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Enhancing Transmission Collision Detection for Distributed TDMA in Vehicular Networks

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The increasing number of road accidents has led to the evolution of vehicular ad hoc networks (VANETs), which allow vehicles and road-side infrastructure to continuously broadcast safety messages, including necessary information to avoid undesired events on the road. To support reliable broadcast of safety messages, distributed time division multiple access (D-TDMA) protocols are proposed for medium access control (MAC) in VANETs. Existing D-TDMA protocols react to a transmission failure without distinguishing whether the failure comes from a transmission collision or from a poor radio channel condition, resulting in degraded performance. In this paper, we present the importance of transmission failure differentiation due to a poor channel or due to a transmission collision for D-TDMA protocols in vehicular networks. We study the effects of such a transmission failure differentiation on the performance of a node when reserving a time slot to access the transmission channel. Furthermore, we propose a method for transmission failure differentiation, employing the concept of deep-learning techniques, for a node to decide whether to release or continue using its acquired time slot. The proposed method is based on the application of a Markov chain model to estimate the channel state when a transmission failure occurs. The Markov model parameters are dynamically updated by each node (i.e., vehicle or road-side unit) based on information included in the safety messages that are periodically received from neighboring nodes. Also, from the D-TDMA protocol headers of received messages, a node approximately determines the error in estimating the channel state based on the proposed Markov model, and then uses this channel estimation error to further improve subsequent channel state estimations. Through mathematical analysis, we show that transmission failure differentiation, or transmission collision detection, helps a node to efficiently reserve a time slot even with a large number nodes contending for time slots. Furthermore, through extensive simulations in a highway scenario, we demonstrate that the proposed solution significantly improves the performance of D-TDMA protocols by reducing unnecessary contention on the available time slots, thus increasing the number of nodes having unique time slots for successful broadcast of safety messages.

CCS Concepts: •**Networks** → **Link-layer protocols;**

Additional Key Words and Phrases: VANETs, distributed time division multiple access (D-TDMA), medium access control (MAC), channel estimation, collision detection, transmission failure differentiation.

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1. INTRODUCTION

Vehicular ad hoc networks (VANETs) are a promising technology to enable a wide range of novel applications that improve road safety, enhance efficiency of vehicle transportation, and provide comfort to on-board drivers and passengers. In VANETs, vehicles communicate with each other and with stationary road-side units (RSUs) to exchange information generated by a variety of mobile applications, including drive-thru Internet [Baldessari et al. 2007], mobile image localization [Liu et al. 2013], and media content distribution [Silva et al. 2016]. Among the wide range of VANET applications, the category of road safety applications has attracted an immense interest from researchers, engineers, and policy makers. The reason is that, VANET safety applications have a huge potential of providing a safer environment for people on roads, by increasing the public safety standards and reducing the risk and severity of traffic accidents. For instance, according to the National Highway Traffic Safety Administration (NHTSA) of the United States Department of Transportation (US-DoT), approximately 80% of vehicle collisions can be avoided by deploying VANET-enabled safety applications [NHT 2012]. Safety applications are achieved through broadcast of critical safety messages by each node (i.e., vehicle or RSU), either in a periodic or event-driven manner [VSC 2005]. Periodic safety messages are continuously generated and broadcast by a node (normally at least 10 times per second), in order to exchange real-time information, such as the current position, speed, and deceleration of vehicles. On the contrary, event-driven messages are broadcast only when an unusual event occurs on the road, such as an unsafe road condition detection or a sudden lane change conducted by a vehicle. Most of the periodic and event-driven safety messages must be delivered with a high level of precision and within a small delivery delay to all the nodes located in a one-hop transmission distance of the transmitting node. Hence, in order to efficiently deploy VANET safety applications, it is required to have a reliable broadcast service supported by the medium access control (MAC) layer, to ensure successful broadcast of safety messages with stringent quality-of-service (QoS) requirements [Li and Boukerche 2015].

In North America, the current MAC layer proposed for VANETs is based on the IEEE 802.11p standard [IEE 2010]. The standard does not provide a reliable broadcast service and suffers from unbounded delivery delays, especially in high node density scenarios [Borgonovo et al. 2004; Hassan et al. 2011; Jiang et al. 2006]. As a result, distributed time division multiple access (D-TDMA) protocols (e.g., AHODC MAC [Borgonovo et al. 2004] and VeMAC [Omar et al. 2013b]) have been proposed for MAC in VANETs, in order to support a reliable broadcast service with acknowledgement (ACK) of receiving broadcast messages. However, a poor radio propagation channel can have a significant impact on the existing VANET D-TDMA protocols. The reason is that, to avoid transmission collisions in VANET D-TDMA protocols, a node releases its acquired time slot or avoid using a contended (unreserved) time slot and contends to acquire a new one after detecting a failure in delivering a broadcast message to at least one of its one-hop neighboring node [Borgonovo et al. 2004; Omar et al. 2013b]. However, a failure of message delivery may be caused by a poor radio propagation channel condition (not a transmission collision), in which case the transmitting node unnecessarily releases the acquired time slot or avoids using the contended time slot, resulting in throughput degradation due to an increasing number of nodes contending to access the available time slots. Hence, D-TDMA protocols should be able to distinguish transmission collisions and channel errors, in order to take the appropriate action for each of the two sources of a transmission failure. For this purpose, deep-learning techniques can be employed to estimate or predict a high-level abstraction of the wireless channel quality [Lin et al. 2014; Bharati and Zhuang 2016], which can be used by D-TDMA protocols to determine the source of a transmission failure and to make an appropriate decision in retaining or releasing time slots.

In this paper, we focus on studying the impact of differentiating the source of a transmission failure on the performance of D-TDMA protocols in vehicular networks. First, we analyze the effect of an accurate transmission failure differentiation method employed by a node that is attempting to acquire a time slot. Such an analysis provides performance upper-bound of transmission failure differentiation methods, which can be used as the benchmark to evaluate the performance of VANET D-TDMA protocols. Furthermore, we present a practical method for D-TDMA protocols to differentiate the two sources of a transmission failure, by employing a deep-learning technique [Deng and Yu 2014]. That is, a node builds a high-level abstraction of the propagation channel by estimating the channel state when a transmission failure occurs. Then, the node uses such a high-level abstraction of the transmission channel to determine the source of a transmission failure and ultimately detects a transmission collision before releasing its time slot. The high-level abstraction of the transmission channel is represented by a two-state Markov chain model, which is dynamically updated by each node using the local information, such as position and speed, that it receives in the periodic safety messages broadcast by neighboring nodes. Also, by exploiting the received ACKs of messages broadcast by a certain node (as provided by D-TDMA protocols [Borgonovo et al. 2004; Omar et al. 2013b]), the node approximately calculates/updates the average estimation error of the channel state using the proposed Markov model. This average channel estimation error is used by a node in conjunction with the Markov model to further enhance the accuracy of collision detection (or transmission failure differentiation). Hence, when a node broadcasts a message over a certain time slot and fails to deliver the message to any of its neighboring nodes, it decides whether to retain or release the time slot by applying the proposed transmission failure differentiation method. A node releases its time slot and acquires a new one when the transmission failure is estimated solely due to transmission collisions, in order to avoid further transmission collisions. On the contrary, when the transmission failure is estimated to be due to poor radio channel conditions, the release of a time slot is not needed and the node retains its time slot for subsequent message broadcast. Our analysis shows that, such a collision detection mechanism enhances the performance of VANET D-TDMA protocols, by increasing the rate of successful time slot acquisitions. Moreover, to evaluate the proposed solution, computer simulations are conducted in a highway scenario, by using vehicle mobility traces generated by PTV VISSIM, a microscopic multi-modal traffic flow simulator [VIS 2015]. Simulation results show that the proposed method for transmission failure differentiation significantly improves the performance of D-TDMA protocols by allowing nodes to release their time slots only when needed.

The rest of this paper is organized as follows. Section 2 reviews the existing VANET D-TDMA protocols in literature and Section 3 describes the system model under consideration. Section 4 analyzes the performance of an accurate transmission differentiation mechanism, while Section 5 proposes a practical transmission failure differentiation method for D-TDMA protocols in VANETs to make an appropriate decision in retaining or releasing time slots. Section 6 provides the numerical results to study the accuracy of the analysis presented in Section 4. The performance of the newly proposed transmission differentiation mechanism is evaluated in Section 7. Finally, Section 8 concludes this research.

