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Co-DDTMA: Cooperative Distributed TDMA for Vehicular Networks

Zhen Chen[1, 2], Zhengyu Liu[1], Jianghong Han[1], Songhua Hu[1] and Yang Lu[1]
[1]*School of Computer and Information,*
Hefei University of Technology, Hefei 230009, P. R. China
[2]*Computer Studies Department,*
Anhui University, Hefei 230601, P. R. China
[1]*czahu@163.com*

Abstract

In recent years, Vehicular Ad Hoc Networks (VANET) has experienced a rapid development due to the advancement of wireless communication technologies, and now emerges as a promising way to provide road safety, traffic efficiency and infotainment applications. However, it is a challenge to design a reliable and efficient Medium Access Control (MAC) protocol for VANET due to its frequent topology changes and unreliable wireless links. Cooperative communication, on the other hand, can enhance the reliability of wireless links by exploiting the broadcast nature of the wireless communication. A cooperative scheme for MAC is proposed for VANET in this paper, referred to as Cooperative Distributed TDMA (Co-DTDMA). In the Co-DTDMA, neighboring nodes utilize its idle slots for cooperatively retransmitting a packet which has failed to reach the destination. Since the cooperative retransmission is conducted in node's own idle slot, the proposed scheme does not interrupt the normal transmission. Both theoretical analysis and simulation results demonstrate that the proposed scheme greatly increases the probability of successful packet transmission and decreases the packet transmission delay.

Keywords*: Vehicular Ad Hoc Networks; Time Division Multiple Access (TDMA); Cooperative Communication; Reliability*

1. Introduction

With the rapid development of wireless communication technology and automotive industry, vehicles can be equipped with sensors and communication devices. Vehicles use sensors for gathering status information and use wireless medium for communicating with each other or stationary wireless stations which are called roadside units (RSUs). This has given birth to the Vehicular Ad Hoc Network (VANET). As a new type of Mobile Ad Hoc Networks (MANET), VANET is the basis for intelligent transportation, and brings people more efficient and safer driving experience [1].

In addition to various obstacles caused by the unreliable wireless medium, high node speed, frequent topology changes, strict delay and strict reliability constraint of safety messages are common challenges in VANET [1]. The IEEE 802.11p, which is the emerging standard deployed to enable vehicular communication, is a contention-based MAC protocol which suffers from unbounded delay and broadcast storm [2-4]. This disadvantage is particularly important in VANET which is specially designed to improve road safety. [5-8] have proposed the distributed Time Division Multiple Access (TDMA) protocols, namely the ADHOC MAC [5] and the VeMAC [6-8], which are contention-free MAC protocols and facilitate timely and reliable communication in VANET. Simulation results in [7] show that the VeMAC can deliver safety messages with an

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acceptable delivery delay. Moreover, as compared to the IEEE 802.11p, the VeMAC has a low probability of a transmission collision, resulting in a higher throughput [6].

However, in the distributed TDMA schemas, each node occupies a time slot exclusively, and if a node does not transmit any application information during its own time slot, other nodes cannot use the idle slot [6-8]. On the other hand, wireless signal attenuates and is blocked by vehicles and buildings along a road, and Doppler shift is caused by vehicles high speed, leading to an unreliable wireless transmission in VANET [9]. Hence, the distributed TDMA schemas do not take full advantage of wireless channel resources, and cannot avoid the packet dropping due to a poor channel condition in VANET.

In recent years, cooperative communication has drawn a lot of attention from industry and academia, since it can mitigate wireless channel impairments effectively by utilizing the broadcast nature of the wireless communication [10]. In [11-14], cooperative methods for infrastructure based TDMA are proposed. But in these methods, all communication links are established between mobile nodes and a central controller, and cooperation communication is coordinated by the central controller. Thus, these methods cannot be applied in VANET directly. [15] has proposed a cooperative method called the CAH-MAC for the distributed TDMA. But in the CAH-MAC, helper nodes utilize unreserved time slots in a frame to relay a packet cooperatively, that inevitably reduces other nodes' opportunities to get an unreserved time slot, and moreover, sending/receiving mode is required switching within a time slot, thus increasing the system complexity.

