EVC-TDMA: An Enhanced TDMA Based Cooperative MAC Protocol for Vehicular Networks

Tianjiao Zhang and Qi Zhu

Abstract: **In order to optimize the communication mechanism in the vehicular adHoc networks (VANETs), this paper presents an enhanced TDMA based cooperative MAC protocol called EVC-TDMA. In EVC-TDMA, when the vehicles need to transmit multi-hop messages, they choose relay nodes dynamically according to the relative speeds and buffer lengths. By monitoring the broadcasting messages, the other nodes can know the buffer lengths of the relay nodes, they will help transmit the relay messages when their buffer are idle or less. Considering the data arrive follows a Poison Point Process, this paper analyzes the nodes' buffer length based on a two-dimension Markov process. The simulation results show that EVC-TDMA can reduce the dropping rate and improve the throughput of the network.**

Index Terms: **Cooperative communication, multi-hop relay, TDMA, VANETs.**

I. INTRODUCTION

VEHICLES and infrastructures are two essential factors in intelligent transportation systems (ITSs) [1]. With the rapid development of the economy, the contradiction between the rapid increase in the number of vehicles and slow growing scale of infrastructure is becoming increasingly severe. Lack of infrastructure leads to crowded roads and poor transportation efficiency. Therefore, the improvement of real-time communication in vehicular networks has become a viable research field of study in recent years.

When designing an MAC protocol for vehicular adhoc networks VANETs, characteristics such as the speed and dynamic distribution of nodes, which are also the key points for optimizing the protocol, must be considered. IEEE 802.11p [2] is a well-known MAC protocol for VANETs, but it can-not provide an efficient broadcast service because no RTS/CTS and ACK are used in the broadcast frame, which may cause hidden terminal problems [3]. The paper [4] presents the CSMA and self-organizing TDMA MAC (CS-TDMA), which improve network performance by changing the length of the control channel (CCH) and the service channel (SCH) according to the node density of the network. The MAC protocol based on TDMA assigns individual time slots to each vehicle that achieves a collision-free transmission system. The vehicular ad hoc networks MAC (VeMAC) provided in [5] is a distributed TDMA MAC. In VeMAC, the vehicles select the available time slots according to their direction of movement and broadcast the number of the selected time slots to test the slot collision. The author of paper [6] presents the cooperative ad hoc MAC (CAH-MAC) for the VANETs. Considering the channel fading, CAH-MAC let other nodes cooperative transmission the data by using the idle time slots when the data transmission fails, which improves the throughput and reduces the packet drop rate. The cluster-based TDMA system for inter-vehicle communications (CBT) [7] is designed based on cluster, it uses a simple transmit-and-listen scheme to achieve contention-free intra-cluster and inter-cluster communications. Another cluster-based MAC protocol is direction aware cluster-based multi channel MAC (DA-MAC), the cluster head assigns time slots to the cluster members according to their direction fo movement to reduce the merging collision caused by vehicles moving in opposite directions. The unified TDMA-based scheduling protocol (UTSP) [9], [10] is designed for vehicle-to-infrastructure (V2I) communication, the base station collects information of the moving vehicles and assigns individual time slots to the vehicles according to their speeds and channel conditions. Additionally, the cooperative multiple input multiple output (MIMO) technology has been used in the Het-VNETs to minimize end-to-end latency and maximize throughput [11]. Cooperative relaying TDMA (CR-TDMA) [12] is proposed for multi-hop relaying networks, as it allows idle nodes to help transmit multi-hop data. However, it is unsuitable for the VANETs because its relay node is fixed. [13] proposed a contention intensity based distributed coordination scheme for safety message broadcasts. By exploiting the high-frequency and periodical features of the safety message broadcast, the application-layer design of the contention intensity based distributed coordination (CIDC) enables each vehicle to estimate the instantaneous channel contention intensity in a fully distributed manner. However, the cooperative transmission has not been considered in [13].

Considering the communication between vehicles is not just for safe driving in the future, it also can support several data packets transmission, so this paper considers the data arrival rate follows a Poisson point process. An enhanced TDMA-based MAC protocol known as EVC-TDMA is proposed in this paper. When a certain node wants to transmit messages to the destination node, which is out of its one-hop communication range, for example the messages about real-time road conditions need to be broadcasted in a certain area which is far more than one-hop

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communication range, the node selects other nodes to relay the messages according to the relative speed and buffer lengths of the nodes. Cooperative transmission has two modes: If the relay node is relaxed, the other nodes only help in transmitting the relay messages when their buffers are idle, and if the relay node is busy, the other nodes will cooperatively transmit messages when their buffers are less busy. Cooperative communications are transmitted in the reserved slots of the nodes without occupying other channel resources. In this study, the buffer state fo the nodes has been analyzed in a two-dimensional Markov chain. The simulation results show that EVC-TDMA can improve the throughput and packet drop rate of the network. The main contributions of our paper are as follows:

(1) We present a TDMA based MAC protocol for a vehicular ad hoc network, which can assist in multi-mode cooperative transmission. The vehicle nodes will change the cooperative transmission mode according to the buffers of both the relay nodes and themselves.
(2) The queueing models of the normal nodes, cooperative nodes, and relay nodes are analyzed in different ways. The queueing modelof the normal nodes is a traditional one-dimensional Markov model. The queueing model of the cooperative nodes is a one-dimensional state dependent queueing model. The queueing model of the relay nodes is analyzed using a two-dimensional state dependent queueing model.
(3) According to the queueing model, we deduce the distribution of the buffer length by iteration and simulate the network performance of throughput, packet drop rate and delay.

The rest of this paper is organized as follows: The network scenarios and broadcast style is presented in Section II. Section III describes how to elect the relay node and do the cooperative transmission. The buffer state is analyzed in Section IV according to the queueing model. The Section V presents the simulation results to prove the deduction and shows the performance. Finally, Section VI concludes this paper.

