# An Interference-Free Graph Based TDMA Scheduling Protocol for Vehicular Ad-Hoc Networks

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***Abstract*—Vehicular ad-hoc networks (VANETs), as an important component of intelligent transportation systems (ITS), have been attracting more and more research interests for their various promising applications. Although various MAC protocols have been proposed, efficient medium access remains a significant challenge in VANETs, especially in improving the network throughput in heavy traffic vehicular networks. In this paper, we propose an interference-free graph based time-division multiple access (IG-TDMA) protocol for VANETs. In the proposed protocol, roadside units (RSUs), as centralized controllers, collect the information from active vehicles and construct the interference-free graph based on the vehicle locations and a preset interference-free threshold. We further propose a communication link selection algorithm, which can help the RSUs make efficient and effective scheduling decisions with high spatial reuse efficiency and low computational complexity. Simulations verify that the proposed IG-TDMA protocol can improve the network performance significantly compared with the IEEE 802.11p CSMA/CA based EDCA scheme and traditional TDMA protocol.**

***Index Terms*—Vehicular ad-hoc networks (VANETs), time-division multiple access (TDMA), interference-free graph.**

## I. Introduction

Recently, intelligent transportation systems (ITS) [1] have been proposed as a promising system architecture to improve the safety and efficiency of transportation systems. Vehicular ad-hoc networks (VANETs) can provide support for various ITS applications such as emergency warning systems and informative applications, through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications [2][3]. In VANETs, MAC protocol design is a key issue to guarantee high quality of service (QoS) for vehicular communications.

Current MAC protocols can be categorized into contention-based and contention-free protocols [4]. The most widely applied contention-based protocol for VANETs is carrier sense multiple access with collision avoidance (CSMA/CA), which is the basis of the enhanced distributed channel access (EDCA) in the IEEE 802.11p standard. However, with EDCA, when the number of active vehicles in VANETs increases, data transmission congestion due to collisions will become severe and degrade the network performance.

Therefore, in the literature, some contention-free protocols have been proposed to improve the network performance of VANETs, especially the TDMA-based ones that attract most attention. The existing TDMA-based protocols can be categorized into two types, namely distributed TDMA and centralized TDMA. R-ALOHA and ADHOC [5] are basic distributed TDMA-based protocols. Based on these protocols, many other distributed TDMA protocols have been proposed, such as VeMAC [6], and A-ADHOC [7]. But in distributed TDMA protocols, two kinds of collisions may occur, that is, access collisions and merging collisions [8]. Access collisions occur when two or more terminals in the basic channel (BCH) setting-up phase transmit on the same available slot. Whereas merging collisions happen when two or more terminals acquiring the same time slot become members of the same two-hop set. Centralized TDMA-based protocols [4] can avoid these collisions due to efficient scheduling. Besides, centralized TDMA methods can exploit the VANET characteristics more effectively. In VANETs, the vehicle mobility is highly predictable and roadside units (RSUs) can act as central nodes to make MAC scheduling decisions. Some centralized TDMA-based protocols were then proposed, such as R-MAC [9], and UTSP [10][11]. However, in these protocols, time slots are assigned to communication links orthogonally, which limits the network throughput for large-scale VANETs. Moreover, few TDMA-based protocols take access categories (ACs) into consideration.

In this paper, in order to improve the network throughput by utilizing the topology characteristics of VANETs, we propose a novel centralized TDMA-based scheduling protocol based on the interference-free graph. Different from other existing centralized TDMA-based protocols, the proposed protocol employs a flexible spatial reuse strategy, which permits multiple vehicles transmit data simultaneously. In the proposed interference-free graph based TDMA (IG-TDMA) protocol, RSUs act as central schedulers and collect the information from active vehicles periodically. The collected information includes the data transmission requests, the current locations and velocities of the vehicles, and the channel state information. Based on the collected information, RSUs construct interference-free graphs to indicate the interference relationships among current active communication links according to a predetermined interference-free threshold, and make effective scheduling decisions to maximize the network throughput by allowing multiple communication links transmit simultaneously with interference limitation. Then, we further propose a communication link selection algorithm which can effectively find the maximum current simultaneous transmission set in the considered network. Simulations indicate that our proposed interference-free graph based TDMA protocol provides significantly better performance than those of the IEEE 802.11p CSMA/CA-based EDCA scheme and the traditional TDMA protocol.