In this paper, a novel cooperative MAC referred to as Cooperative Distributed TDMA (Co-DTDMA) is proposed for VANET. In the Co-DTDMA, neighboring nodes utilize its idle slots for cooperatively relay a failed packet. Since the cooperative communication is based on node's own idle slot, the Co-DTDMA does not reduce other nodes’ opportunities to get an unreserved time slot. In addition, in the proposed schema, sending/receiving mode is not required switching within a time slot, thus simplifying the system implementation.

The rest of this paper is organized as follows: section 2 describes the system model, section 3 presents detail operations of the Co-DTDMA, section 4 presents performance analysis of the Co-DTDMA, section 5 presents numerical results to evaluate the proposed scheme and section 6 concludes this research.

2. System Model

The network and channel models used for VANET are given in this section, which captures relevant VANET features.

1).Since wireless transmission range is much larger than the width of the road, the 1-D network model is a good approximation of VANET [1, 3]. Nodes are placed on the road according to a Poisson point process [3, 16]. With the network density β (in nodes per meter), the probability *p(i,l)* of finding *i* nodes in the lane of *l* length is given by:

$$p(i,l) = \frac{(l\beta)^i e^{-l\beta}}{i!}, i = 0,1,2,... \tag{1}$$

2).In this paper, the channel access mechanism is based on the distributed TDMA protocol such as the VeMAC. Time is divided into frames consisting of a constant number of time slots and the number of time slots per frame is denoted by *F*. Accessing a time slot demands precise time synchronization among vehicles such that vehicles can detect the start time of a frame and the start time of a time slot. Each vehicle is equipped with a Global Positioning System (GPS) receiver (this is a reasonable enough assumption since the GPS receivers can be deployed on vehicles easily [17]) and synchronization among nodes can be performed using the 1PPS signal provided by any GPS receiver. The rising edge of this 1PPS is aligned with the start of every GPS second with accuracy within

100ns even for inexpensive GPS receivers. Consequently, this accurate 1PPS signal can be used as a common time reference among all nodes [7].

3).For communication models, the unit disk is considered in this paper [16]. All vehicles have the same communication capabilities with the same transmission range *R*. Within the transmission range of a source, a node can receive the transmitted packet successfully with probability *p*, taking account of the channel quality. The parameter *p* does not account for transmission collision. The poorer is the channel quality, the smaller is the *p* value.

4).The distributed TDMA protocol can support point-to-point, multicast, or broadcast modes of communication [5]. To evaluate the performance of Co-DTDMA, the paper only considers point-to-point communication mode.

3. Cooperative Distributed TDMA

3.1. Channel Access

In its own time slot, each node transmits a packet containing Frame Information (FI), which is a vector with *F* entries that specify the status of each of the preceding *F* time slots, as observed by the node itself [5-6]. The time slot status can be either BUSY or FREE: it is BUSY if a packet has been correctly received in the time slot, otherwise it is FREE. In the case of a BUSY slot, the FI also contains the identity of the transmitting node. In the VeMAC, each node is identified by a short identifier (ID) (1-2 bytes), which is shorter than the size of a MAC address. The ID is chosen randomly by each node, included in the header of each packet transmitted on channel, and changed if there is a conflict [6]. Use of such a short ID reduces the MAC overhead. By receiving FIs from one-hop neighbors, a node can determine [15]: 1) its one-hop neighbors, 2) its two-hop neighbors, 3) each time slot owner in a frame. To contend for an unreserved time slot, a node listens to the channel for consecutive *F* time slots (not necessarily in the same frame), and then tries to reserves an unreserved time slot [5].

After a node has successfully reserved a time slot, it transmits a packet in its own time slot in every frame until it encounters a merging collision due to relative mobility among nodes. Merging collision occurs when two or more nodes accessing the same time slot become two hops within each other, resulting in a transmission collision in the same time slot. Merging collision is likely to occur among vehicles moving in opposite directions or between a vehicle and a stationary RSU. To overcome merging collision, the VeMAC separates time slots into three disjoint groups, dedicated to vehicles moving in opposite directions and to RSUs respectively [6-8]. As its ability to decrease the rate of merging collision, the VeMAC provides significantly higher throughput than the ADHOC MAC.