II. SYSTEM MODEL

A. Network Scenarios

As seen from [5], in order to simplify the derivation, without losing generality, it assumes that all vehicles still remain in one frame time (one frame is 0.1 s). To analyze the communication process of a certain node, the process of transmitting or receiving messages can be seen as accomplished in the static network. First, we analyze the algorithm in the static network and then add the variable parameters relevant to the vehicular network to make the algorithm more suitable for vehicular networks. The performance of the protocol is analyzed in two networks: (1) The static network: There are several nodes in the static network, the number is N, and they are relatively stationary. According to the distances between each of the nodes, they can be divided into normal nodes, cooperative nodes or relay nodes. The relay nodes can transmit multi-hop relay data produced by other nodes, the cooperative nodes can help the relay nodes transmit data when their buffer is relaxed, and the normal nodes only transmit the data produced by themselves. A detailed classification method will be introduced in part 3; (2) the highway scenario: N vehicles are moving on the road and each vehicle has its own serial number ($ID \in \{1, 2, \cdots, N\}$). The global position system (GPS) receiver is equipped in the vehicle and they use the received signal to achieve signal synchronization. The interval between two adjacent signals is defined as one frame [13]. All the vehicles continuously communicate with each other when they are moving, which comprise a variable topology network.

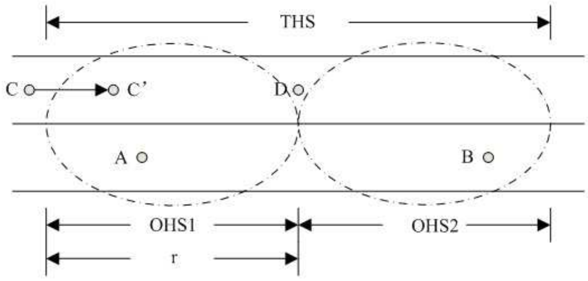

Fig. 1. The illustration of OHS and THS [5].

B. Broadcast Style

Notably, communication in control channel is point to multipoint communication and that in service channels is point to point communication. This paper presents different broadcast styles in the two channels, considering their characteristics. Omni-directional broadcast is used in control channel to ensure that safety data can be transmitted to all vehicles in the transmission range. While in the service channel, the protocol uses the direction broadcast style to transmit point to point data. Data acquisition experiments [16] have proved that the performance of the direction broadcast style is superior to that of the omnidirectional broadcast in ad-hoc networks. In this study, the relay nodes have a higher transmit power than the other nodes to guarantee that their transmission range is twice as far.

C. Neighbor Nodes

The neighbor nodes are divided into one-hop nodes, two-hop nodes and the other nodes according to the relative distance between each vehicle and the communication range [5]. One-hop set (OHS) and two-hop set (THS) are defined as the nodes' set whose relative distance is less than the communication range r or $2r$. As shown in Fig. 1, a THS can be divided into two OHSs like $THS = OHS1 \bigcup OHS2$. For node D, $D \in OHS1, D \in OHS2, D \in THS$, so node D can communicate with node A and B directly. For node A, $A \in OHS1, A \notin OHS2, A \in THS$, so node A can't communicate with node B directly but it can communicate with node B through node D.

III. PROTOCOL DETAILS

Without losing generality, this study assumes that all vehicles keep stillness in one frame time. On the premise of this assumption, this paper presents the communication procedure in detail and expounds different node functions.

A. Communication Procedure

In this protocol, the communication channels are divided into control channel and service channel. The control channel is used to transmit control messages broadcasted by the vehicles, including the vehicles' positions, speeds, moving directions, and number of occupied slots [5]. This indicates that each node should reserve an idle slot on the control channel before it transmits data on the service channel.

After each node has reserved a certain time slot on the control channel, the nodes continue to monitor the control channel and await their reserved time slot. When the time slot of a certain node arrives, this node begins to transmit messages. If it has its own data to transmit, it transmits the data to the destination node directly or finds a relay node to relay the message according to the transmission distance. Conversely, if it monitors relay messages from other nodes, it can perform cooperative transmission actively. After it assists in relaying the messages successfully, the relay node monitors the success of the transmission and deletes the messages in its buffer to avoid wasting buffer capacity.

B. Normal Communication

In an ad-hoc network, it is a normal phenomenon that one node wants to exchange messages with other nodes out of its communication range. This kind of communication is called multi-hop communication, it needs the relay node to help relay the messages to realize the multi-hop communication. Since the nodes in the VANETs move frequently, it's very important to choose a suitable relay node when transmitting the multi-hop messages. The more stable the relative speed is, the longer connect time will be. Let

$$W(F_n)=\frac{\sum_{j=1}^{F_n}|V_i-V_j|}{max\left\{\sum_{j=1}^{F_n}|V_1-V_j|,\sum_{j=1}^{F_n}|V_2-V_j|,\cdots,\sum_{j=1}^{F_n}|V_n-V_j|\right\}} \quad (1)$$

present the relative speed at F_n frame times. In the formula, V_i is the moving speed of node i and V_j is the moving speed of other nodes in its one-hop range.

Let W_{CH} present the average relative speed at F_n frame times. It can be calculated as, $W_{CH}(F_n) = \beta \cdot W(F_n) + (1 - \beta) \cdot W_{CH}(F_{n-1})$.

As said in paper [15], by adding two new modules W_{CH} and R_M in the control message, the nodes can choose the suitable relay node through broadcasting the control packet. The structure of control packet is shown in Fig. 2. Since the value of new module is a number, it just occupies 8 bits which is much less than the payload data (8184 bits), the additional module would not impact the system throughput.

If there is only one relay node in a THS, the multi-hop communication is disrupted when it loses the signal even momentarily. In contrast, if there is a spare node to perform multi-hop relay, the influence of losing the signal is reduced. As indicated by the formula, the speed of the vehicles with smaller W_{CH} values is more stable with the surrounding vehicles, which indicates

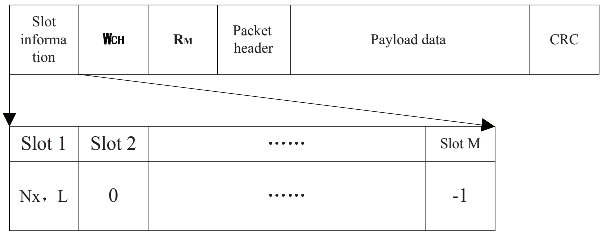

Fig. 2. The structure of the control message.