The rest of this paper is organized as follows. Section II describes the system model. Section III introduces the proposed interference-free graph based TDMA protocol for VANETs. The simulation results and discussions are presented in Section IV. And finally, Section V concludes this paper.

## II. System Model

As illustrated in Fig. 1, we consider a vehicular ad-hoc network consisting of one RSU and a set of vehicles moving on a bidirectional four-lane highway. The RSU, as a centralized controller, collects the channel state information and the individual information of active vehicles within its communication coverage and then makes scheduling decisions for each transmission frame. We assume that the RSU has sufficient computational and storage capacity and the vehicles move in a uniform speed within a frame. The RSU and vehicles are equipped with GPS receivers, which can provide fairly accurate time synchronization between network nodes. Each vehicle can get its real-time geographical location and velocity from its GPS receiver. In addition, the packets are categorized into four different ACs, so that vehicles with higher priority packets can have higher probabilities of accessing the channels.

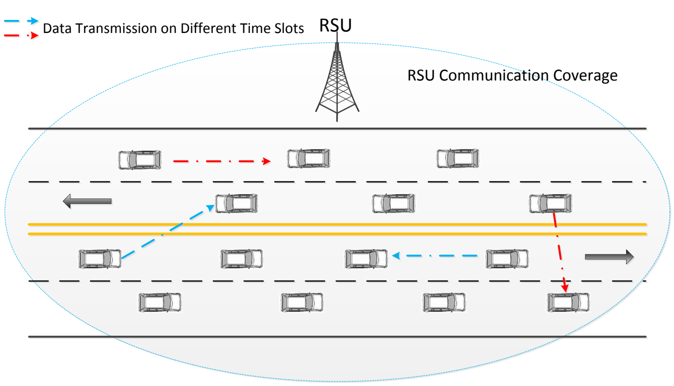


Fig. 1: Scenario for vehicular ad-hoc networks.

In this system, each transmission frame is partitioned into $K$ time slots, and these time slots are of equal length. Multiple communication links may request to access channels simultaneously and severe interference may occur in vehicular ad-hoc networks. To avoid interference among different communication links, we propose a novel centralized TDMA protocol, namely interference-free graph based TDMA protocol for vehicular ad-hoc networks.

## III. Interference-Free Graph Based TDMA Protocol

In this section, we introduce the proposed interference-free graph based TDMA protocol. This protocol can be summarized into four stages. First, at the beginning of each frame, vehicles send their individual information, such as their locations, velocities, the information of messages need to be sent, etc., to the RSU. The RSU collects this information as well as the channel state information. Secondly, the RSU predicts vehicle locations and constructs the interference-free graph. Thirdly, the RSU selects multiple links for simultaneous transmission based on the interference-free graph. Finally, the scheduling decision is broadcast to all involved vehicles and the selected communication links start to transmit. The procedure is illustrated in Fig. 2.

