Motion Prediction Based TDMA Protocol in VANETs

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Abstract: In Vehicular Ad Hoc Networks (VANETs), the high mobility of vehicle nodes makes the network topology change frequently, reducing the forwarding efficiency of MAC protocol. In the existing enhanced TDMA-based MAC protocol, the farthest node in the current transmission range is chosen as the forwarding node to accelerate the multi-hop transmission. However, we use probabilistic model to show that there potentially exist better forwarding nodes, which could effectively improve transmission efficiency. Therefore, we propose a motion-prediction based TDMA protocol, which predicts the network topology in the next frame to select the better forwarding node. The test results of highway and urban scenarios show that the motion-prediction based TDMA protocol effectively reduces the number of hops in multi-hop transmission and decreases the broadcast delay by 50% to cover the whole network.

Keywords: VANET; MAC; TDMA; broadcast

1. Introduction

With the rapid development of Intelligent Transportation Systems (ITSs), a variety of applications such as route identification, cooperative collision avoidance and infotainment propose challenging requirements of low latency [1]. Supported by the large-scale server production clusters [2], Vehicular Ad Hoc Networks (VANETs) share speed, direction, position and other information in data centers for fast processing by utilizing wireless communication technologies to enable effective transmission [3].

However, the unpleasant factors such as the high mobility of vehicle nodes, frequent change of network topology and instability of cluster members significantly reduce the transmission efficiency. In the highly-mobile VANETs, the successful transmission rate of data packets is usually less than 50%, and thus the accessing delay becomes very large and unpredictable [4]. Meanwhile, the vehicle nodes are commonly distributed in clusters since the vehicle movement is constrained by the road topology. The simple broadcast mechanism brings about serious channel congestion. Although the delay-tolerant technology can improve the successful delivery rate of multi-hop transmission [5,6], it is not suitable for the safety applications, which requires broadcasting warning messages to rapidly inform drivers about a dangerous situation such as an accident. Since the vehicle nodes share a common wireless channel by using the same radio frequencies, how to coordinate the transmission of vehicle nodes to avoid the packet collision becomes the key issue to provide effective transmission in the highly dynamic VANETs [7,8].

Medium Access Control (MAC) schemes are designed to share the medium between the different nodes efficiently and fairly. Existing proposals have developed CSMA (Carrier Sense Multiple Access)- and TDMA (Time Division Multiple Access)-based MAC protocols. The CSMA-based protocols adopt the collision avoidance and backoff mechanism to reduce collisions and thus improve the network throughput. The CSMA/CA mechanism does not require any predefined scheduling. Each node will compete for channel access when it needs to transmit, with the result that it is not able to provide...
guarantee of successful transmission. For real-time applications, such as safety applications, this may cause packet loss and large accessing delay [9–11]. On the contrary, TDMA-based MAC protocols assign a single time slot for each node to avoid the channel conflict and provide the bounded-delay of transmission [12]. Compared with CSMA-based ones, TDMA-based protocols are more suitable for the real-time applications [13].

However, when TDMA-based protocols are used in the multi-hop transmission, they all essentially utilize the current network topology to choose the forwarding node in multi-hop transmission. To obtain high transmission efficiency, most existing enhanced TDMA-based protocols select the furthest node in the transmission range as the forwarding node, which inevitably introduces a sampling bias against the rapidly changing network topology. Since the TDMA-based protocols pre-allocate the time slot only according to the current network topology, they are not sensitive for the vehicle node movements and topology changes, making it difficult to ensure the fast and reliable transmission. The key reason for these current approaches is that previous researchers have been severely constrained by the capability of GPS infrastructures to collect and consolidate real-time vehicle data in a timely and low-cost fashion.

Now, the rapid expansion of GPS navigation and electronic map in recent years has offered new research opportunities to exploit real-time data to predict the network topology. In particular, the real-time movement data shared in VANET networks can be consolidated with data from the electronic map to predict the mobility trajectory and thus select better forwarding path. To deepen our understanding on how these data can be used for the study of vehicle mobility, we propose a motion-prediction based TDMA protocol called MPTDMA, which improves the transmission efficiency by uniquely analyzing and predicting the real-time movement. The main work of this paper contains three parts: (1) model and analysis of the reasons for the transmission efficiency degradation; (2) method of motion prediction; and (3) obtain the solution of channel collision in the same time slot. Considering the dynamic network topology due to the change of vehicle movement information such as the direction and speed, MPTDMA gets the optimal forwarding node in the next frame based on the motion prediction to effectively avoid time slot collision and reduce transmission delay. The contributions of our proposed motion-prediction based TDMA protocol are mainly concentrated in three points.