3.2. Transmission Acknowledgement

In addition to the time slot reservation, FI can also help for transmission acknowledgement. In Figure 1, the source node S transmits a packet to the destination node D in the S^{th} time slot in a frame (the S^{th} time slot is reserved by node S and node S transmits only in the S^{th} time slot in a frame). If node D fails to receive the packet from node S, node D does not include the ID of node S in the FI of its packet, and upon receiving the FI from node D in the D^{th} time slot (the D^{th} time slot is reserved by node D in a frame), the neighboring nodes of node D conclude that node D fails to receive the packet from node S in the S^{th} time slot, which is actually a negative acknowledgement (NACK). On the other hand, the ID of node S included in the FI of node D is actually an acknowledgement of a successful transmission from node S to node D.

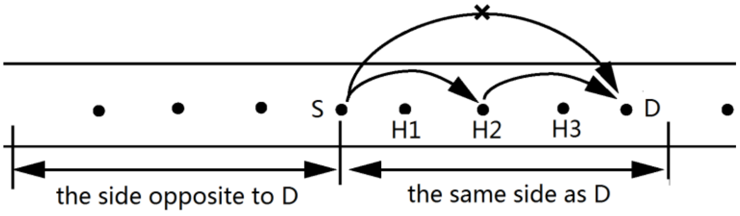


Figure 1. Helper H2 Retransmits a Packet Overheard from Node S Cooperatively

This paper focuses on cooperative communication, and considers a network where nodes are synchronized perfectly and have already reserved their time slots based on the VeMAC. Cooperative communication is only performed by nodes which have their own slots for transmission. When a transmission between the source and the destination fails, a helper performs cooperation to retransmit the packet overheard from the source. In Figure 1, if the transmission between the source node S and the destination node D fails, the helper node H2 retransmits the packet overheard from the source node S cooperatively.

3.3. COOP Header

Figure 2 shows the packet structure in the Co-DTDMA. In its own time slot, a node transmits a packet which consists of PHY Header, MAC Header, FI, COOP Header, Payload Data, and CRC (cyclic redundancy check). The PHY Header, MAC Header, FI, Payload Data, and CRC are the same as the ADHOC MAC and the VeMAC, and the COOP Header is a new field introduced specifically for cooperative communication. If a helper transmits a overheard packet cooperatively: 1) The Flag in its Coop Header is “1”, 2) The Position in its Coop Header is the location of itself, 3) The Source ID, the Destination ID and the Packet Sequence in its COOP Header are the same as in the MAC Header of the packet overheard from the source node, which identify the packet to be retransmitted cooperatively. On the other hand, if a node transmits its own application information in its time slot, the Flag in its Coop header is “0”, the position is the location of itself, and the Source ID, the Destination ID and the Packet Sequence in the COOP Header do not exist.

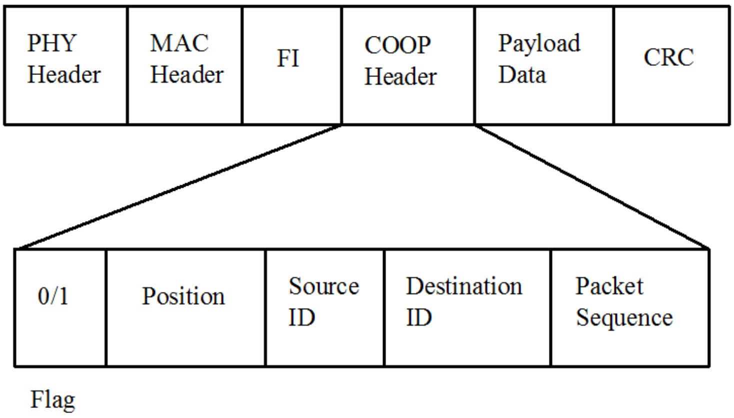


Figure 2. Structure of a Packet in Co-DTDMA

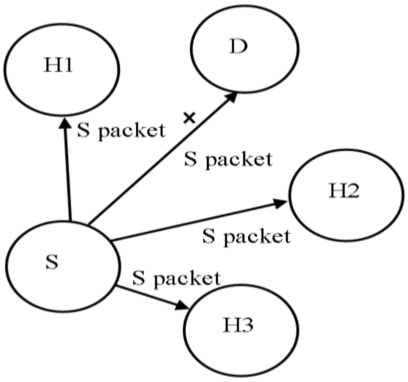
3.4. Cooperation among Neighboring Nodes

If all the following conditions are satisfied, cooperative decision is made and cooperative retransmission is performed:

1) The direct transmission between the source and the destination fails: Cooperation retransmission is trigged by the failure of the direct transmission between the source and the destination.
2) The helper receives a packet from the source successfully: A node can offer cooperation retransmission only if it receives the packet from the source successfully.
3) The helper does not transmit its own application information in its time slot.
4) The helper and the destination are on the same side of the source (as shown in Figure 1).