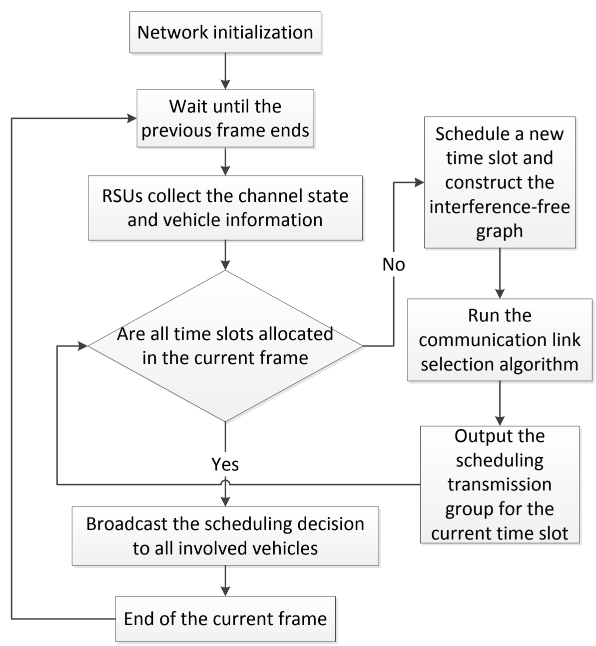


Fig. 2: Flow chart of the proposed interference-free graph based TDMA protocol.

Obviously, link selection in the third stage is crucial to the network throughput. It is desirable to select as many links as possible as long as the interference among them is negligible. Therefore, in this paper, we propose an efficient communication link selection algorithm that would significantly improve the network throughput. The details of the algorithm are described in Section III-B.

### *A. Interference-Free Graph Construction*

To construct the interference-free graph, we must first define the conditions under which the interference between links can be ignored. Consider two links, Link $i$ and Link $j$. $T_i$ and $R_i$ are the transmitting node and receiving node of Link $i$, and $T_j$

TABLE I: Parameters for Four ACs

| AC | AC1 | AC2 | AC3 | AC4 |
| --- | --- | --- | --- | --- |
| $CW_{min}$ | 3 | 3 | 7 | 15 |
| $CW_{max}$ | 7 | 15 | 1023 | 1023 |

and $R_j$ be the transmitting node and receiving node of Link $j$. We ignore the interference between Link $i$ and Link $j$, if

$$\|\boldsymbol{x}_{T_i} - \boldsymbol{x}_{R_j}\| > D_j \tag{1}$$

and

$$\|\boldsymbol{x}_{R_i} - \boldsymbol{x}_{T_j}\| > D_i \tag{2}$$

where $\boldsymbol{x}_k$ is the location of Node $k$, $D_j$ and $D_i$ are the interference-free distances of Link $j$ and Link $i$ respectively. $D_i$ is calculted as

$$20\log_{10}|H(D_i)| = 20\log_{10}|H(\|\boldsymbol{x}_{R_i} - \boldsymbol{x}_{T_i}\|)| - \alpha \tag{3}$$

where $\alpha$ is an interference-free threshold, and $H(\cdot)$ denotes the channel response for a given transmission distance [12][13].

Now, we can construct the interference-free graph, denoted by $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$. The vertex set $\mathcal{V} = \{V_1, V_2, \cdots, V_{|\mathcal{V}|}\}$ denotes the set of communication links. Two vertices $V_i$ and $V_j$ are connected, i. e., $(V_i, V_j) \in \mathcal{E}$, if the transmitting and receiving nodes of their corresponding links satisfy (1) and (2). The density of edges in the graph can be adjusted by varying the interference-free threshold $\alpha$. Intuitively, $\alpha$ should be set as the minimum signal to interference ratio deemed tolerable.

### B. Communication Link Selection Algorithm

Based on the interference-free graph, we propose a communication link selection algorithm to improve the network performance. In each time slot, if the interference between two communication links can be ignored according to (1) and (2), i.e., there is an edge between two vertices, these two communication links can transmit simultaneously. Therefore, communication links should be allowed to transmit simultaneously in the same time slot if their corresponding vertices are in the same clique, that is a complete subgraph, of the interference-free graph.