2. RELATED WORK

The inefficiency and unreliability associated with the broadcast service supported by the IEEE 802.11p standard have led to the development of D-TDMA protocols for VANETs. In D-TDMA, the channel time is partitioned into time frames, which are further divided into time slots. To avoid transmission collisions, a node is only allowed to access the time slots that are not being used by other nodes within its interference range, i.e., within a two-hop transmission distance. In [Borgonovo et al. 2004], a D-TDMA protocol, referred to as ADHOC MAC, is proposed for VANETs. The ADHOC MAC is based on RR-ALOHA [Borgonovo et al. 2003] and supports point-to-point and multi-hop broadcast services. Due to the growing interest in the ADHOC MAC protocol for VANETs, a Markov chain model is proposed to evaluate the ADHOC MAC performance [Wu and Zheng 2016]. However, ADHOC MAC suffers from throughput reduction due to transmission collisions caused by node mobility, which are referred to as merging collisions [Borgonovo et al. 2005]. Various solutions are proposed to avoid merging collisions and reduce their impact. In [Hadded et al. 2016], a centralized scheduling scheme is introduced to avoid transmission collisions, by allowing an RSU to act as a central controller that schedules time slots for vehicles. Another approach to avoid transmission collisions is to allocate time slots based on the position of each node on the road [Hadded et al. 2015]. Alternatively, transmission collisions can be reduced by dynamically changing the number of time slots in a frame, in order to accommodate a larger number of vehicles in high vehicle density scenarios, thus decreasing the probability of a transmission collision [Huang and Chiu 2013]. Different from these solutions, the VeMAC protocol is proposed to minimize the rate of merging collisions, by partitioning each frame into three disjoint sets of time slots, allowing the vehicles moving in opposite directions and the RSUs to access time slots from the disjoint sets [Omar et al. 2013b]. This frame partitioning reduces the rate of merging collisions, by avoiding transmission collisions among vehicles moving in opposite directions and among vehicles and stationary RSUs. Moreover, VeMAC provides ACK for each broadcast message, supports a multi-hop broadcast service, and outperforms the IEEE 802.11p standard [Omar et al. 2013a].

In D-TDMA protocols, if a source node fails to deliver a broadcast message to at least one of its one-hop neighboring nodes, it releases its time slot and attempts to acquire a new one. As mentioned, such a failure in message delivery can be caused by a poor channel condition. To tackle the problem of channel errors and increase the transmission reliability, node cooperation schemes are proposed for D-TDMA [Bharati and Zhuang 2013; 2016; Bharati et al. 2017]. Neighboring nodes cooperate by using the available time slots to relay a message that a node fails to receive directly from the source node of the message. While node cooperation in D-TDMA helps delivering messages that are lost due to poor channel conditions, the impact of channel errors on the performance of a D-TDMA protocol, in terms of the detrimental time slot release that leads to unnecessary contention on time slots, has not been studied, to the best of our knowledge.

3. SYSTEM MODEL

Consider a signal channel in a VANET where a set of vehicles move along a road segment with a same average speed. All the vehicles have the same transmission range, denoted by R, such that vehicles separated by a distance that is greater than R cannot directly communicate. On the contrary, vehicles separated by a distance that is not greater than R can directly communicate and are referred to as one-hop neighbors. A vehicle broadcasts a message, targeting all its one-hop neighbors, with a constant and single transmission power level, denoted by P_t. A broadcast message is successfully decoded by a one-hop neighbor that is at r meters away from the transmitting node $(r \leq R)$, iff the instantaneous received power, denoted by γ_r, is not less than a threshold value, denoted by γ_{th}. Each vehicle is aware of the positions and velocities of its one-hop neighbors, since this information is included in the periodic safety message broadcast by each vehicle for the normal operation of safety applications [VSC 2005].

3.1. Two-State Markov Channel

We consider a Nakagami-m channel model with correlated channel gains, which reflects a realistic driving environment [Cheng et al. 2007]. Such a channel can be represented by a first-order Markov chain [Lin et al. 2014; Bharati and Zhuang 2016]. Here, we consider a two-state Markov chain [Bharati and Zhuang 2016], in which the states represent the channel quality during a given time slot, such that the channel remains in one state during the duration of a time slot and may remain in the same state or transition to the other state in the next time slot. The quality of the channel between a transmitter and a receiver during a time slot is considered to be in the *good* state if a transmitted message can be successfully delivered to the receiving node (i.e., the received power is not less than γ_{th}); otherwise, the channel is considered to be in the *bad* state. The n-step transition probability of the Markov chain is denoted by $p_{s_1 s_2}^{(n)}$, where $n > 1$, $s_1, s_2 \in \{g, b\}$, and the subscripts g and b indicate the *good* and *bad* states of the Markov chain, respectively. The one-step transition probabilities of the Markov chain are given by [Bharati and Zhuang 2016]

$$p_{gg} = \frac{1 - F_{\gamma_{r_i}}(\gamma_{th}) - F_{\gamma_{r_{i+1}}}(\gamma_{th}) + F_{\gamma_{r,2}}(\gamma_{th}, \gamma_{th})}{1 - F_{\gamma_{r_i}}(\gamma_{th})} \tag{1}$$

$$p_{gb} = 1 - p_{gg} \tag{2}$$

$$p_{bb} = \frac{F_{\gamma,2}(\gamma_{th}, \gamma_{th})}{F_{\gamma_{r_i}}(\gamma_{th})} \tag{3}$$

$$p_{bg} = 1 - p_{bb} \tag{4}$$

where $F_{\gamma_{r_i}}(.)$ and $F_{\gamma,2}(.,.)$ are the cumulative distribution function (CDF) and bivariate CDF of the amplitude of received signal at the i^{th} and $(i+1)^{\text{st}}$ time slots. The CDF of the received power for the Nakagami-m channels is given by

$$F_{\gamma_r}(x) = 1 - \frac{\Gamma(m, m\frac{x}{\bar{\gamma}_r})}{\Gamma(m)} \tag{5}$$

where

— $\Gamma(\cdot)$ and $\Gamma(\cdot,\cdot)$ are the Gamma and upper incomplete Gamma functions respectively,

— $\bar{\gamma}_r$ is the average received power at distance r from the transmitting node and is given by

$$\bar{\gamma}_r = \frac{P_t C}{r^{\alpha}}, \tag{6}$$

— α is the path-loss exponent,

— $C = G_t G_r \left(\frac{c}{4\pi f_c}\right)^2$ is a constant,

— G_t and G_r are the antenna gains at the transmitter and receiver respectively,

— $f_c = 5.9$ GHz is the carrier frequency,

— $c = 3 \times 10^8$ m/s is the speed of light, and

— m is the shape parameter of the Nakagami-m channel.

For an integer m value and given two non-negative correlated Nakagami-m random variables, say X_1 and X_2, the bivariate CDF is given by (9) [Lopez-Martinez et al. 2013], where

— $\mu_i = E(X_i^2)$, $i = \{1, 2\}$,

— ρ is the correlation coefficient,

— $\Phi_3(\cdot,\cdot;\cdot,\cdot)$ is the confluent hypergeometric function, which can be approximated as

$$\Phi_3(b, e; \psi, z) \approx \sum_{k=0}^{2m-1} \frac{(b)_k \Gamma(e)}{k!} \frac{\psi^k}{z^{(e+k-1)/2}} I_{e+k-1}(2\sqrt{z}), \tag{7}$$

— $I_v(\cdot)$ is the v^{th} order modified Bessel function of the first kind, and

— $(b)_k$ is the Pochhammer symbol [Lin et al. 2014], which is defined as

$$\begin{aligned} (b)_k &= b(b+1)\cdots(b+k-1), \\ (b)_0 &= 1, \text{ and } k = 1, 2, \cdots. \end{aligned} \tag{8}$$

The correlation coefficient of the amplitude of received signals, ρ, at the start of two successive time slots can be obtained by Jake's model [Jakes and Cox 1994] for the system under consideration

$$
\begin{aligned}
F_{X,2}(x_1, x_2; m, \rho) = 1 - \sum_{k=0}^{m-1} \Bigg[&\exp\left(-\frac{m x_2^2}{\mu_2}\right)\left(\frac{m x_2^2}{\mu_2}\right)^k \frac{1}{k!} \\
&+ \left(\frac{m x_1^2}{\mu_1}\right)^k \frac{1}{k!}(1-\rho)^{-k} \exp\left\{-\frac{m}{1-\rho}\left(\frac{x_1^2}{\mu_1}+\frac{x_2^2}{\mu_2}\right)\right\}\Bigg\{\left(\frac{m x_2^2}{\mu_2}\right)^k \frac{1}{k!} \\
&\times \Phi_3\left(1, k+1; \frac{x_2^2}{\mu_2}\frac{m}{(1-\rho)}, \rho\left(\frac{x_1}{\sqrt{\mu_1}}\frac{x_2}{\sqrt{\mu_2}}\frac{m}{(1-\rho)}\right)^2\right) \\
&- \sum_{i=1}^{m-k}\left(\frac{m x_2^2}{\mu_2}\right)^{k+i-1} \frac{1}{(k+i-1)!} \\
&\times \Phi_3\left(i, k+i; \frac{x_2^2}{\mu_2}\frac{m\rho}{(1-\rho)}, \rho\left(\frac{x_1}{\sqrt{\mu_1}}\frac{x_2}{\sqrt{\mu_2}}\frac{m}{(1-\rho)}\right)^2\right)\Bigg\}\Bigg].
\end{aligned} \tag{9}
$$

[Bharati et al. 2017; Lin et al. 2014] and is given by [Lopez-Martinez et al. 2013]

$$\rho = J_0^2(2\pi f_d \tau) \tag{10}$$

where $J_0(\cdot)$ is the zeroth-order Bessel function of the first kind, τ is the slot duration, and f_d is the average Doppler spread that depends on the driving environment where the receiver and transmitter reside. The average Doppler spread, f_d, of the time variant channel among vehicles moving along a highway is given by [Cheng et al. 2008]

$$f_d = \frac{0.5 f_c}{c\sqrt{2}} v_e + 0.20 \tag{11}$$

where $v_e = \sqrt{v_r^2 + v_t^2}$ is the effective speed between a pair of transmitter and receiver nodes traveling with velocities v_t and v_r respectively.

