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Abstract

This paper proposes a multi-channel token ring media access control (MAC) protocol (MCTRP) for inter-vehicle communications (IVC). Through adaptive ring coordination and channel scheduling, vehicles are autonomously organized into multiple rings operating on different service channels. Based on the multi-channel ring structure, emergency messages can be disseminated with a low delay. With the token based data exchange protocol, the network throughput is further improved for non-safety multimedia applications. An analytical model is developed to evaluate the performance of MCTRP in terms of the average full ring delay, emergency message delay, and ring throughput. Extensive simulations with ns-2 are conducted to validate the analytical model and demonstrate the efficiency and effectiveness of the proposed MCTRP.

Index Terms

Intelligent transportation system, Inter-vehicle communications, Token ring, Multi-channel MAC

I. Introduction

With the rapid development of communication and networking technologies, vehicular ad-hoc network (VANET) has been emerging to enable new mobile services and applications including vehicular safety applications (e.g., collision, congestion, or injury warning and reporting) and non-safety multimedia applications (e.g., Internet access, media streaming, and online gaming) [1]. Generally, vehicular communications can be classified into two categories: inter-vehicle communications (IVC) and roadside-to-vehicle communications (RVC) [2]–[4]. In the IVC system, information is exchanged between vehicles, while in a RVC system, vehicles communicate with the roadside unit (RSU). Compared with RVC system which is dependent

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on the roadside infrastructure, IVC system can operate autonomously in an ad-hoc mode and is more flexible, rendering more attractive vehicular related applications. However, the lack of infrastructure support, high mobility of vehicles and dynamic topology changes, make efficient resource management in VANET extremely challenging. In addition, various applications have different QoS requirements. For instance, safety related applications demand quick and reliable message delivery, while non-safety applications usually require high throughput and good fairness performance. Therefore, it is very important to design efficient MAC protocol in IVC system to meet different QoS requirements of vehicular applications in VANET.

Token ring protocols have attracted much attention from wireless communication communities due to their QoS provisioning in terms of reserved bandwidth and bounded delay. Wireless token ring protocol (WTRP) was proposed for Intelligent Transportation systems (ITS) [5] and first deployed in Partners for Advanced Transit and Highways (PATH) vehicle safety systems program [6]. To the best of our knowledge, existing token ring protocols are mainly based on a single communication channel. For efficiently utilizing the network resources of VANET, the multi-channel structure should be considered.

In this paper, we propose a multi-channel token ring MAC protocol (MCTRP) for vehicular networks. We employ the multi-channel structure defined in IEEE 802.11p in the protocol design. Through effective ring coordinations and dynamic channel scheduling, vehicles can be autonomously organized into multiple rings operating on different service channels. The asynchronous CSMA/CA mechanism is applied for emergency message exchange, which provides satisfactory delay performance under low traffic load and contention level. To further improve the throughput performance of non-safety multimedia applications, we present a token-based data exchange protocol which ensures high resource utilization of wireless channels.

The main contributions of the paper are three-fold. First, we propose a novel multi-channel token ring protocol for VANET, considering the particular features of vehicular networks, including no infrastructure support, dynamic topology changes due to high mobility, hostile wireless transmission environment, etc. Second, we develop an analytical model to study the performance of MCTRP, e.g., average full ring delay, average emergency message delay, average ring throughput, and average access delay, etc. Third, extensive simulations with ns-2 are conducted to verify the analysis and demonstrate the efficiency and effectiveness of the proposed protocol.

The remainder of this paper is organized as follows. In Section II, we briefly review the related work. The system model is introduced in Section III. The proposed MCTRP is described in Section IV. In Section V, we present an analytical model to study the performance of the proposed MCTRP. Numerical results are given in Section VI, followed by concluding remarks and future work in Section VII.