If the helper is on the side opposite to the destination, the range from the helper to the destination includes the range from the source to the destination, and the distance between the helper and the destination is greater than the distance between the source and the destination. As the transmission from the source to the destination has failed, the helper has little chance for retransmitting the packet overheard from the source successfully. The helper can get its location information via GPS system, and can get other nodes location information via the Position field in packet. Based on the position information of the source, the destination and itself, the helper can decide whether it is on the same side as the destination or not.

Figure 3 shows information exchanges in Figure 1. In Figure 3(a), Source node S transmits a packet to the destination node D during S^{th} time slot and the neighboring nodes of node S overhear the packet from node S; In Figure 3(b), the destination node D transmits a packet during the D^{th} time slot, and after the D^{th} time slot, neighboring nodes of node D can determine whether node D has successfully received the packet from node S or not; In Figure 3(c), if the transmission between the node S and the node D fails, the helper node H2 retransmits the packet overheard from the node S cooperatively in its own idle slot. Upon overhearing the cooperative retransmission from node H2, other potential helpers suspend their own intention to retransmit.



(a)

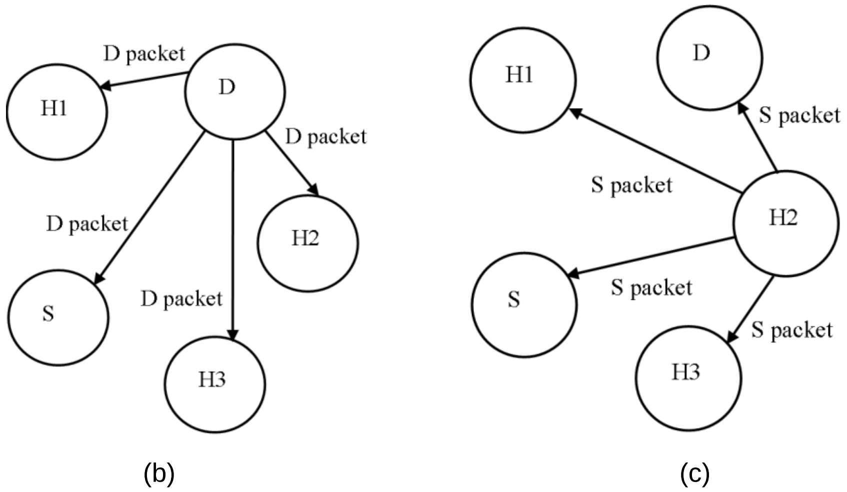


Figure 3. Information Exchanges in the Co-DTDMA

In the distributed TDMA protocol, since the FI in each packet helps for the time slot allocated, it is mandatory for a node to send a dummy packet(no application data is available) in its time slot if the node has no application information to be transmitted [6-8]. Since the dummy packet from a node do not ever compete with other nodes' slots, it does not contribute to any form of channel congestion. The advantage of this, however, is more responsive slot reorganization compared to the out-of-band mechanisms that rely on explicit reallocation signaling.

The above information exchange is based on the wireless broadcasting natural and the determinate manner in which the distributed TDMA accesses the channel, such that the source, the destination and the helper can interact with each other in an order and determinate way. In addition, the above information exchange is coordinated in a fully distributed manner, which makes it suitable for VANET.

The Coop Header includes the Flag (1 bit), the Position (expressed by the latitude and the longitude, and each is 4 bytes), the Source ID, the Destination ID and the Packet Sequence. If the node ID and the packet sequence are set to 2 bytes (that is enough for applications and if the packet sequence number is greater than the maximum number, the sequence restarts from zero), the length of the Coop Header of the helper is 113 bits. Giving the during of a time slot is 1 ms and the channel speed is 18 Mb/s [7], a node can transmit 18874 bits during a time slot. As the size of the COOP Header is far less than the amount of bits transmitted by a node during its time slot, the overhead of the COOP Header is negligible compared to idle slots used by helpers.