3.2. Channel Access

Nodes access the channel following a D-TDMA scheme, where the channel time is partitioned into frames and each frame is further partitioned into time slots. The time slots are of a constant time interval and each frame consists of a fixed and constant number of time slots, denoted by S. With the availability of the one-pulse-per-second (1PPS) signal that a Global Positioning System (GPS) receiver provides, nodes detect the start time of a frame and, consequently, the start time of a time

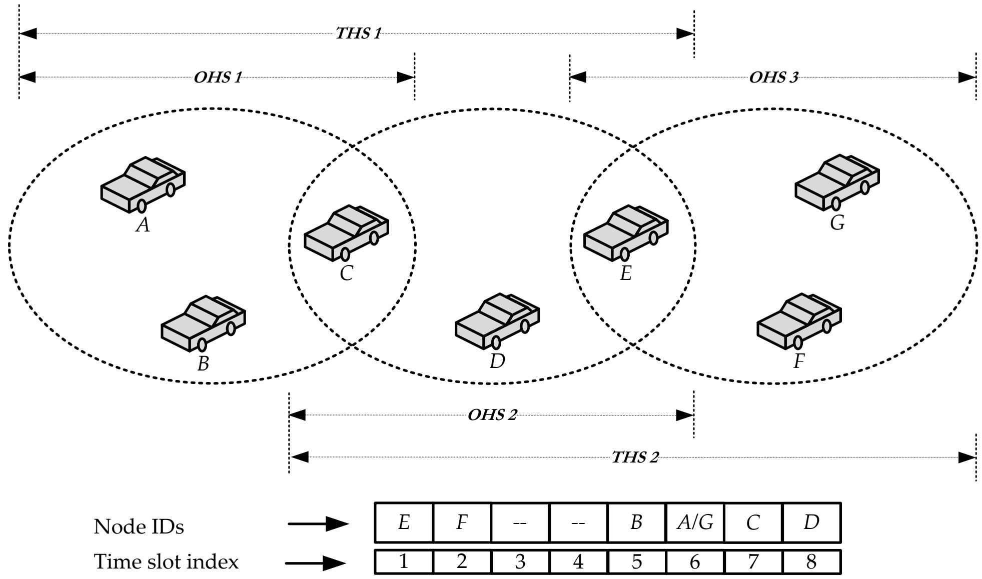

Fig. 1. An illustration of nodes forming two-hop sets to access the channel following a D-TDMA scheme, such that nodes within each other's one-hop set (represented by an ellipse) can directly communicate with each other, and nodes within each other's two-hop set (represented by two overlapped ellipses) access the channel without interfering with each other.

slot [Ding et al. 2008]. Each second includes an integer number of frames, denoted by M. The time slots in each frame are indexed from 1 to S and the frames in each second are indexed from 1 to M.

Each node maintains sets of neighboring nodes that are in its one-hop and two-hop transmission distances, referred to as one-hop set (OHS) and two-hop set (THS) respectively, based on information received from the nodes within its transmission range [Borgonovo et al. 2004; Omar et al. 2013b]. The node members of the same OHS can directly communicate with each other, while those members of the same THS can reach each other in two hops at most. Consequently, if two nodes are members of the same THS, they cannot access the same time slot in a frame, in order to avoid transmission collisions (including transmission collisions among hidden nodes). On the contrary, two nodes that are not members of the same THS can simultaneously access the same time slot in a frame without causing any transmission collision, since there is no other node that can hear the transmission of both nodes. Figure 1 illustrates the D-TDMA channel access mechanism. As shown in Figure 1, nodes A and G can access the same time slot without resulting in any transmission collision, since they are not member of the same THS. Contrarily, nodes A, B, C, D, and E are accessing different time slots in a frame since they all belong to THS1.

In order to periodically broadcast safety messages, each node should reserve a time slot that it keeps accessing in each frame, unless a transmission collision is detected on this time slot. How the slot reservation is achieved and how a transmission collision is detected are described in details in [Borgonovo et al. 2004; Omar et al. 2013b] and summarized briefly in the following. To reserve a time slot, a node first listens to the channel over a period of one complete frame, and then attempts to reserve a time slot among the available ones. After successfully reserving a time slot, a node must broadcast a MAC layer protocol data unit (MPDU) over its reserved time slot in each frame. An MPDU consists of frame information (FI), payload data, and other MAC layer control information. The FI field of an MPDU includes the IDs of the transmitting node's one-hop neighbors, from which the transmitting node has successfully received MPDUs in the previous S time slots. Hence, by receiving the FI broadcast from all the one-hop neighbors, a node is informed of the IDs of and the time slots occupied by all the node members of its two-hop neighborhood. Also, the FI serves as an implicit ACK to detect transmission failures due to transmission collisions [Omar et al. 2013b] or poor channel conditions. That is, a node detects a transmission failure on its time slot after failing to receive its ID in the FI broadcast by any of its one-hop neighbors. In the next section, we discuss how to distinguish the reason of a transmission failure, so that a node can decide whether or not to release its time slot after a transmission failure detection.

4. EFFECTS OF TRANSMISSION COLLISION DETECTION

In this section, we study the effects of transmission collision detection on the performance of VANET D-TDMA protocols. Here, we consider a transmission failure differentiation method, such that a node is able to accurately differentiate the source of a transmission failure due to a poor channel condition or due to a transmission collision. Although this is not a realistic method to implement, it provides an upper-bound of the performance gain of the transmission failure differentiation method, which can be further used as a benchmark for performance evaluation. In the following, we study how an accurate method for transmission failure differentiation (or transmission collision detection) helps to enhance the performance and provides the maximum achievable performance gain in D-TDMA protocol VANETs. We first derive and/or define various probability distribution functions and then analyze the performance in terms of the number of successful time slot acquisitions in a time frame.

4.1. Node Distribution

We consider a multi-lane road segment where vehicles (or communicating nodes) are randomly distributed over each lane of the road segment, such that the inter-vehicle distances are independent and identically distributed (i.i.d.) exponential random variables. Thus, the probability mass function (pmf) of the number of nodes sharing a same frame (i.e., the number of nodes that exist in a distance on the road segment equal to twice the communication range), also referred to as THS nodes, follows a Poisson distribution. Thus, by denoting the number of THS nodes by N_T, the pmf of N_T is given by [Bharati and Zhuang 2013]

$$\Pr\{N_T = n_t\} = \frac{(2\rho R)^{n_t} e^{-2\rho R}}{n_t!}, \qquad n_t = 0, 1, 2, ... \tag{12}$$

where ρ is the vehicle density, defined as the average number of vehicles per unit length of the road segment under consideration.

4.2. Distribution of Unreserved Time Slots

Consider a parameter $\eta \in (0, 1]$, referred to as the reserved ratio, which is the ratio of the allowable number of reserved time slots in a frame to the total number of time slots per frame, S [Bharati et al. 2017]. Such that, in a frame, on average, up to ηS time slots are allowed to be reserved and at least $(1 - \eta)S$ time slots are unreserved. The η (or 1-η) value represents the number of reserved (or unreserved) time slots in a frame and depends on relative mobility and other networking conditions in the network. Let U denote the number of unreserved time slots in a frame, after nodes in the two-hop neighborhood reserved their time slots. Given the reserved ratio, η, only up to ηS time slots are allowed to be reserved and we have

$$U = \begin{cases} S - N_T, & N_T < \eta S \\ S - \eta S, & N_T \geq \eta S. \end{cases} \tag{13}$$

Without the loss of generality and for a tractable analysis, we consider ηS as an integer. Thus, from (12) and (13), the pmf of U is given by

$$\Pr\{U = u\} = \begin{cases} 1 - \sum_{j=1}^{\eta S-1} \frac{(2\rho R)^j e^{-2\rho R}}{j!}, & u = S - \eta S \\ \frac{(2\rho R)^{S-u} e^{-2\rho R}}{(S-u)!}, & S - \eta S < u \leq S - 1. \end{cases} \quad (14)$$

Note that, as only ηS time slots are allowed to be reserved, there must be at least $S - \eta S$ unreserved time slots in a frame. Moreover, there must be at least one node in the corresponding THS, or $S - 1$ unreserved time slots in a frame, for a time frame to exist [Bharati and Zhuang 2013]. Hence, if a frame exist, $S - \eta S \leq u \leq S - 1$.