II. Related Work

The U.S. Federal Communications Commission (FCC) has approved 75 MHz frequency band for ITS wireless communications. As shown in Fig. 1, the frequency between 5.850 – 5.925 GHz is divided into seven channels in [7]. One of the seven channels, CH178, is designated as the control channel (CCH) which is used for high priority message exchanges, such as safety related applications, system control and management. The other six channels are used as service channels (SCH) which support non-safety applications. Based on the multi-channel structure defined by the FCC, several MAC protocols have been proposed for VANET. In [8], the vehicular mesh network (VMESH) MAC protocol applies a reserved TDMA scheme to improve network throughput. VMESH further partitions the CCH into a beacon period (BP) and a safety period (SP). The BP is divided into multiple slots and each vehicle chooses a unique beacon slot to broadcast its control information. By employing the beacon-enabled MAC, each vehicle is able to keep awareness of its neighbors and coordinate resource allocation in the SCHs. Therefore, the bandwidth is efficiently shared among vehicles, and high network throughput can be achieved. However, VMESH mainly focuses on throughput performance, without considering other QoS performance (e.g., delay) of safety applications. In [9], a cluster based multi-channel MAC protocol is proposed to provide quick emergency message dissemination and bounded delay. However, due to the lack of efficient topology control mechanism, the cluster-based approach is more suitable for VANET with less topology variation. Some other multi-channel MAC protocols are proposed for general wireless networks. For example, the Dynamic Channel Assignment

(DCA) in [10] requires each node be equipped with two radios, where one radio is dedicated to control message exchange, and the other is for data message exchange. The adoption of multiple channels is helpful to reduce the co-channel interference between the two radios, but it is very difficult to fully utilize the radio resource in both channels due to the inefficient coordination between them.

On the other hand, many studies on token or ring structure based MAC protocols have appeared in the literature. Wireless token ring protocol (WTRP) is proposed in [5] to provide bounded delay and fairness to nodes for data communications without considering the special safety-related applications in VANET. In [11], a token based control scheme is presented to emulate the window-based flow and congestion control in wireless/wired Networks. In [12], a token based scheme is presented to ensure guaranteed priority for voice traffic in single-hop networks. In [13], an overlay token ring protocol (OTRP) is proposed for IVC, and it operates in two modes. In the ordinary mode, a token circulates along the ring, and each vehicle has the same opportunity to transmit their data packets by holding the token for the same time interval. In case of accidents, it changes to emergency mode in which the emergency messages are delivered to all nearby nodes. By adopting the token and different operation modes, OTRP is capable of supplying stringent throughput and rapid emergency messages delivery. Nevertheless, OTRP uses single channel architecture, and does not consider interference among multiple rings. The MAC protocols in [14]–[16] mainly focus on safety applications in VANET. But they cannot guarantee quick and reliable emergency delivery and high throughput data transmission simultaneously. As far as we investigate, our work is the first to jointly consider the different QoS requirements of safety-related applications and the high volume data applications in IVC, based on the token ring and the multi-channel structure specified by the FCC.

III. System Model

We consider a vehicle network where one or multiple *virtual rings* are dynamically formed according to the velocity of vehicles and road traffic conditions. The maximum number of vehicles in a ring is referred to as the ring size $N_{\max}$. As shown in Fig. 2, nodes (the terms "node" and "vehicle" are used interchangeably throughout the paper, and important symbols are summarized in Table I) in the system can operate on different states as follows.

1) **ring founder node (RFN)**: a node that initially sets up a ring (details will be given in Sec. IV-A) and has the authority to cancel a ring. The RFN is also responsible for adding new nodes into the ring and deleting nodes from the ring.
2) **token holder node (THN)**: a node which is in a ring and holds a token.
3) **ring member node (RMN)**: a node which is in a ring, but does not hold a token.
4) **dissociative node (DN)**: a node which does not belong to any ring, and does not start the joining process.
5) **semi-dissociative node (SDN)**: a node which receives the joining invitation and connection notification messages from the RFN and is ready to connect to its successor.

The state transition diagram is shown in Fig. 3. A DN becomes a RFN after it sets up a ring successfully. A DN becomes a SDN when it successfully receives a joining invitation from a RFN and starts to join the ring. If the joining procedure completes within a constant period, a SDN turns to be a RMN; otherwise, a SDN becomes a DN. A RMN becomes a DN if it is deleted from the ring or the ring is canceled by the RFN, and becomes a THN after receiving a token. Note that both RFNs and THNs are special types of RMNs.

In the system, all vehicles are equipped with two radios, e.g., Radio-I and Radio-II. All DNs operate over CH178 using Radio-I only, while other types of nodes can simultaneously operate over CH178 with Radio-I and one of the six SCHs with Radio-II, as shown in Fig. 1. Time in the system is synchronized with the aid of GPS and partitioned into fixed time periods of a duration T composed of a control period and a data period, which are further divided into safety period T_s, ring coordination period T_c and data exchange period T_d as depicted in Fig. 4. The detailed description of each period will be presented in Sec. IV.