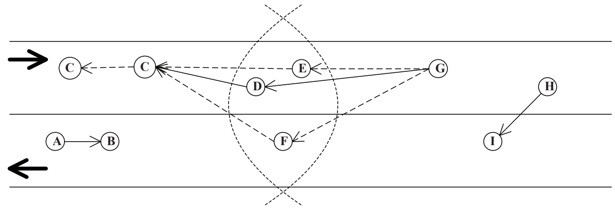

Fig. 3. The intercepted area of VANET.

that they can communicate with other vehicles for a longer duration. Thus, in this study, the nodes with the smallest or penultimate W_{CH} values in a THS are the relay nodes,which change the R_M value from 0 to 1. W_{CH} is refreshed with each frame, and by broadcasting the new W_{CH} value, the nodes can select a new relay node or keep using the current relay node.

By electing the relay node and backup relay node, in each THS, two nodes can transmit the relay packets. When other nodes need to transmit relay packets, they choose the relay node with the shortest buffer length to assist in transmitting these relay packets. The buffer length of the relay nodes can be broadcasted in the control message in their occupied time slots.

C. Cooperative Communication

The network contains numerous relaxed nodesthat have less messages to send in the current time. If some of these nodes are in close proximity to the relay node, they can also monitor multi-hop messages, and thus, achieve the multi-hop relay similar to the relay node. This type of node is called a cooperative node, and Fig. 3 presents the cooperative transmission. If node G wants to send a message to node C, and node D is the current relay node in the THS, the transmission route is $G \to D \to C$. The relay messages are stored in the buffer of relay node D, waiting to be sent. However, if the buffer of node E is empty, when it monitors this relay message, the node assists in relaying this message to node D without a waiting time in the buffer. The transmission route changes from $G \to D \to C$ to $G \to E \to C$, and the transmission delay is reduced. Notably, the cooperative relay is only conducted once, and the other nodes monitor the cooperative transmission and do not attempt cooperative relay again if the transmission was successful in the previous instance.

D. Cooperative Transmission Mode

Cooperative transmission has been applied in previous studies [12], [15]. In both studies, the nodes conducted cooperative transmission when their buffers were idle. When the data arrival

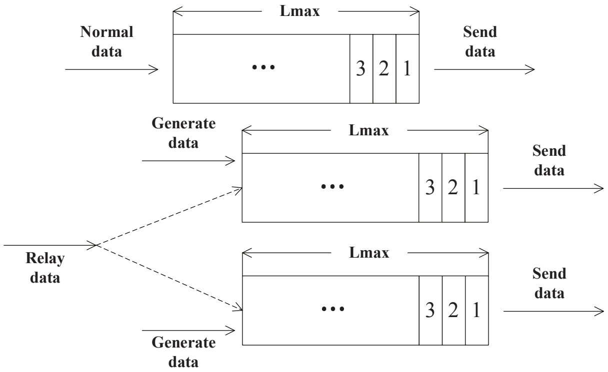

Fig. 4. The buffer state.

rate is similar to the data transmission rate, the buffers may contain messages at all times, which affects the cooperative transmission. This study presents a multi-mode cooperative transmission protocol. The buffer state is divided into three classes: 1. Idle (empty buffer), 2. relaxed (buff less than half full), 3. busy (buffer more than half full).

The cooperative transmission has two modes. When the buffer state of the relay node is relaxed, the transmission load is low in the network, and thus, the normal nodes only cooperatively transmit messages when their buffer is empty. When the buffer state of the relay node is busy, the transmission load is high in the network, and thus, the normal nodes cooperatively transmit messages when their buffer states are relaxed. Consequently, the normal nodes share the load of the relay node according to their buffer states.

E. The Queueing Model

After storing data in the buffer, the node sends these packets following the rule: First in, first out (FIFO). The buffer state of each node can be seen as a single node queueing model.

The queueing models of the normal and relay nodes are shown in Fig. 4. The top iamge depicts the queueing model of the normal node, where the data arriving at each frame is stored in the buffer, which can store $L_{\max}$ packets. When the node can send packets, it sends the first packet according to the FIFO rule. The bottom image depicts the queueing model of the relay node, there the difference is that the arriving packets are produced by itself or from other nodes. Moreover, the relay packets are stored in the buffer of the relay node with the shorter buffer length. The queueing model of the cooperative node is similar to that of the normal node. Because the cooperative transmission is related to the buffers of both the normal and relay nodes, it is a state dependent queueing model and should be solved by iteration.

When the channel condition in the network is poor, it will happen that the packet at the head of the buffer cannot be sent. This head-of-line blocking will interfere other packets in the buffer, so in this paper, when a batch of packets arrives and the buffer is full, the node will drop the packet at the head of the buffer and store a new packet at the end of the buffer.

IV. PERFORMANCE ANALYSIS

To analyze the performance of EVC-TDMA, throughput, dropping rate and delay are three key indicators to consider. To simplify the analysis, there are several assumptions: (1) All the nodes have reserved the time slots on the control channel without conflict; (2) in each one frame time, all the nodes keep stillness, their positions only refresh once in each frame.

A. The Queue Length of The Vehicle Nodes

A.1 Generation Probability of Packets

Several symbols are defined to describe the transmission as follows: F_n^-: The begin of the transmission slots. F_n^+: The end of the transmission slots. p_s: The probability that the packet sends successfully. T_f: The duration of one frame.

Let $P_r(n_r)$ and $P_{nr}(n_{nr})$ present the probability that n relay or non-relay packets arrive to a node. If both of them follow the Poisson point process with parameter λ_r and λ_{nr}. We can find that, $P_r(n_r) = e^{-\lambda_r T_f}(\lambda_r T_f)^{n_r}/(n_r!)$ and $P_{nr}(n_{nr}) = e^{-\lambda_{nr} T_f}(\lambda_{nr} T_f)^{n_{nr}}/(n_{nr}!)$. And the probability that n packets arrive is $P_{\text{sum}}(n) = e^{-\lambda_{\text{sum}}}(\lambda_{\text{sum}} T_f)^n/(n!)$ $(\lambda_{sum} = \lambda_r + \lambda_{nr})$.