4.3. Probability of Successful Time Slot Acquisition

Given an unreserved time slot and a certain number of nodes seeking to acquire an unreserved time slot in a two-hop neighborhood sharing a same time frame, the probability that only one node attempts to reserve the unreserved time slot, denoted as p_a, can be written as [Bharati et al. 2017]

$$p_a = \left(\frac{1-a}{a^{\eta S+1}}\right) e^{-2\rho R} \times \left[(b - \eta S)e^b + \sum_{j=0}^{\eta S-1} (\eta S - j)\frac{b^j}{j!}\right] \quad (15)$$

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

For a tractable analysis, we consider a parameter, $\sigma \in [0, 1]$, such that the probability that a node seeking a time slot fails to deliver its reservation packet due to poor channel conditions to its one-hop neighboring nodes with reserved time slots is $1 - \sigma$. A failure in delivering the reservation packet to some one-hop neighbors, i.e., the probability σ, depends on the channel quality between a node and each of its one-hop neighboring nodes with reserved time slots. On the other hand, the probability p_a depends on the number of nodes seeking to acquire time slots in a frame. As only one node performs time slot reservation during an unreserved time slot and the node must deliver its packet to all of its one-hop neighbors with reserved time slots, the probability that the node successfully acquires a time slot in D-TDMA protocol without a transmission failure differentiation method can be written as σp_a. On the other hand, if a node can accurately differentiate the source of transmission failures, it successfully acquires an unreserved time slot if it is the only node to access the time slot, i.e., the node acquires the unreserved time slot with probability p_a if it is able to detect transmission collisions accurately.

4.4. Expected Number of Successful Time Slot Acquisitions

In D-TDMA protocols, the number of successfully acquired time slots per frame represents the protocol's ability to allow nodes to access the channel using their own time slots. Thus, to analyze the performance of the proposed transmission differentiation method, we consider the number of successful time slot acquisitions in a frame. The larger the number of time slot acquisitions, the larger the number of nodes with their own time slots and smaller the number of unreserved time slots in a frame. From the preceding discussion, in D-TDMA protocols, an unreserved time slot can be successfully acquired by a node seeking a time slot with probability σp_a. Thus, given the number of unreserved time slots $U = u$, the number of successful time slot acquisitions in a frame, denoted by Z, follows a binomial distribution with parameters $(u, \sigma p_a)$ and its conditional pmf is given by

$$\begin{aligned} &\Pr\{Z = z|U = u\} \\ &\quad = \binom{u}{z}(\sigma p_a)^z(1-\sigma p_a)^{u-z}, \quad z = 0,1,2,...,u \text{ and } S - \eta S \leq u < S. \end{aligned} \tag{16}$$

Consequently, the expected value of Z given $U = u$ is

$$E[Z|U = u] = u\sigma p_a. \tag{17}$$

From (14) and (17), the expected number of successful time slot acquisitions in a frame, $E[Z]$, can be written as

$$\begin{aligned} E[Z] = \sigma p_a \sum_{u=1}^{\eta S-1}(S-u)\frac{(2\rho R)^u e^{-2\rho R}}{(u)!} \\ + \sigma p_a(S-\eta S)\left(1 - \sum_{u=1}^{\eta S-1}\frac{(2\rho R)^u e^{-2\rho R}}{u!}\right). \end{aligned} \tag{18}$$

Similarly, if a node can accurately differentiate the source of transmission failures or detect transmission collisions, the expected number of successful time slot acquisitions in a frame, as in (18), changes to

$$\begin{aligned} E[Z_e] = p_a \sum_{u=1}^{\eta S-1} (S-u) \frac{(2\rho R)^u e^{-2\rho R}}{(u)!} \\ + p_a(S-\eta S)\left(1-\sum_{u=1}^{\eta S-1}\frac{(2\rho R)^u e^{-2\rho R}}{u!}\right) \end{aligned} \tag{19}$$

where Z_e is a random variable, denoting the number of successful time slot acquisitions in a frame with an accurate transmission failure differentiation method.

5. TRANSMISSION FAILURE DIFFERENTIATION

In addition to effectively reserving time slots in a frame, a collision detection method can also be used to make a time-slot usage decision by a node that already has its own time slot after suffering from a transmission failure, i.e., to decide whether to release its time slot or continue using it. As an accurate transmission failure differentiation method is difficult to realize (as discussed in Section 4), this section presents a practical transmission failure differentiation method which employed a deep-learning technique [Deng and Yu 2014]. In the proposed method, neighboring nodes share their local information, such as position and velocity, to build a high-level abstraction of the propagation channel, which is represented by a two-state Markov chain model. The Markov chain parameters are updated every time a node receives the local information from its neighboring nodes. Such an updated high-level abstraction of the propagation channel is then used to estimate the quality of transmission channel. Moreover, the received ACKs of the broadcast messages are further used to calculate/update the average estimation error of the channel state. An appropriate decision on time slot usage is taken based on the Markov chain and the estimation error. In the following, we discuss the procedures for channel state estimation, estimation error calculation, distinction of transmission collisions and poor channel conditions, and release or retention of time slots.

5.1. Channel State Estimation

The estimation of the channel quality is done by extracting a high-level abstraction of the radio propagation channel. This abstraction is represented by the two-state Markov chain model described in Subsection 3.1. The Markov model is dynamically adjusted, based on up-to-date information that is shared among nodes via periodically broadcast safety messages. That is, when a node, x, receives a safety message from its one-hop neighbor, y, node x is informed of the current position and speed of node y. Consequently, since node x is always aware of its own position and speed, it can determine its separation distance and effective speed with respect to node y. Accordingly, node x calculates the one-step transition probabilities of the Markov chain that models the channel between nodes x and y [equations (1)-(11)]. The one-step transition probabilities are updated by node x each time it successfully receives a safety message from node y with new position and speed information. Node x employs the same procedure to dynamically model the propagation channel to each of its one-hop neighbors (by using a different Markov chain for each one-hop neighbor).

Based on the Markov chain model, node x can estimate the state of the channel between itself and each one-hop neighbor that fails to receive a message broadcast by node x. For instance, consider that node x is accessing the i^{th} time slot in each frame and broadcasts a message that is not successfully delivered to its one-hop neighboring node y during the j^{th} frame of a second ($j > 1$, without loss of generality). In that case, node y will not include node x's ID in the FI broadcast over node y's time slot. Consequently, node x needs to estimate the state of the channel between itself and node y at the i^{th} time slot of the j^{th} frame, when the transmission failure occurred. To perform the channel estimation, consider that the message broadcast by node x over the i^{th} time slot of the $(j-1)^{\text{st}}$ frame was successfully delivered to node y, indicating a *good* state of the channel between nodes x and y during this time slot. As the number of time slots (steps) between the i^{th} time slot in the $(j-1)^{st}$ and j^{th} frames is the number of time slots per frame, S, the probability that the channel is in *good* or *bad* state at the i^{th} time slot of the j^{th} frame is $p_{gg}^{(S)}$ or $p_{gb}^{(S)}$, respectively. For a sufficiently large S value, the probabilities $p_{gg}^{(S)}$ and $p_{gb}^{(S)}$ (and similarly $p_{bg}^{(S)}$ and $p_{bb}^{(S)}$) can be approximated by the the Markov chain steady state probabilities, π_g and π_b respectively, which are given by [Bharati and Zhuang 2016]

$$\pi_g = \frac{1 - p_{bb}}{2 - p_{gg} - p_{bb}} \tag{20}$$

$$\pi_b = 1 - \pi_g \tag{21}$$

Hence, node x estimates that the channel was in a *good* state when the transmission failure occurred, iff $\pi_g > \xi$, where ξ is a specified threshold. Given the channel state estimation, node x decides whether or not to release its time slot, by taking into consideration the channel estimation error, as discussed in the following.