IV. Multi-channel Token-ring Protocol

To provide different QoS performance and achieve efficient resource utilization, the proposed MCTRP employs three sub-protocols as follows.

1) **Ring coordination protocol** is designed for ring management including setting up or dismissing a ring, admitting new nodes to the ring, deleting nodes from the ring, and scheduling SCHs for each ring.
2) **Emergency message exchange protocol** is responsible for collecting emergency messages in a ring, and delivering them to other rings.
3) **Data exchange protocol** controls the token delivery in a ring for efficient intra-ring data communications.

A. Ring Coordination Protocol

The ring coordination protocol includes ring initiation process, node joining process, node leaving process, ring updating process, and ring termination process.

Ring Initialization Process – When a DN declares to set up a ring, it broadcasts the ring founding message (RFM) to the nearby nodes in the T_c interval with Radio-I, and starts a ring founding timer. The RFM also includes the selected SCH number for the intra-ring data communications. If the SCH number has been occupied by another ring in its neighborhood, the RFN of the neighboring ring using this SCH will invite the DN to join the existing ring provided the number of the RMNs is less than $N_{\max}$. Otherwise, the RFN will simply notify the DN to re-select a SCH, and the DN will re-initiate the ring initialization process. The re-initialization process continues until all the six SCHs are occupied by neighboring rings, in which case the DN will stop broadcasting its RFMs, and keep monitoring the control channel with Radio-I until it is admitted into a ring. If the DN has not received any response until the ring founding timer expires, the DN creates a ring and becomes a RFN, which opens its Radio-II and operates on the selected SCH.

Joining Process – After a ring has been established, the RFN will broadcast the joining invitation message (JIM) using Radio-I in each T_c after a random backoff, if the number of RMNs in the ring is less than $N_{\max}$. The broadcast JIM includes the moving speed of the RFN, the selected SCH number, the amount of the current RMNs, the expected lifetime of the ring, and time period T, T_s, T_c, T_d. A DN receiving the JIM will compare its moving speed with that of the RFN. If the difference is smaller than a predefined speed threshold, v_d, the DN will reply the RFN a joining acknowledgement message (JAM) using Radio-I after a random backoff. The v_d is used to ensure that there is comparatively small speed difference between nodes within the same ring. When a DN receives multiple JIMs, it will choose to join the ring with the least speed difference. Therefore, the topology of a ring is relatively stable and the ring management overhead can be significantly reduced. After receiving a JAM, the RFN replies a connection notification message (CNM) to the DN that first responses, indicating the MAC address of the successor that the DN should connect to. If all messages are exchanged successfully, the DN becomes a SDN and then opens its Radio-II to the specified SCH in JIM. The SDN then sends a connecting successor message (CSM) to its successor with Radio-II. If the SDN receives a connection acknowledge message (CAM), it will transmit a joining success message (JSM) to the RFN, which includes its valid time in the ring. The RFN always takes the newly joined RMN as its default successor. Thus, the new RMN successfully joins the ring if it can connect to its successor in the joining process. After receiving a JSM, the RFN will broadcast an address notification message (ANM) that contains all the MAC addresses of RMNs in the ring, so that each RMN can keep its ring information. All the packet exchanges in the joining process are shown in Fig 5.

The communications in the T_c employ the contention based CSMA/CA scheme for efficient control message exchange. Notice that it is possible some messages in the joining process may be lost due to collisions or corrupted in a wireless fading channel. If the RFN can not successfully receive the JSM at the end of T_c, it will delete the SDN information, and the SDN will return to the DN state. To reduce potential collisions caused by hidden terminal problem, some control messages, including JAM, CNM, and CSM, contain a time field representing the time duration that the node will occupy the channel, and other nodes which overhear them update their network allocation vector (NAV) and postpone their channel access accordingly.