Each frame time, the probability that a certain node produces relay packets is $p = 1 - P_r(0)$. When there are N nodes in the system, the probability that x nodes produce relay packets is $P(x) = C_N^x p^x (1-p)^{N-x}$. Considering there are N_c cooperative nodes, the probability that the relay node receives k packets is

$$P\{C=k\} = \begin{cases} \sum_{x=k}^{N} P(x) C_x^k [(1-P_{c-idle})^{N_c}]^k [1-(1-P_{c-idle})^{N_c}]^{x-k}, \\ 0 \le L \le \frac{1}{2} L_{\max} \\ \sum_{x=k}^{N} P(x) C_x^k [(1-P_{c-\text{relax}})^{N_c}]^k [1-(1-P_{c-\text{relax}})^{N_c}]^{x-k}, \\ \frac{1}{2} L_{\max} \le L \le L_{\max}. \end{cases} \tag{2}$$

In the formula, $C_x^k = x!/(k!(x-k)!)$, $P_{c-\text{idle}}$ is the probability that the buffers of cooperative nodes are empty and $P_{c-\text{relax}}$ is the probability that the buffer states of the cooperative nodes are relaxed.

B. Transition Probability of Buffer Length

After F_n frame times, the buffer length is L_{F_n}. Obviously, $P\left(L_{F_n} = k_n | L_{F_1} = k_1, L_{F_2} = k_2, \cdots, L_{F_{n-1}} = k_{n-1}\right) = P\left(L_{F_n} = k_n | L_{F_{n-1}} = k_{n-1}\right)$. The buffer lengths of the nodes at the current time only related to the buffer lengths one frame time before. So the transition of buffer lengths is Markov procedure. The Markov chain diagram is shown in Fig. 5.

After one frame time, the buffer length may changes in three cases: (1) If there are packets arrive, the buffer length will increase any value until the buffer length is full; (2) if the node exactly both accepts and sends one packet, the buffer length will be unchanged; (3) if none packet arrives but node sends a packet, the buffer length will minus one.

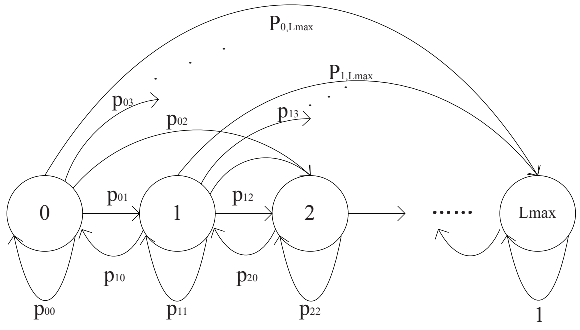

Fig. 5. The Markov chain.

B.1 Markov Chain of Normal Node

When the nodes' buffer states do not satisfy the condition of cooperative transmission, they only send packets produced by themselves. This kind of nodes is called normal node. A_n is the number of arrival packets at the time F_n^-, B_n is the number of dispatching packets at the time F_n^+.

Let P_{ij}^n=$P\left\{L_{F_{n+1}}=j|L_{F_n}=i\right\}$ described the probability that the normal node's buffer length is i at the current time, after one frame time, it changes to j. It can be found that:

$$L_{F_{n+1}}=\begin{cases}L_{F_n}+A_{n+1}-B_n,\ F_n\geq 1\\ A_1\ ,\ F_n=0.\end{cases} \tag{3}$$

At the time F_n^-, the number of arrival packets follows:

$$P\left\{A=k\right\}=P_{nr}(k),\ k=0,1,2,\cdots. \tag{4}$$

At the time F_n^+, the node can send one packet with probability p_s, so

$$P\left\{B_n=1\right\}=p_s,\ P\left\{B_n=0\right\}=1-p_s. \tag{5}$$

Substitute formula (4) and (5) to (3), we can know,

$$P_{ij}^n=\begin{cases}P_{nr}(j),\ i=0,0\leq j<L_{\max}\\ \sum\limits_{k=L_{\max}}^{\infty}P_{nr}(k),\ i=0,j=L_{\max}\\ p_s\cdot P_{nr}(0),1\leq i\leq L_{\max},j=i-1\\ p_s\cdot P_{nr}(j-i+1)+(1-p_s)\cdot P_{nr}(j-i),\\ \ 1\leq i\leq L_{\max},i\leq j<L_{\max}\\ p_s\cdot\sum\limits_{k=L_{\max}-i+1}^{\infty}P_{nr}(k)+(1-p_s)\cdot\sum\limits_{k=L_{\max}-i}^{\infty}P_{nr}(k),\\ \ 1\leq i\leq L_{\max},j=L_{\max}.\end{cases} \tag{6}$$

B.2 Markov Chain of Cooperative Node

When the buffer states and positions of normal nodes satisfy the condition of cooperative transmission, they change to cooperative nodes automatically. The transition probability is different when $0\leq i\leq(1/2)L_{\max}$.

When $i=0$,

$$P_{0j}^c=\begin{cases}P_{\text{sum}}(0)\cdot P\left\{C_{n+1}=0\right\},j=0\\ P_{\text{sum}}(0)\cdot P\left\{C_{n+1}=1\right\}+P_{\text{sum}}(1)\cdot P\left\{C_{n+1}=0\right\},j=1\\ \sum\limits_{a=0}^{j}P_{\text{sum}}(a)P\left\{C_{n+1}=j-a\right\},1<j<L_{\max}\\ 1-\sum\limits_{k=0}^{L_{\max}-1}P_{0k}^c,j=L_{\max}.\end{cases} \tag{7}$$

When $0<i\leq(1/2)L_{\max}$,

$$P_{ij}^c=\begin{cases}P_{r-\text{relax}}\cdot p_s\cdot P_{\text{sum}}(0)+P_{r-\text{busy}}\cdot p_s\cdot P_{\text{sum}}(0)\cdot P\left\{C_{n+1}=0\right\},\\ j=i-1\\ P_{r-\text{relax}}[(1-p_s)\cdot P_{\text{sum}}(j-i)+p_s\cdot P_{\text{sum}}(j-i+1)]\\ +P_{r-\text{busy}}\begin{Bmatrix}(1-p_s)\cdot\sum\limits_{k=0}^{j-i}P_{\text{sum}}(k)\cdot P\{C_{n+1}=j-i-k\}\\ +p_s\cdot\sum\limits_{k=0}^{j-i+1}P_{\text{sum}}(k)\cdot P\{C_{n+1}=j-i+1-k\}\end{Bmatrix}\\ i\leq j<L_{\max}\\ 1-\sum\limits_{k=0}^{L_{\max}-1}P_{ik}^c,j=L_{\max}.\end{cases} \tag{8}$$

In the formula, $P_{r-\text{relax}}$ is the probability that the buffer state of relay node is relaxed and $P_{r-\text{busy}}$ is the probability that the buffer state of relay node is busy.