5.2. Channel Estimation Error

As mentioned in Subsection 5.1, when a node, x, fails to detect its ID in the FI received from a one-hop neighboring node y, node x employs the Markov chain model to estimate the state of the channel between itself and node y during the time slot over which a transmission failure occurred. In addition to estimating the state of the channel between nodes x and y in case of a transmission failure, node x also estimates the channel state (using the same Markov model) when it successfully delivers a message to node y. The objective of the channel estimation for a successful transmission is to approximately calculate the average channel estimation error using the proposed Markov chain model. The channel estimation error is a binary random variable that takes value 0 iff node x correctly estimates the state of the channel between itself and node y and value 1 otherwise. Each time node x successfully delivers a message to node y, node x obtains a sample of the channel estimation error (to be discussed) and calculates the average estimation error over the previous K samples, where K is a predefined constant. The i^{th} sample of the channel estimation error is denoted by $\epsilon_i, i = 1, ..., K$, while the average channel estimation error is denoted by ϵ, where $\epsilon = \frac{1}{K}\sum_{i=1}^{K}\epsilon_i$ and $\epsilon \in [0, 1]$. The ϵ value is calculated by node x independently for the channel between itself and each one-hop neighbor y as follows. When node x detects the presence of its ID in the FI received from node y, i.e., node y acknowledges the reception of the previous message broadcast by node x, which is considered as a confirmation that the channel was in a *good* state during the time slot when node x broadcast its message. Hence, node x employs the Markov model to estimate the channel state (as described in Subsection 5.1) and calculate a new sample, $\epsilon_i, i = 1, ..., K$, of the channel estimation error, such that ϵ_i is equal to 0 iff node x estimates that the channel was in a *good* state, i.e., $\pi_g > \xi$. Consequently, node x uses this new sample of channel estimation error to update the ϵ value, by always considering the K most recently calculated samples. The ϵ value is used with the Markov model to decide whether or not a time slot release is necessary upon detection of a transmission failure, as explained next.

5.3. Release or Retention of Time Slots

When a node, x, detects a failure of delivery of a broadcast message to at least one of its one-hop neighbors, y, node x should decide whether or not to release the time slot corresponding to that of the transmission failure. First, node x applies the channel estimation method in Subsection 5.1 to estimate the channel state, i.e., *good* or *bad*, during the time slot of the transmission failure. The probability of correctly estimating the channel state is represented by $1 - \epsilon$, where the ϵ value is obtained as explained in Subsection 5.2. Accordingly, if the channel state is estimated as *good*, i.e., it is estimated that a transmission collision occurred, node x releases its time slot with a probability $1 - \epsilon$. The probability $1 - \epsilon$ is to take account of the channel estimation error. Similarly, if the channel state is estimated as *bad*, i.e., it is estimated that the transmission failure is due to a poor channel condition, node x retains its time slot with a probability $1 - \epsilon$ or in other words, node x releases its time slot with a probability ϵ. Figure 2 summarizes the procedures for a node to estimate the channel state, calculate the average estimation error, and decide whether to release or retain a time slot.

6. NUMERICAL RESULTS

This section presents numerical results obtained from computer simulations to validate the performance analysis of collision detection mechanism presented in Section 4. Computer simulations are performed in MATLAB with parameters given in Table I. In the simulations, a road segment of length 10 kilometers with three lanes is considered, such that a lane with 5 meters width is repre-

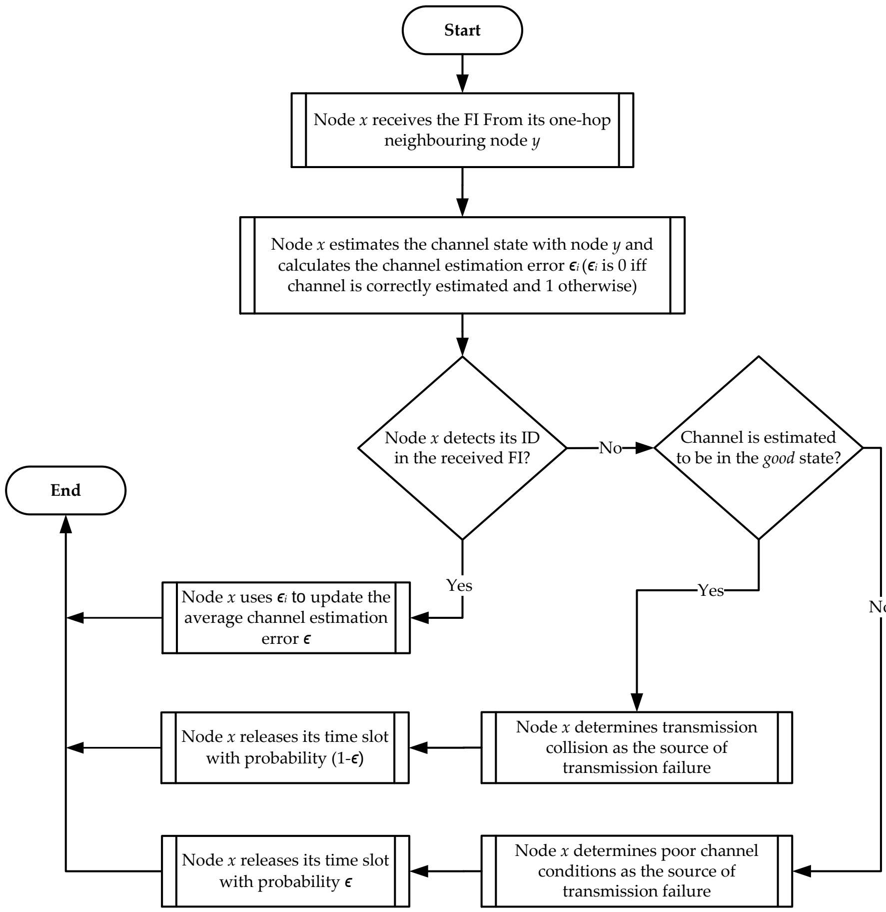

Fig. 2. Proposed transmission failure differentiation method

Table I. Simulation Parameters

Parameter	**Value**
Path loss exponent (α)	2, 3 and 4
Transmission power (P_t)	20 mW
Threshold received power (γ_{th})	-95 dBm
Transmission range (R)	100 meters
Shape parameter (m)	2
Threshold probability value (ξ)	0.90
Number of samples for error calculation (K)	15 samples
Number of time slots per frame (S)	50 time slots
Time slot duration	1 millisecond
Simulation time	15 seconds

sented by a line in the road segment. At the beginning of simulation, vehicles are generated and distributed following a Poisson distribution along the road segment such that vehicles are represented by points on the lines representing lanes. The vehicles draw their speeds following a truncated normal distribution[1], with mean 100 kilometer per hour and standard deviation 20 kilometer per hour [Khabbaz et al. 2012]. All the vehicles move with the same constant speeds which are drawn at the beginning beginning of simulation. Throughout the simulations, the vehicles do not leave the road segment to avoid any unnecessary release of time slots. In order to analyze and compare the performance, two versions of D-TDMA protocol are considered - an existing D-TDMA protocol without any collision detection mechanism and a modified D-TDMA protocol with a mechanism to detect collision by accurately differentiating the source of transmission failure. To validate the close-form expressions in Section 4, the expected number of successful time slot acquisitions by nodes without (with) their own reserved time slots, referred to as contending (resident) nodes, are obtained for both the versions of D-TDMA protocol for several η and σ values.

Figs. 3−5 show the expected number of successful time slot acquisitions with several η values. The simulation results (S) match well with the analytical results (A), which validates the close-form expressions derived in Section 4. From the figures, it can be seen that for a given average number of THS nodes the expected number of successful time slot acquisitions is always higher in D-TDMA protocol with collision detection. Furthermore, a smaller η value results in a larger number of time slot acquisitions. The reason is that, a larger η value results in a smaller number of contending nodes and, consequently, a smaller or less number of reservation attempts. A larger number of average THS nodes ($\overline{N}_T$ value) also results in a larger number of reservation attempts and thus increases the expected number of successful time slot acquisitions. However, for a smaller $\overline{N}_T$ value, the number of time slot acquisitions is smaller for a larger η value. This is due to the fact that with a smaller $\overline{N}_T$ and η values, the number of contenting nodes as well as the reservation attempts decrease, decreasing the expected number of successful time slot acquisitions. Furthermore, in the existing D-TDMA protocols, as the channel quality degrades (i.e., as σ value decreases) the number of successful time slot acquisitions decreases. When the propagation channel is in a poor condition,

[1] Velocities which are below and above the maximum (130 kilometer per hour) and minimum (90 kilometer per hour) velocities respectively are ignored while drawing speed of a vehicle. In addition, the maximum and minimum velocities are fixed making them consistent with VISSIM parameters in the next section.