4. Performance Analysis

Let p_s denote the successful transmission probability during a reserved time slot in the situation of direct transmission. In the VeMAC, nodes moving in same directions are relatively stationary with respect to each other in a frame, thus the relative mobility among those nodes in a frame is negligible. Hence, the transmission fails just because of poor quality of wireless channel, and p_s should be equal to p [15]. In the following, the paper calculates the successful transmission probability with cooperation communication in the current frame. The current frame is from the source current time slot to its next time slot, which includes F time slots.

4.1. The Probability of Finding the Helper

Let N_c denote the number of nodes which are within the transmission range of the source and on the same side as the destination. The probability mass function of N_c is given by:

$$\Pr\{N_c = u\} = \frac{(R\beta)^u e^{-R\beta}}{u!}, u = 0,1,2,... \tag{2}$$

If $N_c \leqslant 2$, the helper does not exist, since the source and the destination cannot be the helper. If $3 \leqslant N_c \leqslant F$, up to N_c-2 nodes can be the helper if they receive the packet from the source successfully. If $N_c > F$, only F-2 nodes which have reserved a time slot in a frame can be the helper.

After the destination transmits FI during its own time slot, the helper can confirm whether the destination has successfully received the packet from the source or not. If the transmission between the source and the destination fails, the helper cooperatively transmits the overheard packet from the source during its own time slot. Hence, the helper's time slot must be behind the destination's slot in the current frame. The paper assumes the probability of a time slot behind the destination's in the current frame is $\frac{1}{2}$. Giving $N_c = u$, except the source and the destination, the probability of finding k nodes which's time slots are behind the destination's in the current frame is $C_{u-2}^{k}(\frac{1}{2})^{k}(\frac{1}{2})^{u-2-k}$,that is $\frac{C_{u-2}^{k}}{2^{u-2}}$, for $0 \leqslant k \leqslant u\text{-}2$, $3 \leqslant u \leqslant F$.

If a node's time slot is behind the destination's time slot in the current frame, the node still cannot act as the helper if one of the following events occurs:

1).The node fails to receive the packet from the source.
2).The node has to transmit its own application information during its time slot.

Let p_d denote the data transmitting probability (the probability of a node transmitting its own data during its time slot). Giving k nodes which's time slots are behind the destination' time slot in the current frame, the probability of all the k nodes still cannot act as the helper is $\sum_{v=0}^{k} C_k^v p_s^v p_d^v (1-p_s)^{k-v}$, where v is the number of nodes which have overheard the packet from the source successfully. Hence, giving $N_c = u$, except the source and the destination, the probability of find k nodes which's time slots are behind the destination's time slot in the current frame and all the k nodes cannot act as the helper is $\frac{C_{u-2}^{k}}{2^{u-2}} \sum_{v=0}^{k} C_k^v p_s^v p_d^v (1-p_s)^{k-v}$, for $0 \leqslant k \leqslant u\text{-}2$, $3 \leqslant u \leqslant F$.

Let N_h denote the number of potential helpers for a failed transmission. Giving $N_c = u$, the probability of finding no helper is given by:

$$\Pr\{N_h = 0 \mid N_c = u\} = \begin{cases} \sum_{k=0}^{u-2} (\frac{C_{u-2}^{k}}{2^{u-2}} \sum_{v=0}^{k} C_k^v p_s^v p_d^v (1-p_s)^{k-v}), 3 \le u \le F \\ \sum_{k=0}^{F-2} (\frac{C_{F-2}^{k}}{2^{F-2}} \sum_{v=0}^{k} C_k^v p_s^v p_d^v (1-p_s)^{k-v}), u > F \end{cases} \tag{3}$$

Consequently, giving $N_c = u$, the probability of finding the helper is given by:

$$\Pr\{N_h > 0 \mid N_c = u\} = 1 - \Pr\{N_h = 0 \mid N_c = u\}$$
$$= \begin{cases} 1 - \sum_{k=0}^{u-2} \left(\frac{C_{u-2}^{k}}{2^{u-2}} \sum_{v=0}^{k} C_k^v p_s^v p_d^v (1-p_s)^{k-v} \right), 3 \le u \le F \\ 1 - \sum_{k=0}^{F-2} \left(\frac{C_{F-2}^{k}}{2^{F-2}} \sum_{v=0}^{k} C_k^v p_s^v p_d^v (1-p_s)^{k-v} \right), u > F \end{cases} \tag{4}$$