B.3 Markov Chain of Relay Node

The relay node not only sends packets produced by itself, but also sends the multi-hop relay packets. C_n is the number of multi-hop relay packets. This paper uses a two-dimension Markov progress to express the variety of relay nodes' buffer length. The state space of relay nodes' buffer length is $(0,0),(0,1),\cdots,(1,0),(1,1),\cdots,(L_{\max},L_{\max})$.

The variety of state space has the following cases:

Case 1: There is none packet in the buffer of relay node 1 and 2.

The state space: $(0,0)\rightarrow(l,0)$

$$P_{c_1}(l)=\begin{cases}\sum\limits_{k=1}^{l}P\{C=k\}\cdot P_{\text{sum}}(l-k),\ 0\leq l<L_{\max}\\ 1-\sum\limits_{a=1}^{L_{\max}-1}P_{c_1}(a),\ l\text{=}L_{\max}\end{cases} \tag{9}$$

Case 2: Only the buffer of relay node 1 has packets and it transmits one packet.

The state space: $(i,0)\rightarrow(i-1,l)$.

$$P_{c_2}(l)=\begin{cases}p_s\cdot\sum\limits_{k=1}^{l}P\{C=k\}\cdot P_{\text{sum}}(l-k),\ 0\leq l<L_{\max}\\ p_s-\sum\limits_{a=1}^{L_{\max}-1}P_{c_2}(a),\ l\text{=}L_{\max}\end{cases} \tag{10}$$

Case 3: Only the buffer of relay node 1 has packets and it does not transmit one packet.

The state space: $(i,0) \to (i,l)$.

$$P_{c_3}(l) = \begin{cases} (1-p_s)\cdot \sum_{k=1}^{l} P\{C=k\}\cdot P_{\text{sum}}(l-k),\ 0 \le l < L_{\max} \\ 1-p_s - \sum_{a=1}^{L_{\max}-1} P_{c_3}(a),\ l{=}L_{\max} \end{cases} \quad (11)$$

Case 4: Only the buffer of relay node 2 has packets and it transmits one packet.

The state space: $(0,j) \to (l,j-1)$.

$$P_{c_4}(l) = P_{c_2}(l) \quad (12)$$

Case 5: Only the buffer of relay node 2 has packets and it does not transmit one packet.

The state space: $(0,j) \to (l,j-1)$.

$$P_{c_5}(l) = P_{c_3}(l) \quad (13)$$

If there exists packets in the buffers of the two relay nodes. And the packets in the buffer of relay node 1 are more than the other.

Case 6: They both transmit one packet.

The state space: $(i,j) \to (i-1,j-1+l)$.

$$P_{c_6}(l) = \begin{cases} p_s^2\cdot \sum_{k=1}^{l} P\{C=k\}\cdot P_{\text{sum}}(l-k),\ 0 \le l < L_{\max}-j \\ p_s^2 - \sum_{a=1}^{L_{\max}-1} P_{c_6}(a),\ l \ge L_{\max}-j \end{cases} \quad (14)$$

Case 7: The relay node 1 transmits one packet but the relay node 2 does not transmit.

The state space: $(i,j) \to (i-1,j+l)$.

$$P_{c_7}(l) = \begin{cases} p_s(1-p_s)\cdot \sum_{k=1}^{l} P\{C=k\}\cdot P_{\text{sum}}(l-k),\ 0 \le l < L_{\max}-j-1 \\ p_s(1-p_s) - \sum_{a=1}^{L_{\max}-1} P_{c_7}(a),\ l \ge L_{\max}-j-1 \end{cases} \quad (15)$$

Case 8: The relay node 2 transmits one packet but the relay node 1 does not transmit.

The state space: $(i,j) \to (i,j-1+l)$.

$$P_{c_8}(l) = \begin{cases} p_s(1-p_s)\cdot \sum_{k=1}^{l} P\{C=k\}\cdot P_{\text{sum}}(l-k),\ 0 \le l < L_{\max}-j \\ p_s(1-p_s) - \sum_{a=1}^{Lmax-1} P_{c_8}(a),\ l \ge L_{\max}-j \end{cases} \quad (16)$$

Case 9: They both do not transmit packets.

The state space: $(i,j) \to (i,j+l)$.

$$P_{c_9}(l) = \begin{cases} (1-p_s)^2\cdot \sum_{k=1}^{l} P\{C=k\}\cdot P_{\text{sum}}(l-k),\ 0 \le l < L_{\max}-j-1 \\ (1-p_s)^2 - \sum_{a=1}^{L_{\max}-1} P_{c_9}(a),\ l \ge L_{\max}-j-1 \end{cases} \quad (17)$$

If the buffer of relay node 2 is more than relay node 1. It also has four cases which are similar to case 6 to case 9.

B.4 Markov Transition Matrix

Let $d_i = \{(i,j)|0 \le j \le L_{\max}\}, 0 \le i \le L_{\max}$. d_i is called level, it can express the buffer length variety of relay node 1. Every j in d_i is called phase, it can express the buffer length variety of relay node 2.

A cellular matrix K_{rn} is used to express the buffer length transition probability of the relay nodes.

$$K_{rn}=\begin{bmatrix} B_0 & C_{01} & C_{02} & C_{03} & \cdots & \cdots \\ A_1 & B_1 & C_{11} & C_{12} & \cdots & \cdots \\ 0 & A_2 & B_2 & C_{21} & \cdots & \cdots \\ \vdots & \ddots & \ddots & \ddots & \cdots & \cdots \\ \vdots & \cdots & \ddots & \cdots & \ddots & \cdots \\ 0 & \cdots & \cdots & 0 & A_{L_{\max}} & B_{L_{\max}} \end{bmatrix} \quad (18)$$

Every element in the cellular matrix K_{rn} is also a matrix. $A_i(1 \le i \le L_{\max})$ is the case that the level decrease. B_0, $B_i(1 \le i \le L_{\max})$ is the case that the level remain unchanged. $C_{0k}(1 \le k \le L_{\max})$, $C_{ik}(1 \le i \le L_{\max}, 1 \le k \le L_{\max})$ is the case that the level increase k.