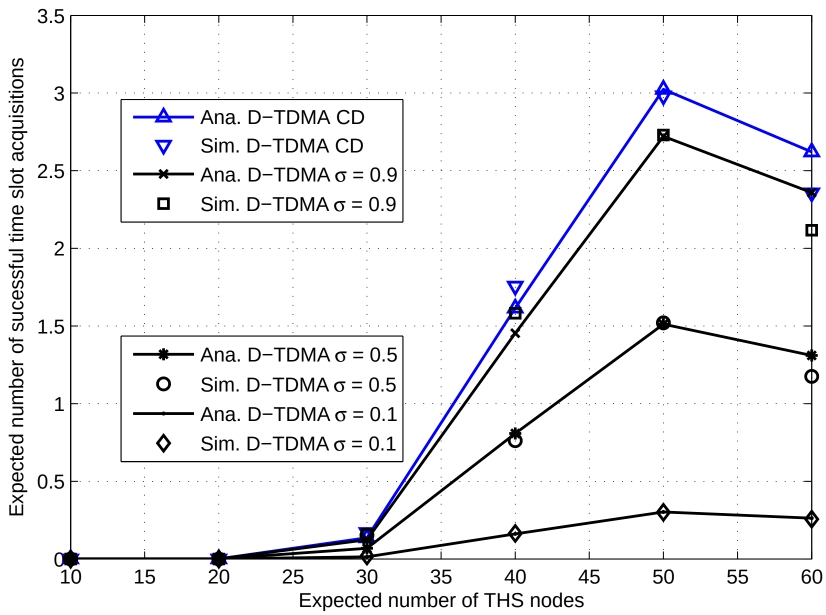

Fig. 3. Comparison of the expected number of successful time slot acquisitions in the existing D-TDMA protocol (D-TDMA) and the D-TDMA protocol with collision detection mechanism (D-TDAM CD) with $\eta = 0.8$.

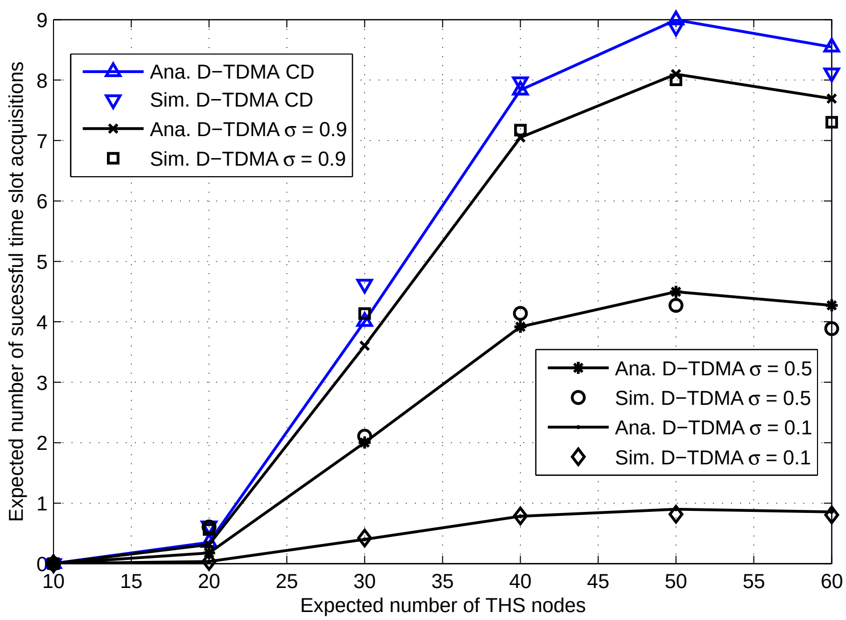

Fig. 4. Comparison of the expected number of successful time slot acquisitions in the existing D-TDMA protocol (D-TDMA) and the D-TDMA protocol with collision detection mechanism (D-TDAM CD) with $\eta = 0.5$.

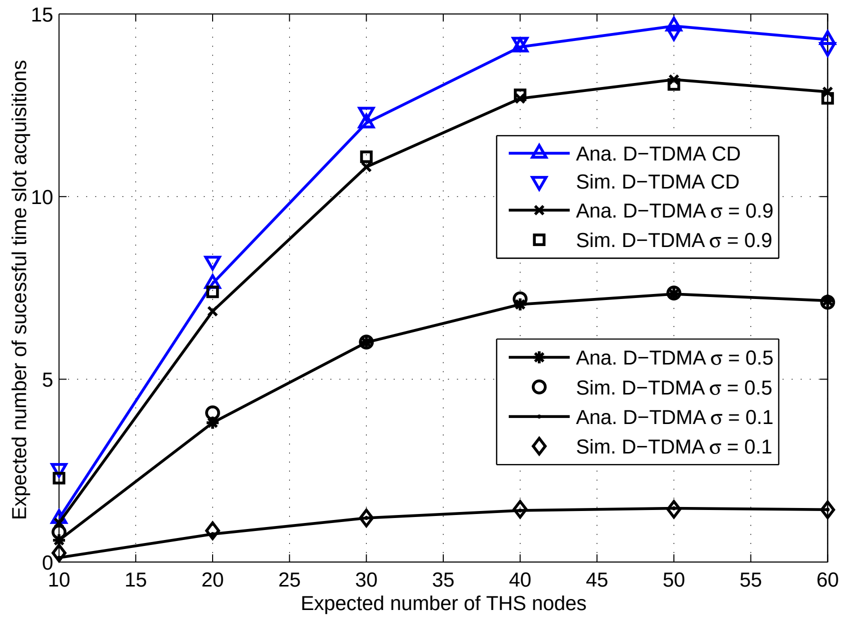

Fig. 5. Comparison of the expected number of successful time slot acquisitions in the existing D-TDMA protocol (D-TDMA) and the D-TDMA protocol with collision detection mechanism (D-TDAM CD) with $\eta = 0.2$.

contending nodes fail to deliver their reservation messages to their respective OHS nodes. On the other hand, if a node can differentiate the source of transmission failures and ultimately detect transmission collisions, it can successfully acquire an unreserved time slot even in poor channel conditions or avoid using it after detecting transmission collisions. Hence, the poorer the channel quality, the higher the performance gain due to the collision detection method as it differentiates the source of transmission failures and stops contenting nodes from unnecessarily avoiding the use of unreserved time slots.

7. SIMULATION

Computer simulations are performed in the presence of relative vehicle mobility and correlated channel gains. Performance of a D-TDMA protocol enabled with the proposed enhanced collision detection method is analyzed and compared with existing D-TDMA protocol in terms of the ability to distribute the available time slots among nodes in the network. The fraction of resident (contending) nodes, among all the the nodes in a THS sharing a common time frame is considered as a metric for performance evaluation. The fraction of resident nodes in a THS represents how well the channel is used by nodes to exchange their information. The larger this fraction, the higher the channel utilization and the higher the number of nodes that can successfully access the channel.

7.1. Simulation Scenario

Correlated channel gains are generated using MATLAB by considering a Nakagami-m channel model. To generate the channel coefficients, autocorrelated Nakagami-m envelope sequences are generated following the procedure defined in [Filho et al. 2007]. First, the correlation coefficient of the generated sequence is calculated as in (10). The correlation coefficient is then used to generate the required Nakagami-m sequence which follows the rank statistics of the reference Rayleigh sequence with the same correlation coefficient.

To generate vehicle mobility traces, the well-known vehicle traffic simulator PTV VISSIM [VIS 2015] is used. A one-way highway segment with three lanes, based on a segment of Highway 401 of the Canadian province of Ontario, is replicated in VISSIM. In doing so, speed limits and other traffic rules are defined for realistic scenarios. To prevent vehicles from leaving the simulation region, a road network in the form of a ring is configured. As the ring of highway is formed, the vehicles move in the ring and do not exit throughout the simulation. Decisions to perform lane changes (left or right turns), follow the headway traffic, etc., are taken based on the Wiedemann99 Car Following Model [Wiedemann 1974]. To generate the vehicle traces, vehicles (such as cars, heavy goods vehicles and buses) are injected to the road networks, with rate 2100, 2400, and 7200 vehicle per hour. After an injection period of 5 minutes, the number of vehicles in the network, denoted by $\aleph$, becomes 364, 496, and 622 respectively for each vehicle injection rate. These vehicles are then allowed to move according to the corresponding traffic rules and road network parameters as given in [Bharati et al. 2017]. To reduce any transient state effects, vehicle traces are not recorded for a warm-up period of 5 minutes after the injection period. The actual simulation starts only after the end of the warm-up period, i.e., 10 minutes from the time of generation of the first vehicle. During a simulation period of 5 minutes, vehicle traces are recorded periodically, every 0.1 second. The vehicle traces consist of vehicle positions and their speeds at a given time. The functionalities of a D-TDMA scheme are implemented in MATLAB, which uses the generated vehicle mobility traces and channel coefficients for the simulations. Parameters that are used in the simulation are given in Table I.