Leaving Process – Three cases can trigger the leaving process. First, each node reports to the RFN its valid time in the ring in JSM. In each T_c, the RFN checks the MAC information base (MIB) for the time record and deletes the node if its valid time expires. Second, if a THN can not pass the token to its successor after several attempts, it will consider the successor has left the ring and report this to the RFN. Third, each THN will pass the token to its successor by broadcasting, and the RFN will also record the THN on receiving the broadcast token, which implies the THN is still in the ring. After the token circulates the ring for a cycle, the RMNs that can't be heard by the RFN will be deleted in the T_c period. The RFN will notify its RMNs to update local ring information after deleting the departure node, and the predecessor and successor of the departure node will connect to each other consequently. Note that a node may be deleted if it is isolated from the ring due to deep fading for a long time. If a node does not receive any message from its predecessor and the RFN for a certain period, or it finds it is not included in the list of MAC addresses of RMNs, it will return to the DN state.

Ring Updating Process – The RFN needs to update the ring setting information when some changes occur. For example, the RFN needs to select another SCH if the co-channel interference on the current SCH becomes overwhelming for intra-ring data communications. This is possible in highly mobile vehicle networks. In the initialization process, two or more rings may choose the same SCH because they are out of each other's transmission range. However, due to the mobility, these rings may move into each other's interference range or even transmission range, which causes serious co-channel interference to each other. The following cases will lead to the ring updating.

- During T_c interval, the RFN broadcasts a JIM which includes the SCH number of the ring with Radio-I, if the number of its RMNs is less than $N_{\max}$. If a neighboring RFN overhears the message and finds the selected SCH overlaps with its own SCH, it will communicate with the RFN using Radio-II. Otherwise, if the number of RMNs has reached $N_{\max}$, there will be no JIM broadcasting, and instead the RFN will broadcast a message containing its SCH number in each T_c interval. The neighboring RFN that operates on the same SCH will also communicate the sender with Radio-II. The ring which has a smaller number of RMNs will notify its RMNs to stop data transmission on the overlapped SCH and search a free SCH for its intra-ring communications. If a clear SCH is detected, it will broadcast a changing channel notification message (CCNM) including the new SCH. All RMNs will change their SCH on Radio-II upon receiving the CCNM. Otherwise, the ring has to be terminated and all RMNs become DNs.

- If a THN detects a busy SCH in the data exchange process, which implies that two neighboring rings use the same SCH, it will hold the token and stop the data transmission. In the next T_c, it broadcasts a SCH overlapped message including the number of current RMNs in its ring denoted as $|N_i|$ with Radio-II. A RMN that operates on the same SCH with Radio-II in another ring overhears the message, and compares its $|N_i|$ with that of the sender. If its $|N_i|$ is larger than that of the sender, it will reply the sender, and the sender then notifies its RFN to switch SCH. Otherwise, the RMN will notify its RFN to switch SCH. The RFN that receives a SCH switch notification from its RMN will select another SCH and broadcast a CCNM to its RMNs. The message exchanges during T_c period use contention-based CSMA/CA mechanism.
- A RFN may change the speed or the expected ring lifetime that is declared in JIM in the course of moving, and it will broadcast the updated information to its RMNs during the period T_c. Those RMNs that do not accept the speed or time will notify the RFN and leave the ring. A RMN may also update the valid time declared in JSM, and report it to its RFN within T_c. After receiving these messages, the RFNs can update the ring information accordingly for efficient ring management.

Ring Termination Process – When the lifetime time declared by a RFN expires, the RFN will broadcast the ring termination message to its RMNs with Radio-II. The RMNs receiving this message certainly become DNs.

B. Emergency Message Exchange Protocol

Emergency messages are the most important information in IVC which should be broadcast to vehicles in the system as fast and reliable as possible. When a RMN detects an accident, it will quickly report this to its RFN with Radio-II during the T_s period. Then the RFN will broadcast the emergency message to all nearby nodes using both Radio-I (inter-ring notification) and Radio-II (intra-ring notification) during the same T_s period. Therefore, the delivery of emergency messages takes four main steps: i) a RMN detects an accident and transmits an emergency message to its RFN by adopting CSMA/CA on Radio-II during the T_s interval; ii) upon receiving the emergency message from Radio-II, the RFN will reply an acknowledgement to the RMN, and then broadcast the emergency message to all its RMNs with Radio-II; iii) at the same time, the RFN broadcasts the emergency message to its neighboring DNs, SDNs, RFNs with Radio-I; iv) neighboring RFNs rebroadcast the emergency message with Radio-I by adopting simple flooding [17] for multi-hop emergency message relaying. They also broadcast the emergency message to their RMNs with Radio-II in the meantime. It is possible that two nodes in the same ring detect the some accidents simultaneously and both will deliver emergency messages to their RFNs, which may cause packet collisions. However, by applying efficient ring management along with adaptive channel scheduling described in IV-A, the contention level within a ring or in each SCH during the T_s period is very low and negligible. Our simulation results show that contention based CSMA/CA can provide efficient message delivery under low traffic and contention levels, which is confirmed by the results shown in [18]. Therefore, the emergency message delivery performance can be guaranteed by adopting the multi-channel ring structure.