In the matrix A_i, $Q_1(a) = P_{c_6}(a) + P_{c_7}(a-1)$ is the sum of the probability that the buffer length of relay node 1 decreases and the buffer length of relay node 2 remains unchanged or increases.

$$B_0=\begin{bmatrix} P_{c_1}(0) & 0 & \cdots & \cdots & \cdots & 0 \\ P_{c_4}(0) & P_{c_5}(0) & 0 & \cdots & \cdots & \vdots \\ 0 & P_{c_4}(0) & P_{c_5}(0) & 0 & \cdots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \ddots & 0 \\ 0 & \cdots & \cdots & 0 & P_{c_4}(0) & P_{c_5}(0) \end{bmatrix} \quad (20)$$

In the matrix B_i, $Q_2(b) = P_{c_{12}}(b) + P_{c_{13}}(b-1)$ is the sum of the probability that the buffer length of relay node 1 remains unchanged and the buffer length of relay node 2 remains unchanged or increases. $Q_3(1) = P_{c_{12}}(0) + P_{c_{10}}(1)$ is the sum of the probability that the buffer length of relay node 1 remains unchanged and the buffer length of relay node 2 decreases. $Q_4(1) = P_{c_{13}}(0) + P_{c_8}(1)$ is the sum of the probability that the buffer length of relay node 1 remains unchanged and the buffer length of relay node 2 also remains unchanged.

$$C_{0k}=\begin{bmatrix} P_{c_1}(k) & 0 & \cdots & \cdots & \cdots & 0 \\ P_{c_4}(k) & P_{c_5}(k) & 0 & \cdots & \cdots & \vdots \\ 0 & P_{c_4}(k) & P_{c_5}(k) & 0 & \cdots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \ddots & 0 \\ 0 & \cdots & \cdots & 0 & P_{c_4}(k) & P_{c_5}(k) \end{bmatrix} \quad (22)$$

$$A_i=\begin{bmatrix} P_{c_2}(0) & P_{c_2}(1) & P_{c_2}(2) & \cdots & \cdots & \cdots & \cdots & \cdots & P_{c_2}(L_{\max}) \\ P_{c_6}(0) & Q_1(1) & Q_1(2) & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & P_{c_6}(0) & Q_1(1) & Q_1(2) & \cdots & \cdots & \cdots & \cdots & \cdots \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \cdots \\ \vdots & \ddots & \ddots & 0 & P_{c_{10}}(0) & P_{c_{11}}(0) & 0 & \cdots & \cdots \\ \vdots & \ddots & \ddots & \ddots & 0 & P_{c_{10}}(0) & P_{c_{11}}(0) & 0 & \cdots \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \cdots \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \cdots \\ 0 & \cdots & \cdots & \cdots & \cdots & \cdots & 0 & P_{c_{10}}(0) & P_{c_{11}}(0) \end{bmatrix} \tag{19}$$

$$B_i=\begin{bmatrix} P_{c_3}(0) & P_{c_3}(1) & P_{c_3}(2) & \cdots & \cdots & \cdots & \cdots & \cdots & P_{c_3}(L_{\max}) \\ P_{c_{12}}(0) & Q_2(1) & Q_2(2) & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & P_{c_{12}}(0) & Q_2(1) & Q_2(2) & \cdots & \cdots & \cdots & \cdots & \cdots \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \cdots \\ \vdots & \ddots & \ddots & 0 & Q_3(1) & Q_4(1) & 0 & \cdots & \cdots \\ \vdots & \ddots & \ddots & \ddots & 0 & Q_3(1) & Q_4(1) & 0 & \cdots \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \cdots \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \cdots \\ 0 & \cdots & \cdots & \cdots & \cdots & \cdots & 0 & Q_3(1) & Q_4(1) \end{bmatrix} \tag{21}$$

$$K_n=\begin{bmatrix} P^n_{00} & P^n_{01} & P^n_{02} & \cdots & \cdots & \cdots & P^n_{0L_{\max}-1} & 1-\sum_{l=1}^{L_{\max}-1} P^n_{0l} \\ P^n_{10} & P^n_{11} & P^n_{12} & P^n_{13} & \cdots & \cdots & P^n_{0L_{\max}-2} & 1-\sum_{l=1}^{L_{\max}-2} P^n_{0l} \\ 0 & P^n_{21} & P^n_{22} & P^n_{23} & P^n_{24} & \cdots & P^n_{0L_{\max}-3} & 1-\sum_{l=1}^{L_{\max}-3} P^n_{0l} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \vdots \\ 0 & \cdots & \cdots & \cdots & \cdots & 0 & P^n_{L_{\max}L_{\max}-1} & 1-P^n_{L_{\max}L_{\max}-1} \end{bmatrix} \tag{24}$$

$$C_{ik}=\begin{bmatrix} 0 & \cdots & \cdots & \cdots & \cdots & \cdots & 0 \\ 0 & \cdots & \cdots & \cdots & \cdots & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & 0 & Q_5(k) & Q_6(k) & 0 & \cdots & \vdots \\ \vdots & \vdots & 0 & Q_5(k) & Q_6(k) & 0 & \vdots \\ \vdots & \vdots & \cdots & \ddots & \ddots & \ddots & 0 \\ 0 & \cdots & \cdots & \cdots & 0 & Q_5(k) & Q_6(k) \end{bmatrix} \tag{23}$$

In the matrix C_{ik}, $Q_5(k) = P_{c_{10}}(k+1) + P_{c_{12}}(k)$ is the sum of the probability that the buffer length of relay node 1 increases and the buffer length of relay node 2 decreases. $Q_6(k) = P_{c_{11}}(k+1) + P_{c_{13}}(k)$ is the sum of the probability that the buffer length of relay node 1 increases and the buffer length of relay node 2 remains unchanged.

Assuming the buffer length distribution is $\pi^{(t)} = ({\pi_0}^{(t)}, {\pi_1}^{(t)}, \cdots, {\pi_{L_{\max}}}^{(t)})$ after t frames. In the formula, ${\pi_i}^{(t)} = ({\pi_{i0}}^{(t)}, {\pi_{i1}}^{(t)}, \cdots, {\pi_{iL_{\max}}}^{(t)}), 0 \le i \le L_{\max}$. So $\pi^{(t)} = \pi^{(0)} \cdot K^t_{rn}$, in the formula, ${\pi_0}^{(0)} = (1, 0, 0, \cdots, 0)$.