- First, we exploit the impact of vehicle mobility on transmission efficiency in highly dynamic scenarios and demonstrate experimentally and theoretically why the transmission efficiency is degraded when the TDMA-based MAC protocols choose the forwarding node only according to the current network topology.
- Secondly, the control messages for prediction in the control time slot are composed by the set of vehicle movement information, such as vehicle ID, longitude and latitude coordinates, moving speed, moving direction and service time slot number. The motion prediction method predicts the network topology and chooses the forwarding node in the next frame according to the moving information.
- Third, to avoid channel conflict, we design a collision resolution strategy based on the rate change of neighbor nodes to reduce the reallocation delay after collision occurs. The simulation results demonstrate that MPTDMA can broadly improve the transmission efficiency and effectively reduce the transmission delay and count.

The rest of the paper is organized as follows. Section 2 compares the related works. Section 3 analyzes the impact of vehicle speed on the performance of TDMA-based protocols. Section 4 introduces the protocol design and the implementation detail of our design. Section 5 evaluates the protocol performances in the highways and urban scenarios. Section 6 discusses the main features of TDMA-based protocols. Section 7 concludes this paper.
2. Related Work

Generally, VANET MAC protocols fall into one of two broad categories: CSMA-based and TDMA-based. The CSMA-based protocols do not require any predefined scheduling. Each node will compete for channel access when it needs to transmit. IEEE 802.11p is the standard MAC protocol in VANETs [14], employing both Enhanced Distributed Channel Access (EDCA) and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanisms to access the shared wireless channel. Self-organizing time division multiple access (STDMA) outperforms CSMA of 802.11p. However, the probability of collision in both IEEE 802.11p and STDMA will inevitably increase when the network is becoming saturated, leading to higher channel accessing delay. ReC [15] uses geographical information to reduce the packet collision and transmission delay in the multi-hop transmission. In ReC, the selected forwarding node is the nearest vehicle to the centroid of neighboring vehicles that have not received the packet. Once receiving the packet, the selected forwarding node retransmits the packet immediately to reduce the packet collision and transmission delay. ReC significantly suppresses unnecessary retransmission, but each node is assigned forwarding priority based on the local knowledge, potentially leading to packet loss or additional retransmissions due to frequent temporary disconnection in VANETs. PIVCA [16] utilizes the Hello messages to get the real-time position information of nearby vehicles and prioritizes farther vehicles in forwarding packets by assigning the farther vehicle with smaller contention window (CW). This novel Intervehicle communication (IVC) architecture is able to support a wide set of application classes [17] and reduces redundant transmissions, but it is not easy to be widely deployed due to the privileged architecture.

Essentially, although providing a fair channel-accessing, CSMA-based MAC protocols do not ensure a reliable broadcast mechanism with bounded communication delay. Furthermore, to reduce the channel overhead, the RTS/CTS channel reservation mechanism is not used in typical CSMA-based MAC protocols (i.e., IEEE 802.11p). Thus, the channel conflict inevitably happens when two nodes send data simultaneously, degrading the transmission reliability [18] and the performance of delay-sensitive applications [19].

Compared with the CSMA-based MAC protocols, the TDMA-based MAC protocols divide the time into different frames and each frame is divided into several time slots which are assigned to each node. By providing equal access to the channel for all vehicle nodes, TDMA-based MAC protocols ensure the high reliability of communications and deterministic access time even with a high traffic load.