C. Data Exchange Protocol

When a node receives the data from the upper layer, it first checks whether the next hop node is in the same ring or not based on the local ring information. The node uses Radio-I and Radio-II for inter-ring and intra-ring data communications, respectively. The inter-ring data are transmitted with CSMA/CA mechanism. In the following sections, we focus on efficient token based intra-ring data communications.

In MCTRP, a RMN has two data buffers, e.g., intra-ring data buffer (IADB) which stores packets to be transmitted to RMNs in the same ring and inter-ring data buffer (IRDB) which stores packets to be delivered to the nearby DNs, SDNs, and RMNs in different rings. We propose a token based data exchange protocol for efficient intra-ring data communications. The maximum token holding time of each node is denoted by T_{MTH}. When a node receives a token from its predecessor, it first checks its IADB. If the buffer is non-empty during the T_{MTH}, the THN starts data transmissions, and passes the token to its successor when T_{MTH} is reached. To ensure token delivery, the THN will retransmit the token if no acknowledgement (ACK) is received before the token retransmission timer is timeout. If the maximum retry limit T_{retry} is reached, the THN will report to the RFN that its current successor is not reachable (the successor is in deep fading for a long time or has left the ring due to mobility), and the RFN will delete the successor from the ring and update the ring information in the next T_c, as described in Sec. IV-A. The THN then attempts to connect to the next node since all nodes in the ring have the ring topology information. After successfully passing the token to the next node, the THN switches to the RMN status. If the IADB of the THN is empty during T_{MTH}, the THN will start a timer and keep checking the buffer status. The THN will pass the token to its successor if no data arrives before the timer expires. This is to ensure the following nodes with intra-ring data packets can acquire the token as soon as possible. The psuedo code of the token based data exchange is presented in Algorithm 1. Note that the token is delivered by broadcasting, and the RFN will keep record of each token passing process. If the RFN can not receive any broadcast token for a fixed time interval, which implies the token has been lost, it will generate a new token.

V. Performance Analysis

In this section, we develop an analytical model to study the performance of the proposed MCTRP, in terms of the time for a ring having its N_{max} RMNs, the average delay of emergency message delivery, the average throughput of intra-ring communications, and the delay for a RMN receiving the token. We consider a network consisting of multiple rings and enough DNs to join different rings. Inter-ring data communications are based on CSMA/CA mechanism with RTS/CTS control frames since data packets are usually larger than the RTS threshold.

A. Full Ring Delay

A ring is said to be *full* if it has its maximum number of RMNs. The time for a ring to be *full* is thus called the *full* ring delay. It is used to evaluate the efficiency of the distributed ring coordination among multiple nodes. For a given number of vehicles, a less number of rings are formed with more members in each ring, which is desirable for contention based inter-ring communications due to the reduced contentions among rings. Moreover, more rings not only increase the potential collisions among inter-ring nodes, but also require more SCHs and thus may increase the inter-ring co-channel interference. On the other hand, if more DNs can quickly join rings, a fewer number of DNs would need to contend for channel access with Radio-I operating on CH178, which is favorable for inter-ring communications.