Under all conditions, the probability of finding the helper is given by:

$$\Pr\{N_h > 0\} = \Pr\{N_h > 0 \mid 3 \le N_c \le F\} + \Pr\{N_h > 0 \mid N_c > F\} \tag{5}$$

For $3 \leqslant N_c \leqslant F$:

$$\begin{aligned} \Pr\{N_h > 0 \mid 3 \le N_c \le F\} &= \sum_{u=3}^{F} \Pr\{N_h > 0 \mid N_R = u\} \Pr\{N_c = u\} \\ &= \sum_{u=3}^{F} \left(1 - \sum_{k=0}^{u-2} \left(\frac{C_{u-2}^{k}}{2^{u-2}} \sum_{v=0}^{k} C_k^v p_s^v p_d^v (1-p_s)^{k-v} \right)\right) \Pr\{N_c = u\} \end{aligned} \tag{6}$$

For $N_c > F$:

$$\begin{aligned} \Pr\{N_h > 0 \mid N_c > F\} &= \sum_{u=F+1}^{\infty} \Pr\{N_h > 0 \mid N_R = u\} \Pr\{N_c = u\} \\ &= \sum_{u=F+1}^{\infty} \left(1 - \sum_{k=0}^{F-2} \left(\frac{C_{F-2}^{k}}{2^{F-2}} \sum_{v=0}^{k} C_k^v p_s^v p_d^v (1-p_s)^{k-v} \right)\right) \Pr\{N_c = u\} \\ &= \left(1 - \sum_{k=0}^{F-2} \left(\frac{C_{F-2}^{k}}{2^{F-2}} \sum_{v=0}^{k} C_k^v p_s^v p_d^v (1-p_s)^{k-v} \right)\right) \sum_{u=F+1}^{\infty} \Pr\{N_c = u\} \\ &= \left(1 - \sum_{k=0}^{F-2} \left(\frac{C_{F-2}^{k}}{2^{F-2}} \sum_{v=0}^{k} C_k^v p_s^v p_d^v (1-p_s)^{k-v} \right)\right) \left(1 - \sum_{u=0}^{F} \Pr\{N_c = u\}\right) \end{aligned} \tag{7}$$

4.2. The Probability of Successful Packet Transmission

With the introduction of cooperation retransmission, a transmission is successful either direct transmission is successful or cooperative retransmission is successful. Hence the successful transmission probability with cooperation, denoted by $p_s^{Co-DTDMA}$, is given by:

$$p_s^{Co-DTDMA} = p_s + (1-p_s) \Pr\{N_h > 0\} p_s \tag{8}$$

4.3. Packet Transmission Delay

Upon transmission failure, a source tries to retransmit a packet until it reaches the destination successfully. The packet transmission delay (PTD) is defined as the number of frames that is required to transmit a packet to the destination successfully [18]. For the direct transmission, the probability of i frames required to transmit a packet to the destination successfully is given by:

$$\Pr(PTD = i) = (1-p_s)^{i-1} p_s \tag{9}$$

PTD follows a geometric distribution and the expected value of PTD is given by:

$$E(PTD) = \frac{1}{p_s} \tag{10}$$

For Co-DTDMA, PTD as the above formula changes to:

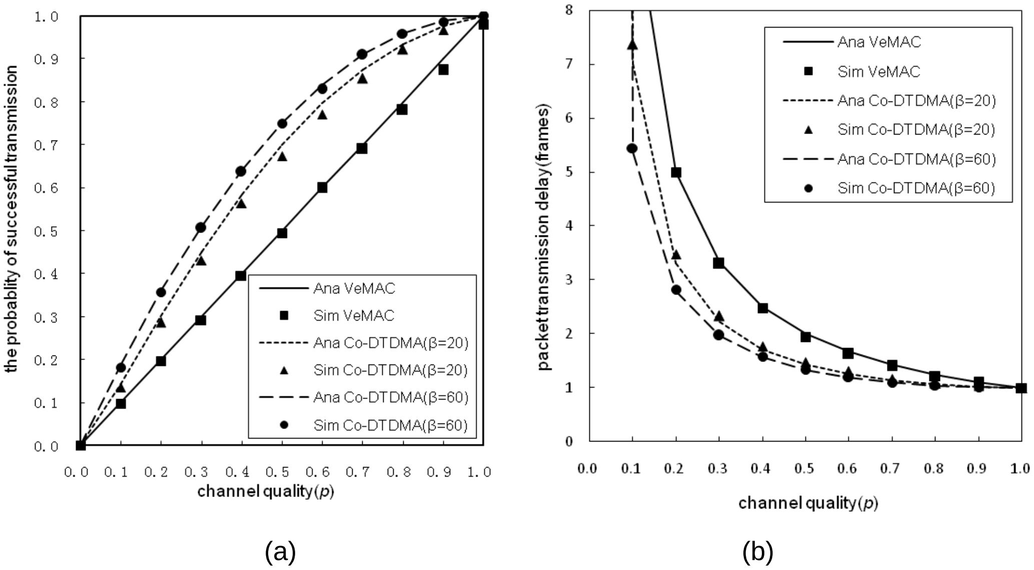
$$E[PTD_{Co-DTDMA}]=\frac{1}{p_s^{Co-DTDMA}} \tag{11}$$

5. Numerical Results

The simulation is performed in MATLAB simulator. The road has two lanes and each lane width is 5 m. The number of vehicles over a segment lane follows the Poisson distribution. Vehicles density per lane, denoted by β_l (vehicles/m), is kept equal and hence $\beta=2\beta_l$. In simulation, the number of slots in a frame is 80. The VeMAC separates time slots into three disjoint groups, dedicated to vehicles moving in opposite directions and to RSUs respectively. The simulation does not consider the RSUs and the number of slots per lane is 40. Each simulation result is obtained from 100 different network topologies.

In addition to the channel quality (p), the successful packet transmission probability of the Co-DTDMA depends on vehicle density (β), data transmitting probability (p_d) and wireless transmission range (R). Figure 4 to Figure 6 show that the Co-DTDMA significantly increases the probability of successful packet transmission and decreases the packet transmission delay in various network parameters. When a node fails to transmit a packet, the helper retransmits the failed packet during its own idle time slot cooperatively.

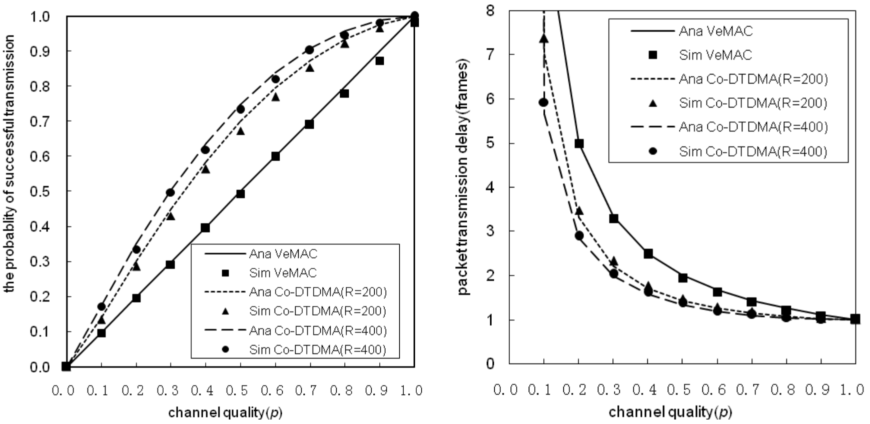
Figure 4 shows that with an increase in the vehicles density β, the successful packet transmission probability of the Co-DTDMA increases and the packet transmission delay of the Co-DTDMA decreases. For the given R and p_d, increasing β also increases the number of neighboring nodes of the source, thus increases the probability of finding the helper. Consequently, with an increase in β, the successful packet transmission probability of the Co-DTDMA increases and the packet transmission delay of the Co-DTDMA decreases.