ADHOC MAC [20,21] is a TDMA-based MAC protocol without any centralized coordination. ADHOC MAC shares the status of time slots used by the other vehicles within the two-hop neighborhood and chooses the free time slot to transmit its data. Thus, ADHOC MAC avoids the packet collisions, while it does not need any coordination by cluster head. RV-MAC [20] designs a region marking scheme and a collision avoidance scheme to, respectively, address the hidden-terminal under the multi-hop network topology and handle the collisions due to channel competition and the mobility of vehicles. RV-MAC effectively improves throughput and reduces network delay. LMA-CT [21] mitigates merge collisions through disjoint slot assignment and channel distribution. LMA-CT resolves hidden terminal problem and ensures bounded delay. However, RV-MAC and LMA-CT, due to the lack of network topology and node mobility prediction, potentially suffer from collisions in the congested urban traffic environment. In addition, ADHOC MAC is a single channel protocol, not suitable for multiple channels.

As a multi-channel MAC protocol, VeMAC [22] exchanges the status information of time slots with its one-hop neighbors in the control channel and determines its time slot in the service channel, achieving contention-free accessing channel. To avoid merge collisions in ADHOC MAC due to node mobility, VeMAC assigns disjoint time slots to vehicles moving in opposite directions and road side units (RSUs). To support not only one-hop but also multi-hop broadcast services on the control channel, the improved VeMAC [23] uses implicit acknowledgments to eliminate the hidden terminal problem. In addition, the authors of VeMAC analyzed the queueing and service delays for both periodic and event-driven safety messages in vehicular networks [24]. VeMAC successfully reduces the rate of
transmission collisions including access collisions and merging collisions, resulting in high throughput on the control channel. However, all packet errors are considered as transmission collisions, leading to unnecessary release of time slots on the control channel especially under the asymmetric wireless channels. UTSP [25] uses the road side units to collect the information including the channel state, moving speed, and access category of the vehicles within its communication range and then assigns the time slots to vehicles based on a weight-factor-based scheduler. The weight factor jointly considers the channel quality, the speed of vehicles and the different access categories to, respectively, maximize the network throughput, ensure fairness among vehicles and distinguish the access priorities. However, UTSP is designed only for supporting the throughput-sensitive applications [26]; it is not suitable for the mobility scenarios that mainly oriented to road safety issues.

In [27], the authors proposed a delay-aware control policy for resource allocation in Long Term Evolution (LTE) vehicular network by leveraging a cross-layer approach. The method formulates the throughput and latency in the dynamic communication system as a stochastic network optimization problem and uses the improved branch and bound algorithm to search for the optimal solution. It effectively reduces latency and maximizes system throughput simultaneously, however, it does not consider the change of network topology over time.

In contrast with the existing CSMA- or TDMA-based MAC protocols, our solution MPTDMA tackles the channel accessing issue through a different perspective: we assign the time slots based on the prediction of vehicle movement. The key difference is that existing solutions are based on the current network topology, while our solution introduces motion-prediction based on node speed and direction into the channel reservation procedure to address the dynamic scenarios with high speed vehicles, where existing solutions become ineffective.

3. Problem Analysis

In VANETs, the high-speed movement of the vehicle nodes frequently changes the network topology. In this section, we first take the highway scene as an example to analyze the impact of vehicle movement. Then, we demonstrate theoretically why the transmission efficiency is degraded when the forwarding node is determined only according to the current network topology.

3.1. Impact of Vehicle Movement

We use a typical example to show the impact of vehicle movement on transmission efficiency. The network scenario is a segment of a two-way vehicle traffic highway. A vehicle can communicate with all vehicles within its communication range. Each vehicle moves with a constant speed drawn from a uniform distribution between 80 and 120 km/h. The transmission range of each vehicle is 500 m, and there are 100 vehicles in range of the two-hop transmission. Each node uses the TDMA strategy to divide channel with the time slot length and frame length as 0.01 and 1 s, respectively. Then, after one frame time, the distance each vehicle can move is from 22 to 33 m.

We depict the bi-directional highway scene in Figure 1. The sender S transmits data to the other nodes right at time $t_0$. A, B and C in the transmission range of S are three potential forwarding nodes. As shown in Figure 1a, since B is the furthest node from S according to the network topology at time $t_0$, S selects B as the next-hop forwarding node to obtain larger coverage. However, as shown in Figure 1b, when B starts to forward data at time $t_1$, its coverage range becomes very limited because B moves quickly to the vicinity of S. While at this time, the fast backward movement of node A makes it furthest from S. If A is selected as the forwarding node, A can forward data to not only D, but also to the furthest node E.
3.2. Model Analysis

In the following, we use the probability model to further analyze the probability of existence of a better forwarding node under different vehicle speed, compared with the traditional method of selecting the furthest node as the forwarding node.