The average length of relay node 1 is $Queue_1 = i \cdot \sum_{j=0}^{L_{\max}} \pi_{ij}^{(t)}$, and the average length of relay node 2 is $Queue_2 = j \cdot \sum_{i=0}^{L_{\max}} \pi_{ij}^{(t)}$.

The transition probability matrixes of normal node and cooperative node are conventional matrix as (24).

The matrix of cooperative node K_c also can be written in the similar form. At the beginning time, the probability distribution of buffer length is $\varphi^{(0)} = (\varphi^{(0)}(0),\ \varphi^{(0)}(1),\ \cdots) = (1,\ 0,\ 0,\ \cdots,\ 0)$, after t frame times, the probability distribution changes to $\varphi_n^{(t)} = \varphi_n^{(0)} \cdot K_n^t$ and $\varphi_c^{(t)} = \varphi_c^{(0)} \cdot K_c^t$.

The buffer state can be calculated as:

$$\begin{cases} P_{c-\text{idle}} = \varphi_c^{(t)}(0) \\ P_{c-\text{relax}} = \sum_{i=0}^{1/2 \cdot L_{\max}} \varphi_c^{(t)}(i)\ , \\ P_{c-\text{busy}} = 1 - P_{c-\text{relax}} \end{cases} \tag{25}$$

$$\begin{cases} P_{r-\text{relax}} = \sum_{i=0}^{1/2 \cdot L_{\max}} \sum_{j=0}^{1/2 \cdot L_{\max}} \pi_{ij}^{(t)} \\ P_{r-\text{busy}} = 1 - \sum_{i=0}^{1/2 \cdot L_{\max}} \sum_{j=0}^{1/2 \cdot L_{\max}} \pi_{ij}^{(t)}. \end{cases} \tag{26}$$

Setting the initial value of $P_{c-\text{idle}}$, $P_{c-\text{relax}}$, $P_{c-\text{busy}}$, $P_{r-\text{relax}}$ and $P_{r-\text{busy}}$, we can calculate the buffer length distribution by iteration.

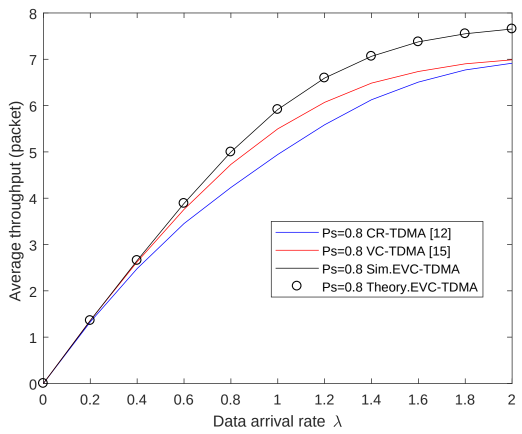

Fig. 6. Average throughput with data arrival rate λ.

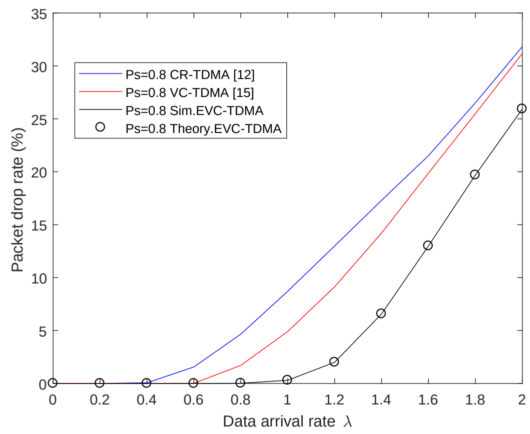

Fig. 7. Packet drop rate with data arrival rate λ.

V. ANALYTICAL AND SIMULATION RESULTS

A. *Simulation in Static Network*

This section presents simulation results to evaluate the performance of EVC-TDMA, firstly we simulate the performance in the static scene. Assumptions are as follows: In the system, there exists 10 nodes and two of them are chosen to be relay nodes, other nodes distributed randomly in the relay nodes' one-hop range. The position of each node is fixed. The maximum buffer length of nodes is 10. The simulation results are obtained by simulating 5000 different network topologies, each simulation time is 100 frame times. The simulation results are shown below.

Fig. 6 shows the average throughput with varying data arrival rate. It's simple to find that the average throughput increases with the rising data arrival rate, and it exists an upper bound value when the data arrival rate continues to increase. The upper bound value is depended on the success rate of the transmission instead of the data arrival rate. VC-TDMA [15] can improve the throughput by dynamic changing the relay node compared with CR-TDMA [12], because in VC-TDMA, less nodes will be idle and waste their occupied time slots resource when the data arrival rate is low. With the increasing data arrival rate, the cooperation efficiency decreases, because the less nodes are idle to help cooperative transmission. While EVC-TDMA will change the cooperative transmission mode, it can remain the cooperation efficiency and achieve a higher throughput when the data arrival rate increases compared with [12], [15].

Fig. 7 shows the average packet drop rate with varying data arrival rate. When the data arrival rate is lower, the queueing system is a stable. It means all the arrival packet can be stored in the buffer and wait time to be sent. With the increasing data arrival rate, the transmission rate of nodes cannot satisfy the communication load requirements, large amount of packets are piled up in the buffer. When new packets arrive, the phenomenon that nodes drop parts of the packets happens. The packet drop rate soars with the increasing data arrival rate. VC-TDMA [15] shows lower packet drop rate when the data arrival rate is close to data transmission rate compared with CR-TDMA [12]. But with the increasing of data arrival rate, the advantage of VC-TDMA gradually reduces because the normal nodes cannot do cooperative transmission in high load network. But in EVC-TDMA, the cooperative transmission is still effective when the data arrival rate is high, so it greatly reduces the packet drop rate even the data arrival rate is more than data transmission rate.

Table 1. The specific parameters of highway scenario.