(a) (b)

Figure 4. The Probability of Successful Packet Transmission and the Delay of the Two Methods as a Function of β

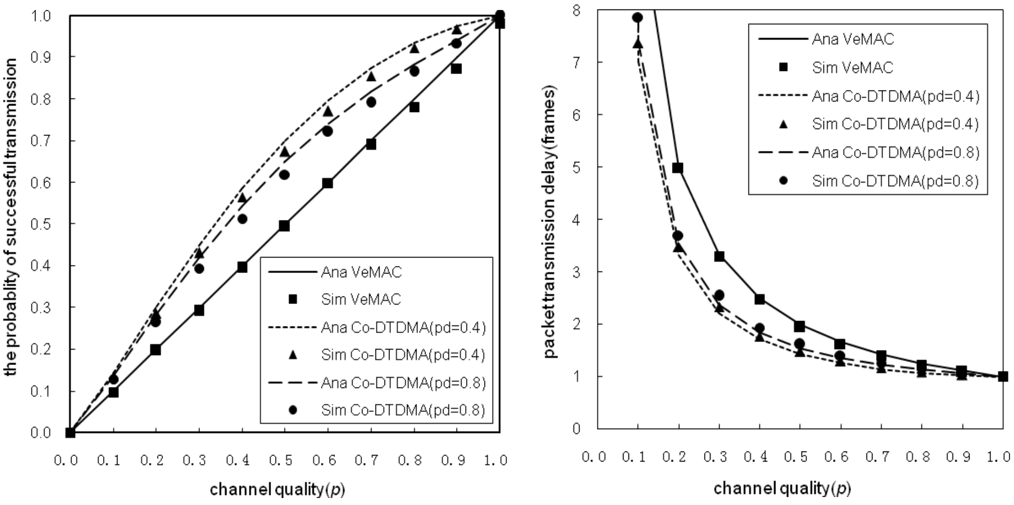
Figure 5 shows that with an increase in wireless transmission range R, the successful packet transmission probability of the Co-DTDMA increases and the packet transmission delay of the Co-DTDMA decreases. For the given β and p_d, increasing R also increases the number of neighboring nodes of the source. Hence, with an increase in R, the successful packet transmission probability of the Co-DTDMA increases and the packet transmission delay of the Co-DTDMA decreases.



(a) (b)

Figure 5. The Probability of Successful Packet Transmission and the Delay of the Two Methods as a Function of *R*

Figure 6 shows that with an increase in the data transmitting probability p_d, the successful packet transmission probability of the Co-DTDMA decreases and the packet transmission delay of the Co-DTDMA increases. For the given R and β, increasing p_d decreases the number of the nodes with the idle time slot, thus decreases the probability of finding the helper. Consequently, with an increase in p_d, the successful packet transmission probability of the Co-DTDMA decreases and the packet transmission delay of the Co-DTDMA increases.



(a) (b)

Figure 6. The Probability of Successful Packet Transmission and the Delay of the Two Methods as a Function of p_d

Figure 4-6 show that both protocols perform equally at two extreme channel quality ($p = 0$ and $p = 1$). If $p = 0$, all transmissions fail. Thus for the Co-DTDMA, all neighboring nodes fail to receive the packet from the source nodes, consequently the helper is not found and there is no cooperative retransmission. For both protocols, the successful packet transmission probability is 0, and the delay of packet transmission is infinite. If $p =$

1, all transmissions succeed. For both protocols, the successful packet transmission probability is 1, and the packet transmission delay is 1. Thus for the Co-DTDMA, cooperative retransmission is not trigged.

6. Conclusion and Future Work

This paper presents a cooperative MAC (Co-DTDMA) protocol for VANET. In the Co-DTDMA, when the destination does not successfully receive a packet from the source, the helper takes advantage of its own idle time slots to retransmit the failed packet. All the Co-DTDMA operations, such as synchronization among nodes, reserving a time slot, cooperation decision and cooperative transmission are done in a fully distributed manner, which makes it suitable for VANET. As the destination has more chances to receive the independent copies of the packet from the source, the probability of successful packet transmissions increased. Both analysis and simulation results show that Co-DTDMA improves the probability of successful packet transmission, decreasing the delay of packet transmission.

In this work, the mathematical analysis is based on the basic channel model. The future work will further study the effects of more realistic channel models on the performance of the proposed protocol.

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Author

Zhen Chen (1980) Male, PhD student, research interests: medium access control, routing, and cooperative communication in vehicular ad hoc networks.