Since the transmission range \( R \) is much larger than the road width, we simplify the highway scene as the linear topology shown in Figure 2. We suppose that \( N \) nodes are distributed uniformly in the transmission range \( R \) of node \( S \), which broadcasts the message backward (i.e., in the right direction) to all the following vehicles along the highway. In the transmission range of \( S \), suppose that \( f \) is currently the farthest node to \( S \) with distance to \( S \) as \( R \). Obviously, \( f \) is the best forwarding node according to the current topology.

![Figure 2. Network topology.](image)

In the following, we analyze the probability of existence of a potentially better forwarding node than \( f \). The distance between the other node \( i \) and \( f \) can be expressed as \( d_i \),

\[
d_i = \frac{2R \times i}{N},
\]

where \( 1 < i < N - 1 \) is the vehicle number, which increases with the distance to node \( f \).

Assume the vehicle speed \( v \) follows a normal distribution \([23]\) as

\[
f(v) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{(v-\mu)^2}{2\sigma^2}},
\]

where \( \mu \) and \( \sigma \) are the average speed and the speed variation range, respectively.

We assume that \( S \) sends the message in the right direction and analyze the following four cases according to the movement direction of the source node \( S \), forwarding node \( f \) and potentially better forwarding node \( i \).

(1) Assume that \( i \) and \( f \) are moving in the left direction (opposite to the direction of message transmission). The probability of this case is 0.25. We use slot to denote the length of time slot. After a transmission cycle (i.e., \( N \times \text{slot} \)), the probability \( p_i \) that node \( i \) becomes a better forwarding node is calculated as

![Figure 1. Bi-directional highway scene.](image)
\[ p_i = 0.25 \times p \{ v_f - v_i > \frac{d_i}{N \times \text{slot}} \} \]
\[ = 0.25 \times \left( 1 - p \{ \frac{v_f - v_i}{\sqrt{2}\sigma} < \frac{d_i}{N \times \text{slot} \times \sqrt{2}\sigma} \} \right) \]
\[ = 0.25 - 0.25 \times \phi \left( \frac{d_i}{N \times \text{slot} \times \sqrt{2}\sigma} \right). \quad (3) \]

Then, we calculate the probability \( P' \) that at least one node is better than node \( f \) as

\[ P' = 1 - (1 - p_1)(1 - p_2) \cdots (1 - p_{N-1}) \]
\[ = 1 - \prod_{i=1}^{N-1} \left( 0.75 + 0.25 \times \phi \left( \frac{2iR}{N^2 \times \text{slot} \times \sqrt{2}\sigma} \right) \right). \quad (4) \]

(2): Assume that \( i \) and forwarding node \( f \) are moving in the right direction (in the same direction of message transmission). The probability of this case is also 0.25. Similarly, we calculate the probability \( P'' \) that at least one node is better than \( f \) after a transmission cycle as

\[ P'' = 1 - \prod_{i=1}^{N-1} \left( 0.75 + 0.25 \times \phi \left( \frac{2iR}{N^2 \times \text{slot} \times \sqrt{2}\sigma} \right) \right). \quad (5) \]

(3): Assume node \( i \) and \( f \) are moving toward each other. The probability of this case is 0.25. The probability \( P''' \) that there is at least one node which is better than \( f \) after one transmission cycle is

\[ P''' = 1 - \prod_{i=1}^{N-1} \left( 0.75 + 0.25 \times \phi \left( \frac{2iR - N\mu}{N^2 \times \text{slot} \times \sqrt{2}\sigma} \right) \right). \quad (6) \]

(4): Assume node \( i \) and \( f \) are moving apart. It is obvious that node \( i \) cannot be a better forwarding node than \( f \).