To obtain the *full* ring delay, we capture the dynamic change of the number of vehicles in a ring using a discrete-time Markov chain on state space $\{0, 1, 2, \cdots N_{\max}\}$, where each state variable X_i $\{i = 0, 1, 2, \cdots\}$ represents the number of vehicles in a ring at step i, as shown in Fig. 6. The one-step transition probability of the Markov chain can be obtained as follows. The probability p_j represents the joint probability that a DN joins the ring successfully and none of the RMNs leaves the ring, given there are j RMNs in the ring. Let $\mathsf{E_j}$ denote the event that a DN joins a ring successfully, and $\mathsf{E_l}$ denote the event that one of RMNs leaves its ring successfully, then $p_j = Pr[\mathsf{E_j} \bigcap \overline{\mathsf{E_l}}]$. $Pr[\mathsf{E_j}] = p_{jr1} \cdot p_{jr2}$, is the joint probability that a DN transmits a JAM and receives a CNM successfully denoted as p_{jr1}, and the SDN (the DN becomes a SDN) connects to its successor and transmits a JSM successfully denoted by p_{jr2}. Similarly, $Pr[\overline{\mathsf{E_l}}] = (1 - p_{lr1} \cdot p_{lr2})^j$, where p_{lr1} is the probability a RMN leaves a ring, and p_{lr2} is the probability that it is deleted successfully. Therefore, p_j is expressed as

$$p_j = p_{jr1} p_{jr2} (1 - p_{lr1} p_{lr2})^j. \tag{1}$$

Using the similar argument, the probability q_j which denotes the joint probability that one of RMNs leaves the ring successfully and no DN joins into the ring successfully is given as

$$q_j = \binom{j}{1} p_{lr1} p_{lr2} (1 - p_{lr1} p_{lr2})^{j-1} (1 - p_{jr1} p_{jr2}). \tag{2}$$

Finally, r_j denotes the joint probability that no DN joins the ring and no RMN leaves the ring, and can be obtained according to

$$\begin{cases} p_0 + r_0 = 1, \\ q_{N_{\max}} + r_{N_{\max}} = 1, \\ p_j + r_j + q_j = 1, \quad j \in [1, N_{\max} - 1]. \end{cases} \tag{3}$$

The transition probability matrix of the Markov chain is given as

$$\mathbf{P} = \begin{bmatrix} r_0 & p_0 & 0 & \cdots & 0 & 0 & 0 \\ q_1 & r_1 & p_1 & \cdots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & q_{N_{\max}-1} & r_{N_{\max}-1} & p_{N_{\max}-1} \\ 0 & 0 & 0 & \cdots & 0 & q_{N_{\max}} & r_{N_{\max}} \end{bmatrix}. \tag{4}$$

Let $M = \min_k(X_k = N_{\max})$ denote the minimum number of steps for a ring to be *full* from the current state j at step 0. $e_j = E[M|X_0 = j]$ denote the average value of M, and it can be expressed as

$$e_j = E[M|X_0 = j] = \sum_{k=0}^{\infty} k \cdot Pr[X_k = N_{\max}|X_0 = j] \quad \text{(5-A)}$$

$$= \sum_{k=0}^{\infty} k \sum_{l=j-1}^{j+1} Pr[X_k = N_{\max}|X_0 = j, X_1 = l] \cdot Pr[X_1 = l|X_0 = j] \quad \text{(5-B)}$$

$$= \sum_{k=0}^{\infty} k \sum_{l=j-1}^{j+1} Pr[X_k = N_{\max}|X_1 = l] \cdot Pr[X_1 = l|X_0 = j] \quad \text{(5-C)}$$

$$= q_j \sum_{k=0}^{\infty} k \cdot Pr[X_k = N_{\max}|X_1 = j-1] + r_j \sum_{k=0}^{\infty} k \cdot Pr[X_k = N_{\max}|X_1 = j]$$

$$+ p_j \sum_{k=0}^{\infty} k \cdot Pr[X_k = N_{\max}|X_1 = j+1]$$

$$= q_j \cdot E[M|X_1 = j-1] + r_j \cdot E[M|X_1 = j] + p_j \cdot E[M|X_1 = j+1] \quad \text{(5-D)}$$

$$= q_j(E[M|X_0 = j-1] + 1) + r_j(E[M|X_0 = j] + 1) + p_j(E[M|X_0 = j+1] + 1) \quad \text{(5-E)}$$

$$= q_j \cdot e_{j-1} + r_j \cdot e_j + p_j \cdot e_{j+1} + 1, \quad 0 < j < N_{\max}. \tag{5}$$