Additionally, communication links with high channel quality should be served with high priority. Similar to the scheduler designed in [13], we introduce a channel factor for each link. For Link $i$, $i \in \{1, \cdots, |\mathcal{V}|\}$, its channel factor $C_i$ can be calculated as

$$C_i = \log_2\left(1 + \frac{P_t|H(d_i)|^2}{\sigma^2}\right) \tag{4}$$

where $P_t$ is the transmit power, $d_i$ is the transmission distance of Link $i$, and $\sigma^2$ is the noise power.

In the IEEE 802.11p EDCA scheme, the packets are categorized into four different ACs, i.e., $AC_i$, $i = 1, 2, 3, 4$. Each category has its access parameters such as the contention window (CW) and arbitration interframe space (AIFS). The duration of the CW decides the transmission priority of the packet. Similar with EDCA, there are also four different ACs in the proposed IG-TDMA protocol. Contention windows for different ACs are shown in Table I. In addition, according to the work in [11], we introduce an AC factor for each packet $i$, $ACF_i$, to guarantee that nodes with higher priority packets have higher probabilities to access channels. The AC factor is calculated as

$$ACF_i = \frac{1}{CW_{max}(AC_i)} + \frac{1}{CW_{min}(AC_i)} \tag{5}$$

where $CW_{max}(AC_i)$ and $CW_{min}(AC_i)$ are the minimum and maximum CWs for $AC_i$.

Considering the channel quality and packet priorities, we assign a Q-value for each communication link to guarantee different QoS for packets with different priorities based on these two factors, i.e., each vertex in the interference-free graph has a Q-value. For the communication Link $i$, denoted by Vertex $V_i$ in the graph, its Q-value is defined as

$$Q(V_i) = \frac{C_i \cdot ACF_i}{N(i)} \tag{6}$$

where $C_i$ is the channel factor of Link $i$, $N(i)$ is the number of successful transmitted packets of the communication link within a time window. With the factor $N(i)$, the QoS of communication links with bad channel conditions can also be guaranteed. Now, by summing the Q-value of the vertices in a clique, we can get a Q-value for each clique and choose the clique with the highest clique Q-value for transmission in a time slot. The communication link selection algorithm is described in Algorithm 1.

**Algorithm 1** Communication link selection algorithm

**Require:**
A graph $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$, where $\mathcal{V} = \{V_1, V_2, \cdots, V_{|\mathcal{V}|}\}$
**Ensure:**
The set of selected vertices $\mathcal{S}$, which represents the links to be transmitted simultaneously
**Initialization:** $\mathcal{S}_i = \{V_i\}$, where $i \in \{1, 2, \cdots, |\mathcal{V}|\}$
**for all** $i \in \{1, \cdots, |\mathcal{V}|\}$ **do**
  $\mathcal{N}_i \leftarrow$ the set of neighboring vertices of $V_i$;
**end for**
**for all** $i \in \{1, \cdots, |\mathcal{V}|\}$ **do**
  $\mathcal{C}_i = \mathcal{N}_i$;
  **while** $\mathcal{C}_i \neq \varnothing$ **do**
    $j^* = \arg\max_{j, V_j \in \mathcal{C}_i}(Q(V_j))$;
    $\mathcal{S}_i = \mathcal{S}_i \cup \{V_{j^*}\}$;
    $\mathcal{C}_i = \mathcal{C}_i \cap \mathcal{N}_{j^*} \setminus \{V_{j^*}\}$;
  **end while**
**end for**
**for all** $i \in \{1, \cdots, |\mathcal{V}|\}$ **do**
  $Q(\mathcal{S}_i) = \sum_{V_k \in \mathcal{S}_i} Q(V_k)$;
**end for**
$\mathcal{S} = \arg\max_{\mathcal{S}_j, j \in \{1, 2, \cdots, |\mathcal{V}|\}}(Q(\mathcal{S}_j))$ .