Based on the above analysis, we get the probability of existence of a potentially better forwarding node than \( f \) as

\[ P = P' + P'' + P''' \]
\[ = 3 - 2 \times \prod_{i=1}^{N-1} \left( 0.75 + 0.25 \times \phi \left( \frac{2iR}{N^2 \times \text{slot} \times \sqrt{2}\sigma} \right) \right) \]
\[ - \prod_{i=1}^{N-1} \left( 0.75 + 0.25 \times \phi \left( \frac{2iR - N\mu}{N^2 \times \text{slot} \times \sqrt{2}\sigma} \right) \right). \quad (7) \]

Next, we use the numerical analysis to show the impact of vehicle movement on \( P \). We assume all vehicle nodes are evenly distributed and move in one random direction. Table 1 gives the default values of parameters in the numerical analysis.

| Parameter | Value      |
|-----------|------------|
| \( \mu \) | 100 km/h   |
| \( \sigma \) | 15 km/h    |
| \( N \) | 60         |
| \( R \) | 300 m      |
| \( \text{slot} \) | 0.01 s     |

In Figure 3a, with the increasing fluctuation range of vehicle speed, the probability of the existence of better forwarding nodes is increasing under different vehicle speeds. Since the relative movement
among vehicles becomes more frequent, more vehicles could become the better forwarding nodes. When the speed fluctuation range is 35 km/h, $P$ increases to as large as 0.8. In Figure 3b, the vehicle speed fluctuation range is fixed as 15 km/h. We find that the increasing of vehicle speed also improves the probability of the existence of better forwarding nodes. The reason is that, in some scenarios, especially when the potential and original forwarding node move towards each other, the increasing of vehicle speed leads to a larger value of $P$.

![Figure 3a: Speed fluctuation range](image)

![Figure 3b: Average speed](image)

**Figure 3.** The probability of existence of a better forwarding node.

Our observation of this analysis leads us to conclude that, if each node chooses the next-hop forwarding node only according to the current topology and does not consider the movement characteristics of vehicle nodes such as the direction and speed, it becomes very difficult to ensure the selected forwarding node is still the optimal forwarding node in the next frame. This conclusion motivated us to investigate a novel approach choosing a better forwarding node based on the prediction of network topology.

4. Motion-Prediction Based TDMA Protocol

This section presents motion-prediction based TDMA (MPTDMA), which selects the forwarding node based on the vehicle movement. Specifically, we first describe the frame structure to share the vehicle movement information in MPTDMA protocol. Then, we present the motion-prediction method based on the direction and speed. Finally, a slot-reallocation strategy is proposed to quickly resolve the time slot collision caused by rapid movement of vehicles.

4.1. Frame Structure

In the MPTDMA protocol, time is partitioned to frames consisting of a constant number of time slots. Each frame is divided into control and service time slots. Every vehicle is equipped with a global positioning system (GPS) receiver and can accurately determine its position and moving direction. Each vehicle announces its geographical information in the control time slot and acquires exactly one time slot in the service time slot. After a node transmits data in its service time slot, it announces the release of its occupied service slot in its control time slot. The number of control and service slots is the maximum number $N$ of vehicles in the range of one-hop transmission range.

In a control time slot, the vehicle broadcasts its control message, which includes its ID, longitude coordinate $x$, latitude coordinate $y$, moving speed $v$, moving direction $\phi$ and service time slot number. Specifically, the longitude coordinate $x$ and latitude coordinate $y$ are obtained from the GPS position, and the moving direction $\phi$ is defined as the angle from the X-axis of GPS coordinate system. Moreover, the control message uses 1 bit to identify whether the vehicle is a forwarding node or not. Once receiving the control messages from the neighbor vehicles, each vehicle updates its neighbor list and obtains the real-time moving information of its neighbors.
4.2. Motion Prediction

The MPTDMA protocol predicts the distance $d_{FR}$ between the neighbor node $R$ and the current forwarding node $F$ according to their moving information. The prediction method is described in Figure 4.