Parameter	Value
Length of lanes	1000 m
Number of directions	2
Number of lanes	4
Width of lanes	5 m
The speed mean	100 km/h
The speed variance	20 km/h
GPS time interval	0.1 s
Communication range of vehicles	150 m
The slots' number of one frame	100
Number of vehicles	0–320

B. *Simulation in Vehicular Network*

In highway scenario, all the vehicles are moving with a constant speed in a twin two-lane road. Their initial positions are arranged randomly, each vehicle moves with a constant speed V_{ID} follow a normal distribution. The transmission range of each vehicle is r. To ensure the number of vehicles is a constant in simulation scenario, when a vehicle moves to the terminal of the road, it will move into the road from opposite terminal [3]. In this case, if the distance of a vehicle to the road terminal $d < r$, this vehicle can communicate with the vehicles on the opposite side in the range of $r - d$. The specific parameters of highway scenario are given in Table 1.

The simulation result of network throughput is shown in Fig. 8. When the vehicles' number is few (the number of vehicles is from 0 to 150), the merging collision is rare. So the throughput is a linear ascent with the increasing of vehicles' number. With the increasing number of vehicles (the number of vehicles is from 150 to 200), the probability of merging collisions also increases, so the increasing tendency of normalized

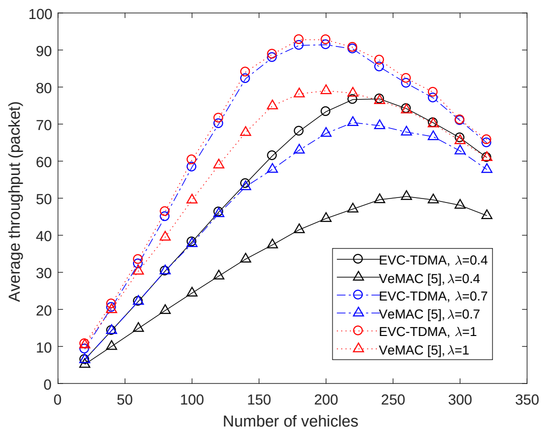

Fig. 8. Throughput in the vehicular network.

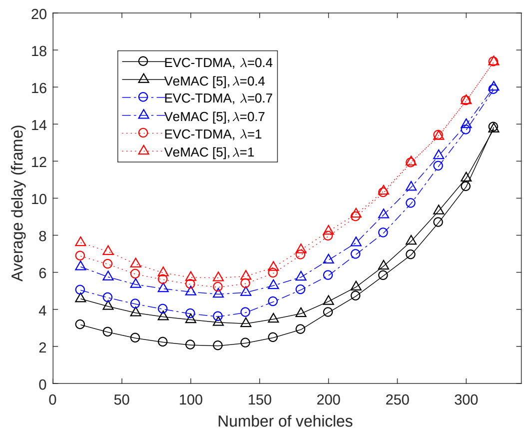

Fig. 10. End-to-end delay in the vehicular network.

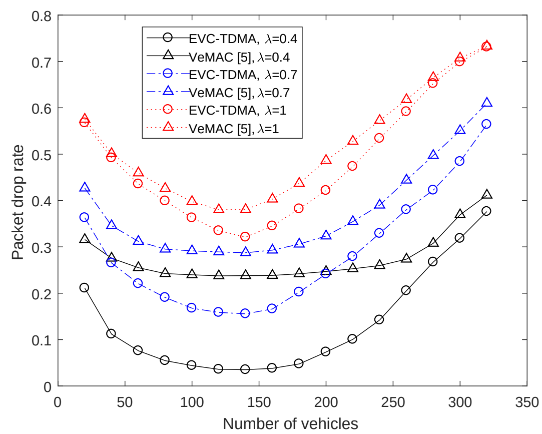

Fig. 9. Packet drop rate in the vehicular network.

throughput slows down. When the vehicles' number increases further (the number of vehicles is more than 200), the serious merging collisions lead to the decrease of occupied slots' number, which lead the throughput begin decline. Compared the EVC-TDMA with VeMAC [5] in the same traffic load case, the performance of EVC-TDMA is better than VeMAC. Because in VeMAC, one relay packet will not be sent immediately when the relay node's buffer is not null, but in EVC-TDMA, it may be sent immediately by the cooperative transmission.

Fig. 9 shows the packet drop rate in the vehicular network. At first, the packet drop rate decreases with the increasing number of vehicles. Because when the number of vehicles is few, there exist several vehicles out of other vehicles' communication range, so the packets cannot be sent which lead to the packet loss. With the increasing number of vehicles, the communication between vehicles becomes stable and diversification, the packet can be sent successfully between each vehicle, so the loss of packet becomes decreasing. When the number of vehicles is moderate (from 100 to 200), the link in the network is stable and the packet drop rate can keep in a low level. Considering a high density network, the merging collision becomes dramatic, so large amounts of packets cannot be sent successfully and will be loss. It can be seen that the cooperative transmission in EVC-TDMA can help vehicles communication. Obviously, the store buffer of nodes is limited, the faster nodes send packets, the later the buffer will be full and the later packet loss happen. So the performance of packet drop rate in EVC-TDMA is better than VeMAC [5].

Fig. 10 presents the simulation result of end-to-end delay. Similar as the analysis in Fig. 9, the delay decreases with the increasing number of vehicles at first because too few vehicles cannot build stable network and the packets may be stored in the buffer a few frames before being sent. While the increasing number of vehicles also lead to lack of slots resources so that the end-to-end delay becomes longer when the number of vehicles is larger. In EVC-TDMA, packets can be sent immediately by cooperative transmission, which means the packets do not need to store in the relay node's buffer and wait to be sent. So the end-to-end delay decreases in EVC-TDMA compared with VeMAC [5].

VI. CONCLUSION

This paper presents an enhanced TDMA-based protocol for vehicular network (EVC-TDMA), in this protocol, each THS has two relay nodes which are chose according to the relative speed between vehicles and other nodes will change cooperative transmission mode according to both the buffer lengths of relay nodes and themselves. In order to avoid head-of-buffer blocking, the node will drop the packet at the head of buffer when the buffer is full. The simulation results show that the network performance of EVC-TDMA is excellent when the speeds of the vehicles are relatively stable. In the future, we may study the effect of the road side units (RSUs) on the selection of the relay nodes to optimize the relay nodes election.

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