases the cooperation gain. It is noted that the throughput gains for parameter pairs [$r = 200$, $\rho_l = 30$] and [$r = 300$, $\rho_l = 20$] are the same, because both cases have the same average number of THS members (i.e., $2\rho r \simeq 24$). The throughout gain decreases when the number of THS members is large as compared with F. For the parameter pair [$r = 300$, $\rho_l = 50$], the average number of THS members ($2\rho r = 60$) is the same as F, resulting in a smaller throughout gain than that in the other cases.

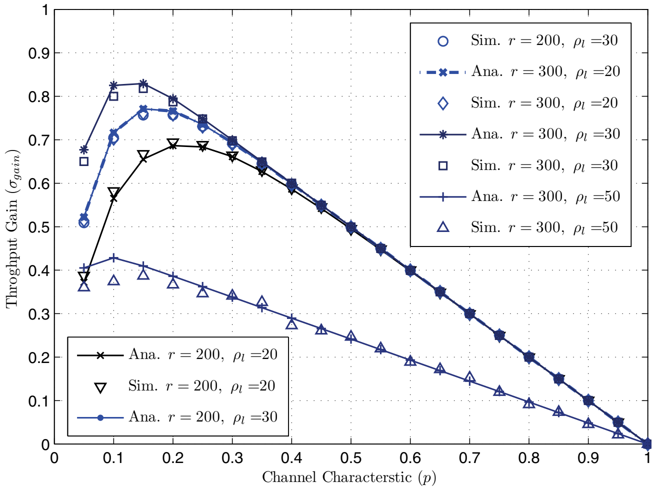

Fig. 11. Throughput gain of CAH MAC over ADHOC MAC with $F = 60$ time slots.

From Figs. 10–11, it can be seen that the throughput gain reaches its peak at a certain p value and starts decreasing as p further increases. With a large p value, the probability of successful direct transmissions increases and hence cooperation may not be triggered. When p is moderate, direct transmissions may suffer from channel errors and hence cooperation helps to retransmit the packet that failed to reach the destination. At a small p value, as the helper is likely to suffer from channel errors, the cooperation gain is not significant. Note that the throughput gain increases with an increase in the transmission range and vehicle density when $F \gg 2\rho r$. As channel characteristic improves (i.e., for $p > 0.4$), the throughput gain decreases linearly with p irrespective of r and ρ_l. In such a case, it is very likely that, at least one neighboring node successfully receives a packet from the source and there are unreserved time slots for cooperation, resulting in $p_{coop} \simeq 1$. From (18), the throughout gain depends only on $p_s (= p)$ as $\sigma_{gain} \simeq 1 - p_s$. Hence, the throughput gain does not change with r and/or ρ_l as long as $F > 2\rho r$, but reduces linearly with p.

VII. CONCLUSION AND FUTURE WORK

In this paper, we present a 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 unreserved time slots are used for retransmission, throughput improvement is achieved. We derive a close-form expression for the throughput of the newly proposed CAH-MAC protocol, which is verified using simulations. Our analysis shows that the CAH-MAC protocol achieves a higher throughput than that of the ADHOC MAC under similar networking conditions. Numerical results demonstrate that throughput gain by cooperation is significant for a moderate channel condition. In addition, the throughput gain is significant 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.

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

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