At time $T_0$, the positions of the nodes $F$ and $R$ are $(x^0_F, y^0_F)$ and $(x^0_R, y^0_R)$, respectively. Assuming the frame time is $T_p$, then the locations of $F$ and $R$ at $T_0 + T_p$ are

$$
(x^p_F, y^p_F) = (x^0_F + v^0_F \times T_p \times \cos \phi^0_F, y^0_F + v^0_F \times T_p \times \sin \phi^0_F), \tag{8}
$$

$$
(x^p_R, y^p_R) = (x^0_R + v^0_R \times T_p \times \cos \phi^0_R, y^0_R + v^0_R \times T_p \times \sin \phi^0_R). \tag{9}
$$

The distance $d_{FR}$ between $F$ and $R$ at the time of $T_0 + T_p$ is calculated as

$$
d_{FR} = \sqrt{(x^p_F - x^p_R)^2 + (y^p_F - y^p_R)^2}. \tag{10}
$$

After each node receives the control message of its neighbor nodes, it calculates the distance $d_{FR}$ between the current forwarding node $F$ and all other nodes (including the neighbor nodes and itself). Finally, the current node selects the node with the largest $d_{FR}$ as the forwarding node in the next frame. If the current node becomes the forwarding node in the next frame, it forwards the received data message directly.

4.3. Collision Resolution

In the case of rapid movement of vehicle nodes, different vehicle fleets continue to merge and disperse. Since the time slot is assigned by each fleet, the vehicles belonging to different fleets may occupy the same time slot, leading to channel conflict. To solve this problem, traditional methods adopt random backoff to reallocate time slots. However, this method results in large reallocation latency, and thus cannot provide the upper bound guarantee of delay. Therefore, this section proposes a collision resolution strategy based on the changing rate of neighbor nodes to reduce the reallocation latency after collision occurs.

The main idea of collision resolution is shown in Figure 5. At the initial time $T_0$, node $x$ and $y$ occupy the third time slot in their respective fleets. After the elapse of time $t$ ($t < T_p$, $T_p$ is a frame time), $x$ moves quickly into the transmission range of $y$. At this time, $x$ and $y$ have not updated their neighbor nodes. In the third time slot, both $x$ and $y$ are transmitting their messages simultaneously, resulting in channel collision. After collision, both nodes randomly select the empty time slots to send data in the next frame. However, if the nodes still select the same time slot, the collision will occur again, resulting in large accessing delay. To solve this problem, we propose a rapid conflict resolution
according to the changing rate of neighbor nodes. We use $r$ to denote the changing rate of neighbor node as

$$
r = \frac{|ns_{T_0} \cup ns_{T_0+t}| - |ns_{T_0} \cap ns_{T_0+t}|}{|ns_{T_0} \cup ns_{T_0+t}|},
$$

where $ns_{T_0}$ and $ns_{T_0+t}$ are the neighbor node sets at $T_0$ and $T_0 + t$, respectively.

When a node detects a channel conflict, it will determine whether the channel collision is caused by itself or not. The judging method is just to compare the neighbor node in two frames before and after the collision. For a given node, if its changing rate $r$ of neighbor nodes is greater than 50%, then it is implied that the node is actively moving into a new fleet and causing the channel collision; otherwise, the node’s transmission is passively collided. When a channel collision occurs, the active node releases the current time slot and selects an empty time slot in the next frame to retransmit its data, while the passive node still uses the same time slot in the next frame.

![Figure 5. Collision resolution.](image)

We use Figure 5 to illustrate our proposed conflict resolution method. The changing rates of the neighbor nodes of $x$ and $y$ are 100% and 33%, respectively. Obviously, $x$ should take the active avoidance and select another empty time slot to retransmit data, while $y$ is the passive node and its next time slot remains unchanged. In this way, $x$ and $y$ will select different time slots in the next frame, avoiding collision again. For the high-speed vehicles, our method resolves the channel collision after only one frame, effectively reducing the accessing delay caused by frequent channel collisions.

5. Performance Evaluation

In this section, we evaluate the performances of ADHOC MAC, VeMAC and MPTDMA in highway and urban scenes in NS2 simulation. The performance metrics include the transmission delay and transmission count. The transmission delay is defined as the dissemination delay of the message from the source vehicle to the last receiver. This metric is a crucial factor in time-critical safety applications of VANETs. The faster the message propagates, the more efficient the corresponding protocol in terms of satisfying the urgent delay requirement of emergency application.

The message dissemination progress can be measured by the transmission count, which includes both the success and failure transmission. The larger transmission count implies the high channel conflict probability and small coverage range per transmission. Only by obtaining both low channel conflict probability and large coverage range can fast message dissemination progress be achieved.