Fig. 3 shows an example of the interference-free graph used in the link selection algorithm. There are five vertices and each vertex $V_i$ has a Q-value $Q(V_i)$. Assuming $Q(V_1) > Q(V_2)$

and $Q(V_3) + Q(V_4) > Q(V_5) > Q(V_3)$, the cliques found by Algorithm 1 are $\mathcal{S}_1 = \mathcal{S}_3 = \mathcal{S}_4 = \{V_1, V_3, V_4\}$ and $\mathcal{S}_2 = \mathcal{S}_5 = \{V_2, V_5\}$. Because $Q(V_1)+Q(V_3)+Q(V_4) > Q(V_2)+Q(V_5)$, the output of the algorithm is $\mathcal{S} = \{V_1, V_3, V_4\}$.

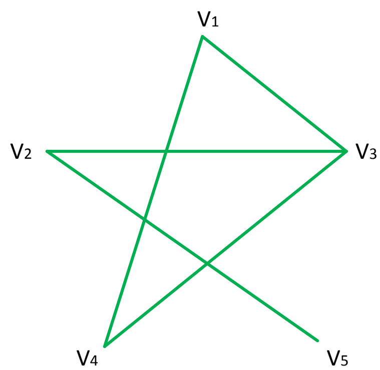


Fig. 3: An example of the interference-free graph.

## IV. Simulations

In this section, we compare the performance of the proposed centralized TDMA protocol with the traditional TDMA protocol and the IEEE 802.11p CSMA/CA-based EDCA scheme in the vehicular ad-hoc network demonstrated in section II. In the following part, first the simulation settings are given and then the results are presented.

### A. Simulation Settings

As illustrated in section II, there are four lanes and $N$ vehicles in each lane. The communication radii of vehicules and the RSU are 100 m and 500 m respectively. Detailed parameter settings are presented in Table II. To simulate the transmission links between vehicles, we randomly select $60\%$ of vehicles as transmitting vehicles and $40\%$ of vehicles as receiving vehicles. Each transmitting vehicle selects a receiving vehicle within its communication coverage to form a link.

The pathloss model of the vehicular network is given as

$$p(d) = -12.88 + 35.22 \log_{10}(d) \text{ dB} \tag{7}$$

where $d$ is the transmission distance [11][14]. And the channel response is calculated as

$$H(d) = \frac{1}{\sqrt{p(d)}}. \tag{8}$$

### B. Performance Comparisons

Fig. 4 shows the network throughput comparison among the traditional TDMA, the IEEE 802.11p CSMA/CA-based EDCA and the proposed IG-TDMA protocols with different packet arrival rate $\lambda$. The packet arrival rate is defined as the number of packets arriving at the transmission queue per millisecond. 40 vehicles, 10 vehicles in each lane, are running on the bidirectional highway with the speed of $60 - 120$ km/h. Each transmitting node selects a neighbor within its communication range to send a packet. The receiving node measures the signal-to-interference-plus-noise ratio (SINR) of

TABLE II: System Parameters

| Parameters | Values |
|---|---|
| Channel Bandwidth | 10 MHz |
| Transmit Power of Vehicles | 20 dBm |
| Noise Power | $-90$ dBm |
| Interference-Free Threshold $\alpha$ | 3 dB |
| Small Scale Fading | Rayleigh fading coefficient $\mathcal{CN}(0,1)$ |
| Velocity of Vehicles | $60 - 120$ km/h |
| Packet Length $T_p$ | 8 $\mu$s |
| Time Slot Length $T_s$ | 8 $\mu$s |

the received packet. If the measured SINR is larger than the SINR threshold, the transmission of the packet is deemed as successful. Here the SINR threshold is 2 dB.