7.2. Simulation Results

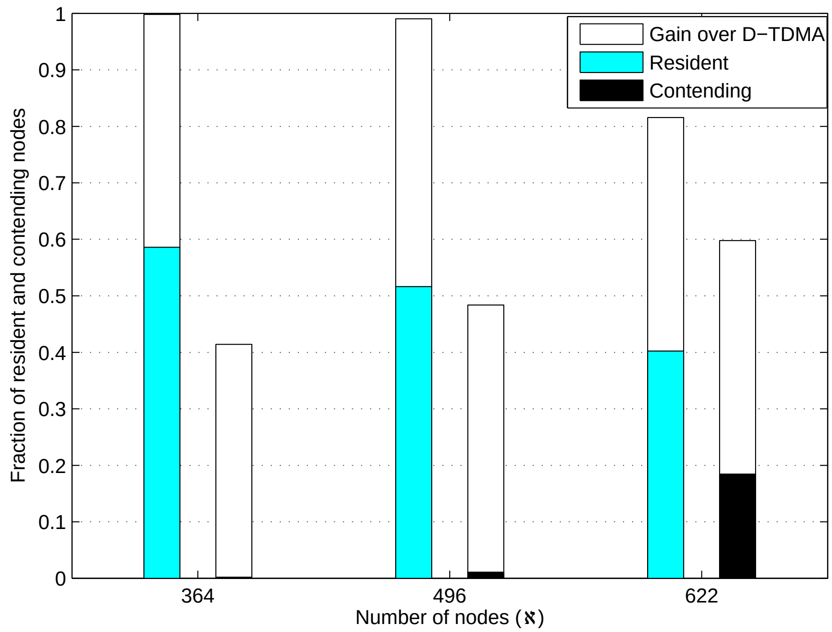

Fig. 6. Increment (decrement) in the fraction of the number of resident (contending) nodes in a THS with the proposed transmission collision detection method over the existing D-TDMA protocol with path loss exponent $\alpha = 2$.

Figures 6-8 show the portion of resident and contending nodes in a THS sharing a common frame at various channel conditions and $\aleph$ values, and the performance improvement achieved by the proposed transmission collision detection method over the existing D-TDMA protocol. It can be observed from Figures 6-8 that the proposed method accommodates a larger (smaller) number of resident (contending) nodes as compared with the existing D-TDMA protocol. This is due to the fact that the existing D-TDMA protocol do not differentiate transmission failures, thus suffers from performance degradation due to the unnecessary release of time slots. On the other hand, the proposed transmission collision detection method enables the D-TDMA protocol to detect transmission collisions and enhances the performance by differentiating the source of transmission failures between poor channel conditions and transmission collisions. The larger number of resident nodes

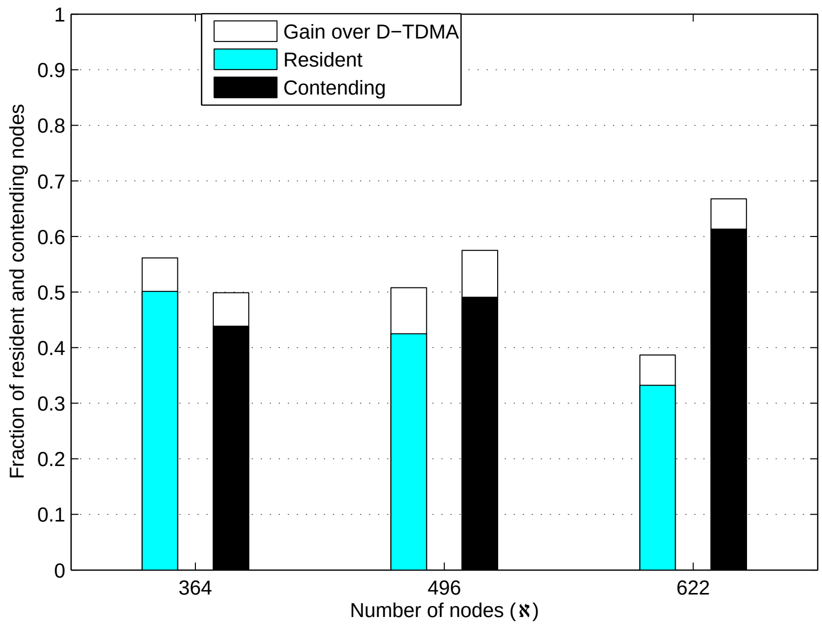

Fig. 7. Increment (decrement) in the fraction of the number of resident (contending) nodes in a THS with the proposed transmission collision detection method over the existing D-TDMA protocol with path loss exponent $\alpha = 3$.

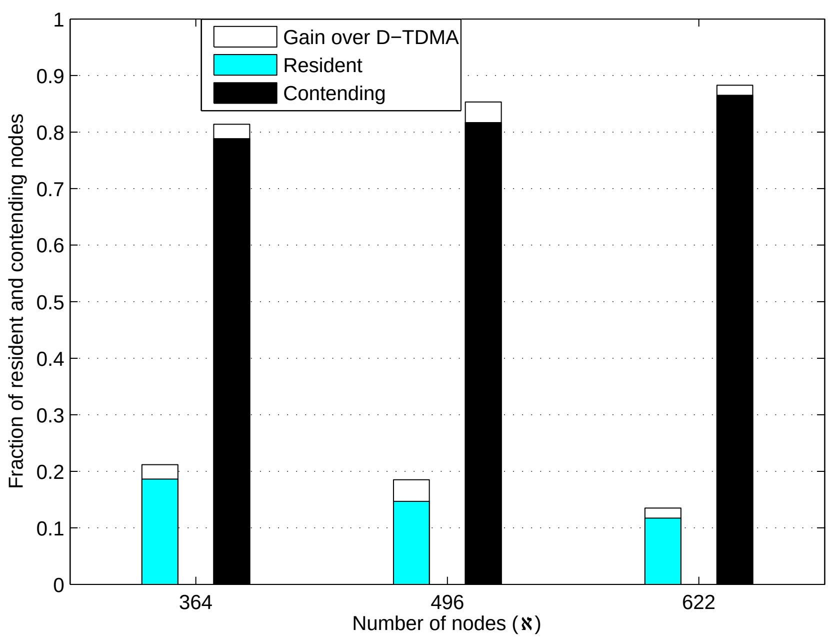

Fig. 8. Increment (decrement) in the fraction of the number of resident (contending) nodes in a THS with the proposed transmission collision detection method over the existing D-TDMA protocol with path loss exponent $\alpha = 4$.

reflects the advantage of differentiating transmission failures and releasing time slots only when it is needed, i.e., in case of occurrence of transmission collisions.

Furthermore, for a given $\aleph$ value, the performance gain due to the proposed method is significant at a lower α value. It can be observed that the performance gain with $\alpha = 2$ is significant as compared to the case with $\alpha = 3$ and 4. The reason is that, the estimation of channel conditions is more accurate at a lower α value than at higher one. A node calculates the channel estimation error and updates the corresponding average value only when it successful receives messages from its one-hop neighboring nodes. At a higher α value, nodes suffers from poor channel conditions and thus, their average channel estimation error values are not frequently updated. This results in an incorrect channel estimation and degrades the performance of the proposed transmission failure differentiation method. Moreover, the proposed method performs well when $\aleph = 364$ and 496 as compared to the case with $\aleph = 622$. The reason is that, with a few or moderate number of nodes relative to the number of time slots in a time frame, the probability that nodes encounter transmission collisions is low. On the other hand, when $\aleph = 622$, the number of nodes sharing a frame increases, which results in an increase in the rate of transmission collisions, consequently, the larger number of nodes that release their time slots. Thus, with the increase in the number of transmission collisions, differentiation of transmission failure is not as effective as in the cases with smaller $\aleph$ values (as most of the failures are due to transmission collisions with a large $\aleph$ value).

8. CONCLUSIONS

Unnecessary release of acquired time slots and avoidance of contended unreserved time slots due to poor channel conditions degrade the performance of VANET D-TDMA protocols and result in an increase in the number of contending nodes in the network. In this work, we introduce the concept of differentiating the source of transmission failures in D-TDMA protocols in vehicular networks due to poor channel conditions or due to transmission collisions. Such a differentiation of the source of transmission failures helps to detect transmission collisions. We study the effects of transmission collision detection method in effectively reserving the unreserved time slots. Furthermore, we propose a deep-learning based novel method for collision detection that is deployed to make a time slot usage decision to improves the VANET D-TDMA performance by avoiding the unnecessary release of acquired time slots. In the proposed method, the two sources of a transmission failure are differentiated by estimating the channel state when the transmission failure occurs. Such a mechanism helps nodes to release their time slots only when necessary, i.e., allows them to release (retain) time slots after suffering from transmission collisions (poor channel conditions), and avoids unnecessary release of time slots. Through mathematical analysis and extensive simulations, we demonstrate the benefit of differentiating the source of transmission failures. Moreover, we observe that the proposed method enhances the performance D-TDMA MAC protocols, results in a larger number of nodes reserving distinct time slots, and increases the utilization of the propagation channel.