5.1. Highway Scene

The first scenario is a segment of a two-way vehicle traffic highway. The highway topology is shown in Figure 1. All vehicles are evenly distributed on a bi-directional two-lane highway with road length of 4800 m. The default average speed of vehicle is 100 km/h and the range of speed fluctuation is 70–130 km/h. The number of vehicle nodes in the two-hop transmission range is 120. The data message is transmitted from the leftmost vehicle node to the rightmost one of the road. The transmission range of each vehicle is 300 m and the default number of vehicle nodes in transmission range is 60. The length of time slot is 0.01 s, and the data transmission rate of wireless channel is 1 Mbps.
5.1.1. Basic Performance

Figure 6 shows the transmission delay of vehicle nodes with MPTDMA, VeMAC and ADHOC MAC protocols. MPTDMA achieves the lowest transmission delay compared to the other two protocols. The reason is that MPTDMA predicts the network topology after one frame according to the current vehicle movement direction, speed and geographical location information and selects the optimal forwarding node in the next frame, which effectively reduces the number of forwarding. Specifically, the transmission delay of MPTDMA is about 20% lower than that of VeMAC protocol. VeMAC protocol selects the farthest node to forward message according to the information of neighbor nodes, and it uses multi-channel to coordinate the transmission time slot, which effectively avoids the channel conflict and reduces delay. ADHOC MAC protocol uses a random method to select forwarding nodes, which is not able to optimize the transmission route according to the real-time network topology, resulting in the increase of forwarding hops and the largest transmission delay.

![Figure 6. Transmission delay.](image)

5.1.2. Impact of Vehicle Density, Vehicle Speed and Transmission Range

Figure 7a,b shows the end-to-end transmission delay, the transmission counts and the number of collisions from the leftmost node to the rightmost node with varying vehicle density, respectively. With the increasing vehicle density, the number of nodes in two hops increases, leading to larger frame length. Thus, the transmission delay of ADHOC MAC, VeMAC and MPTDMA are increased. In contrast, all three protocols have higher probability to choose better nodes to forward the data under larger vehicle density, resulting in lower transmission counts and the number of collisions. Compared with the other two protocols, ADHOC MAC protocol has the worst performance due to randomly selecting forwarding nodes. Unlike VeMAC, which selects the farthest node at the current frame as the forwarding node for the next frame, MPTDMA selects the optimal forwarding node in the next frame according to the motion direction and velocity of the node. Therefore, MPTDMA achieves the minimum transmission delay, transmission counts and number of collisions. For example, in the scenario with vehicle density of 200 vel/km, MPTDMA reduces transmission delay and the number of collisions by 67% and 37% over VeMAC and 77% and 74% over ADHOC MAC, respectively. Moreover, since the probability of having a better forwarding node becomes larger with the increase of vehicle density, the higher the performance improvement of MPTDMA.
Figure 7. The Impact of vehicle density, speed and transmission range. ADHOC-CC, VeMAC-CC and MPTDMA-CC stand for the number of collisions in ADHOC, VeMAC and MPTDMA, respectively. ADHOC-TC, VeMAC-TC and MPTDMA-TC stand for the transmission counts in ADHOC, VeMAC and MPTDMA, respectively.

Figure 7c,d shows the transmission delay, the transmission counts and the number of collisions for all three protocols with varying vehicle speed, respectively. When the vehicle speed increases, the data can be carried and forwarded to a farther vehicle, expanding the transmission range of each hop. As a result, the transmission delay, transmission count and the number of collisions in three protocols are reduced. Because of the advantages of motion prediction for network topology in the next frame, MPTDMA outperforms the other two protocols in terms of both transmission delay and transmission count. ADHOC MAC has the worst performance due to its inability to predict the change of network topology according to the node motion information and select the appropriate forwarding node to avoid collisions. For example, in the scenario with an average speed of 130km/h, MPTDMA reduces transmission delay and transmission count by 15% and 39% over VeMAC and 11% and 36% over ADHOC MAC, respectively.