In Fig. 4, we observe that as the packet rate grows, the network throughput increases at first and then remains stable. The performance of the proposed IG-TDMA protocol is the best. In traditional TDMA protocol, only one communication link is permitted to transmit in each slot, so the resources can not be fully used. The performance of the IEEE 802.11p CSMA/CA-based EDCA is slightly better than that of the tranditional TDMA protocol. However, collisions are severer when the packet rate becomes higher, which limits the increase of the network throughput. The network throughput of our proposed IG-TDMA protocol is much better than that of the EDCA scheme, for it allows multiple communication links transmit in the same slot and also avoids collisions. From Fig. 4, we also observe that the network throughput keeps increasing with the packet arrival rate until the network is saturated. Note that IG-TDMA performs best here in terms of both the network throughput and the packet arrival rate when the network reaches saturation. For IG-TDMA protocol, when $\lambda > 45$ packets/ms, all transmitting vehicles have packets to transmit in every time slot, and full-load performance is reached.

Fig. 5 studies the effect of node density for the traditional TDMA, the IEEE 802.11p CSMA/CA-based EDCA and the proposed IG-TDMA protocols. Here, the packet arrival rate is 40 packets/ms. As the node density increases the network throughput of the IG-TDMA protocol fluctuates. But overall it has an increasing trend and the performance is much better than that of the EDCA scheme and traditional TDMA protocol. When the node density increases, the average distance between nodes decreases and then the interference-free distance decreases according to Eq. (3). Therefore, more communication links can be allowed to transmit in a time slot. As for the CSMA/CA-based EDCA scheme, its performance is limited by collions.

## V. Conclusions

In this paper, based on the interference-free graph we have proposed a novel centralized TDMA-based scheduling protocol, namely the IG-TDMA scheduling protocol, for VANETs. The interference-free graph is constructed according to vehicle positions and a preset interference-free threshold. Then we

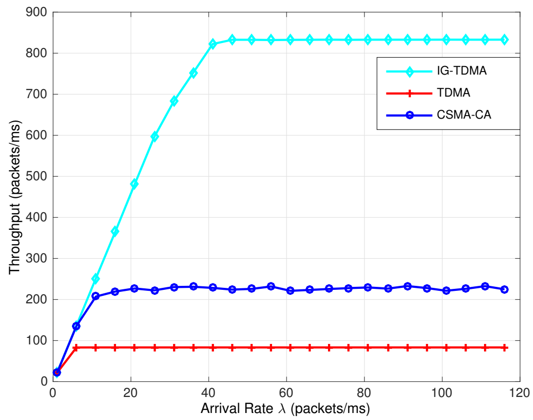


Fig. 4: The network throughput comparison among the traditional TDMA, the IEEE 802.11p CSMA/CA-based EDCA and the proposed IG-TDMA protocols with different packet rates.

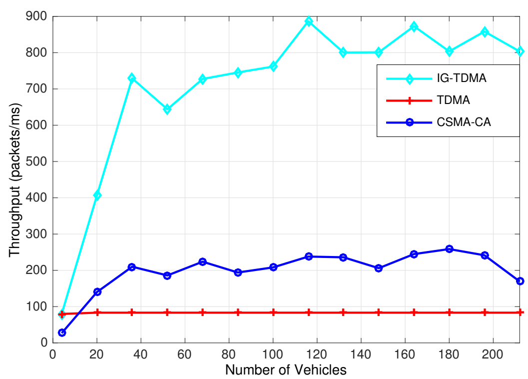


Fig. 5: The network throughput comparison among the traditional TDMA, the IEEE 802.11p CSMA/CA-based EDCA and the proposed IG-TDMA protocols with different node densities.

proposed a communication link selection algorithm to help RSUs make effective scheduling decisions. In the proposed algorithm we introduce two factors, namely the channel factor and the AC factor, to guarantee that communication links with higher channel quality and higher priority can be served with higher probabilities. Our proposed IG-TDMA protocol allows multiple vehicles to transmit simultaneously in each time slot while maintaining low level of interference. Simulations demonstrate that the network performance of the IG-TDMA scheduling protocol is much better than that of the IEEE 802.11p CSMA/CA-based EDCA and the traditional TDMA protocol, and the IG-TDMA protocol also works well in dense vehicular networks.

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