REFERENCES

2005. *Vehicle Safety Communications Project Task 3 Final Report*. Technical Report DOT HS 809 859. The CAMP Vehicle Safety Communications Consortium.

2010. IEEE Standard for Information technology–Local and metropolitan area networks–Specific requirements–Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments. *IEEE Std 802.11p-2010 (Amendment to IEEE Std 802.11-2007 as amended by IEEE Std 802.11k-2008, IEEE Std 802.11r-2008, IEEE Std 802.11y-2008, IEEE Std 802.11n-2009, and IEEE Std 802.11w-2009)* (July 2010), 1–51.

2012. *DOT Launches Largest-Ever Road Test of Connected Vehicle Crash Avoidance Technology*. Technical Report. The United States Department of Transportation (USDoT).

2015. PTV Vissim. (2015). http://vision-traffic.ptvgroup.com/en-us/products/ptv-vissim/ (Last accessed: Mar. 14, 2017).

R. Baldessari, B. Bdekker, A. Brakemeier, M. Deegener, A. Festag, W. Franz, A. Hiller, C. Kellum, T. Kosch, A. Kovacs, M. Lenardi, A. Lbke, C. Menig, T. Peichl, M. Roeckl, D. Seeberger, M. Strassberger, H. Stratil, H.-J. Vgel, Weyl, and W. Zhang. 2007. *Car 2 Car Communication Consortium Manifesto*. Technical Report Version 1.1. CAR 2 CAR Communication Consortium.

S. Bharati and W. Zhuang. 2013. CAH-MAC: Cooperative ADHOC MAC for Vehicular Networks. *IEEE J. Sel. Areas Commun.* 31, 9 (Sept. 2013), 470–479.

S. Bharati and W. Zhuang. 2016. CRB: A Cooperative Relay Broadcasting Framework to Support Safety Applications in Vehicular Networks. *IEEE Trans. Veh. Technol.* 65, 12 (Aug. 2016), 9542–9553.

S. Bharati, W. Zhuang, L.V. Thanayankizil, and F. Bai. 2017. Link-Layer Cooperation Based on Distributed TDMA MAC for Vehicular Networks. *IEEE Trans. Veh. Technol.* (2017).

F. Borgonovo, L. Campelli, M. Cesana, and L. Coletti. 2003. MAC for Ad-Hoc Inter-Vehicle Network: Services and Performance. In *Proc. IEE VTC Fall*.

F. Borgonovo, L. Campelli, M. Cesana, and L. Fratta. 2005. Impact of User Mobility on the Broadcast Service Efficiency of the ADHOC MAC Protocol. In *Proc. IEEE VTC Spring*.

F. Borgonovo, A. Capone, M. Cesana, and L. Fratta. 2004. ADHOC MAC: New MAC Architecture for Ad Hoc Networks Providing Efficient and Reliable Point-to-Point and Broadcast Services. *Wirel. Netw.* 10 (2004), 359–366.

L. Cheng, B. Henty, F. Bai, and D.D. Stancil. 2008. Doppler Spread and Coherence Time of Rural and Highway Vehicle-to-Vehicle Channels at 5.9 GHz. In *Proc. IEEE Globecom*.

L. Cheng, B.E. Henty, D.D. Stancil, F. Bai, and P. Mudalige. 2007. Mobile Vehicle-to-Vehicle Narrow-Band Channel Measurement and Characterization of the 5.9 GHz Dedicated Short Range Communication (DSRC) Frequency Band. *IEEE J. Sel. Areas Commun.* 25, 8 (Oct. 2007), 1501–1516.

Li Deng and Dong Yu. 2014. *Deep Learning: Methods and Applications*. Technical Report. https://www.microsoft.com/en-us/research/publication/deep-learning-methods-and-applications/

W. Ding, J. Wang, Y. Li, P. Mumford, and C. Rizos. 2008. Time Synchronization Error and Calibration in Integrated GPS/INS Systems. *ETRI J.* 30, 1 (Feb. 2008), 59–67.

J.C.S.S. Filho, M.D. Yacoub, and G. Fraidenraich. 2007. A Simple Accurate Method for Generating Autocorrelated Nakagami-m Envelope Sequences. *IEEE Commun. Lett.* 11, 3 (Mar. 2007), 231–233.

M. Hadded, A. Laouiti, R. Zagrouba, P. Muhlethaler, and L.A. Saidane. 2015. *A Fully Distributed TDMA based MAC Protocol for Vehicular Ad Hoc Networks*. Technical Report. Inria Paris Rocquencourt.

M. Hadded, P. Muhlethaler, A. Laouiti, and L.A. Saidane. 2016. A Centralized TDMA based Scheduling Algorithm for Real-Time Communications in Vehicular Ad Hoc Networks. In *Proc. of SoftCom*. Split , Croatia.

M.I. Hassan, H.L. Vu, and T. Sakurai. 2011. Performance Analysis of the IEEE 802.11 MAC Protocol for DSRC Safety Applications. *IEEE Trans. Veh. Technol.* 60, 8 (Oct. 2011).

J.J. Huang and Y.S. Chiu. 2013. A Scheme to Reduce Merging Collisions in TDMA-based VANETs. In *Proc. Internat. Symposium on Wirel. Pervasive Comput.*

William C. Jakes and Donald C. Cox (Eds.). 1994. *Microwave Mobile Communications*. Wiley-IEEE Press.

D. Jiang, V. Taliwal, A. Meier, W. Holfelder, and R. Herrtwich. 2006. Design of 5.9 GHz DSRC-Based Vehicular Safety Communication. *IEEE Wireless Commun.* 13, 5 (Oct. 2006), 36–43.

M. J. Khabbaz, W. F. Fawaz, and C. M. Assi. 2012. A Simple Free-Flow Traffic Model for Vehicular Intermittently Connected Networks. *IEEE Trans. Intell. Transp. Syst.* 13, 3 (Sept. 2012), 1312–1326.

Y. Li and A. Boukerche. 2015. QuGu: A Quality Guaranteed Video Dissemination Protocol Over Urban Vehicular Ad Hoc Networks. *ACM Trans. Multimedia Comput. Commun. Appl.* 11, 4 (Apr. 2015), 55:1–55:23.

S. Lin, Y. Li, Y. Li, B. Ai, and Z. Zhong. 2014. Finite-State Markov Channel Modeling for Vehicle-to-Infrastructure Communications. In *Proc. IEEE WiVeC*.

H. Liu, T. Mei, H. Li, J. Luo, and S. Li. 2013. Robust and Accurate Mobile Visual Localization and Its Applications. *ACM Trans. Multimedia Comput. Commun. Appl.* 9, 1 (Oct. 2013), 51:1–51:22.

F.J. Lopez-Martinez, D. Morales-Jimenez, E. Martos-Naya, and J.F. Paris. 2013. On the Bivariate Nakagami-m Cumulative Distribution Function: Closed-Form Expression and Applications. *IEEE Trans. Commun.* 61, 4 (Apr. 2013), 1404–1414.

H.A. Omar, W. Zhuang, A. Abdrabou, and L. Li. 2013a. Performance Evaluation of VeMAC Supporting Safety Applications in Vehicular Networks. *IEEE Trans. Emerg. Topics Comput.* 1, 1 (Jun. 2013), 69–83.

H.A. Omar, W. Zhuang, and L. Li. 2013b. VeMAC: A TDMA-based MAC Protocol for Reliable Broadcast in VANETs. *IEEE Trans. Mobile Comput.* 12, 9 (Sept. 2013), 1724–1736.

Fabrício A. Silva, Azzedine Boukerche, Thais R. M. Braga Silva, Linnyer B. Ruiz, Eduardo Cerqueira, and Antonio A. F. Loureiro. 2016. Vehicular Networks: A New Challenge for Content-Delivery-Based Applications. *ACM Comput. Surv.* 49, 1 (July 2016), 11:1–11:29.

R. Wiedemann. 1974. *Simulation des Strassenverkehrsflusses*. Schriftenreihe des Instituts fr Verkehrswesen der Universitt Karlsruhe, Band 8, Karlsruhe, Germany.

Q. Wu and J. Zheng. 2016. Performance Modeling and Analysis of the ADHOC MAC Protocol for Vehicular Networks. *Wirel. Netw.* 22, 3 (Apr. 2016), 799–812.