Figure 7e,f shows the transmission delay, the transmission counts and the number of collisions for all three protocols with varying transmission range, respectively. It is clear that MPTDMA achieves lower transmission delay, transmission count and the number of collisions than both VeMAC and ADHOC MAC for all the transmission ranges. For example, at a transmission range of 300 m, MPTDMA reduces transmission delay and transmission count by 14% and 46% over VeMAC and 5% and 43% over ADHOC MAC, respectively. Note that, for a higher transmission range, the transmission delay may increase or decrease because of the randomness of node speed and direction changes increases. Since MPTDMA predicts the changes of network topology based on node mobility, the transmission delay of MPTDMA is relatively stable compared to other protocols. When the transmission range increases from 200 to 400 m, the maximum transmission delay difference of MPTDMA is about 2 s.
5.2. Urban Scene

The second scenario is an urban grid layout covering an area of 1000 m × 1000 m. The horizontal and vertical streets have the same dimensions; they are evenly spaced resulting in four identical square city blocks. The vehicle nodes are evenly distributed on the road with two lanes. The vehicle speed is set as a random value between 40 and 60 km/h. The vehicle nodes in the grid center is the message source. The transmission range of each hop is 100 m, and the number of vehicle nodes in the two-hop transmission range is 120. The time slot length is set as 0.01 s. The data transmission rate of wireless channel is 1 Mbps.

Figure 8 shows the full-network coverage delay that messages spread from the center to the other nodes in the urban scene for ADHOC MAC, VeMAC and MPTDMA protocols. In Figure 8, the lighter is the color, the larger is the delay. The transmission delays from the center to the four vertices of the three protocols are the values indicated by the arrows in Figure 8a–c, respectively. Similar to the highway scenario, MPTDMA protocol provides the lowest transmission delay. Specifically, the average transmission delays of ADHOC MAC, VeMAC and MPTDMA protocols are 11.3, 8 and 6.7 s, respectively. Compared with ADHOC MAC and VeMAC, the full-network coverage latency in MPTDMA is reduced by about 15% and 40%, respectively. Since vehicles frequently change their moving directions in the urban scenario, ADHOC MAC and VeMAC experience more node collisions, leading to increased delay. These results show that MPTDMA is able to select the better forwarding nodes at the road intersection according to the moving direction and speed of vehicle nodes in the urban grid scene. Therefore, MPTDMA effectively improves the transmission performance.

![Figure 8. Full-network coverage delay.](image)

6. Discussion

In terms of transmission over the control channel, the main similarities and differences of ADHOC MAC, VeMAC and MPTDMA protocols can be summarized as follows. Three protocols are TDMA-based MAC protocol. They effectively reduce transmission delay by mitigating access collisions and merging collisions due to channel competition, node mobility and the hidden terminal problem. In addition, they all require each node to broadcast the time slots used by all neighboring nodes within one hop. However, instead of using the current network topology, MPTDMA significantly outperforms ADHOC MAC and VeMAC protocols by predicting network topology in the next frame. Specifically, to reduce the rate of access collision, a new motion prediction method uses the vehicle movement information, such as moving speed, moving direction and longitude and latitude coordinates, to predict the changes of network topology and choose the optimal forwarding node in the next frame. Moreover, to mitigate channel conflict, a new collision resolution method uses the rate change of neighbor nodes to decide which node releases the current time slot. These advantages of MPTDMA effectively ensure the bounded delay and significantly improve transmission efficiency.

Since MPTDMA assumes the vehicle speed \( v \) follows a normal distribution, the prediction results in other scenarios with different rate distributions such as beta distribution will be different from the actual value, so the prediction model should be adaptively adjusted according to the node mobility.
in future work. In addition, we only validated the effectiveness of MPTDMA prediction in the linear topology scenarios. In future work, we will make further prediction and analysis for complex topology in real environment.

7. Conclusions

In this paper, a MAC protocol MPTDMA based on motion-prediction is proposed to choose the forwarding node in the next time frame according to the moving direction, speed and geographical location of the vehicle nodes. We also propose a collision resolution strategy based on the changing rate of the number of neighbor nodes to reduce the accessing delay. The experimental results show that the MPTDMA protocol effectively reduces the multi-hop transmission delay and transmission count, thus enlarging the effective transmission range and improving the transmission efficiency. In future research, we will further evaluate and analyze the protocol performance in the real network scene and study how to utilize the motion-prediction method to improve the CSMA-based MAC protocol in VANETs.

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