By applying the law of total probability, we obtain (5-B). Due to the Markovian property, (5-B) can be re-written as (5-C). Conditioned on the first state $X_1 = j$, the average number of steps for the ring to be *full*, $E[M|X_1 = j] = E[M|X_0 = j] + 1$, where $E[M|X_0 = j]$ is the average number of steps for the ring to be *full* starting from the initial state $X_0 = j$. Similarly, we have $E[M|X_1 = j-1] = E[M|X_0 = j-1] + 1$ and $E[M|X_1 = j+1] = E[M|X_0 = j+1] + 1$, and we can obtain (5-E). Therefore, e_j can be expressed as

$$e_j = \frac{q_j \cdot e_{j-1} + p_j \cdot e_{j+1} + 1}{p_j + q_j}, \quad 0 < j < N_{\max}. \tag{6}$$

$e_M = E[M|X_0 = M]$ means there are already M nodes in the ring at step 0, and $e_M = 0$, while $X_0 = 0$ means the ring does not exist at step 0, so $Pr[X_M = N_{\max}|X_0 = 0] = 0$, and consequently $e_0 = E[M|X_0 = 0] = 0$. We then have

$$e_{j-1} = \begin{cases} 0 & j = 1, \\ (1 + \frac{p_j}{q_j})e_j - \frac{p_j}{q_j} e_{j+1} - \frac{1}{q_j} & 1 < j < N_{\max}, \\ 0, & j = N_{\max} + 1, \end{cases} \tag{7}$$

which gives

$$e_{N_{\max}-2} = \left(1 + \frac{p_{N_{\max}-1}}{q_{N_{\max}-1}}\right) e_{N_{\max}-1} - \frac{1}{q_{N_{\max}-1}} \tag{8}$$

Based on Eq. (7) and Eq. (8), we can obtain e_j as

$$\begin{aligned} e_j = {} & \left(1 + \sum_{k=j+1}^{N_{\max}-1} \prod_{m=j+1}^{k} \frac{p_m}{q_m}\right) \cdot \frac{\sum_{k=1}^{N_{\max}-1} \frac{1}{q_k}(1 + \sum_{n=1}^{k-1} \prod_{m=1}^{n} \frac{p_{k-m+1}}{q_{k-m}})}{1 + \sum_{k=1}^{N_{\max}-1} \prod_{m=1}^{k} \frac{p_m}{q_m}} \\ & - \sum_{k=j+1}^{N_{\max}-1} \frac{1}{q_k} \left(1 + \sum_{n=1}^{k-1} \prod_{m=1}^{n} \frac{p_{k-m+1}}{q_{k-m}}\right), \quad 0 < j < N_{\max}, \end{aligned} \tag{9}$$

B. Average Emergency Message Delay

The emergency message generated by a RMN takes four steps to reach other nodes: (1) an emergency message is delivered to its RFN during the period T_s; (2) the RFN then broadcasts the emergency message to all its RMNs; (3) through contentions, the RFN wins the opportunity to broadcast the emergency message to its neighboring DNs and other RFNs; (4) a RFN that receives the emergency message broadcasts it to its RMNs. Therefore, the delay of an emergency message is dependent on node types. For RMNs in the same ring, they only need to go through the steps (1) and (2) to receive the emergency message. DNs and SDNs would take steps (1) and (3) to receive the emergency message, while other RMNs in different rings receive the emergency message through steps (1), (3) and (4).

Let T_{xy} denote the delay of the emergency message transmitted from a RMN x to a node y, and $I(x)$ is the RFN of node x. If y is a DN or SDN, $I(y) = \emptyset$. When a RMN x transmits an emergency message, the emergency message delay is given by

$$T_{xy} = \begin{cases} t_s + t_r & \text{if } I(x) = I(y), \\ t_s + t_m & \text{if } I(y) = \emptyset, \\ t_s + t_m + t_r & \text{if } I(y) \neq \emptyset \text{ and } I(x) \neq I(y), \end{cases} \tag{10}$$

where t_s is the time for transmitting an emergency message from a RMN to its RFN, t_r is the time spent by the RFN broadcasting an emergency message to its RMNs, and t_m is the duration that the RFN broadcasts an emergency message to its neighboring RFNs, DNs and SDNs. It is possible that two nodes in the same ring detect an accident, and deliver emergency messages to their RFN simultaneously. However, the number of RMNs in each ring can not be larger than N_{max}, and moreover the collision probability of intra-ring emergency message exchange is very little. Consequently, the contentions in steps (1), (2) and (4) are negligible, and the corresponding time spent in these steps are bounded. Therefore, a RMN only waits for a t_{sifs} before accessing the channel in the T_s interval and there is no contention for the transmission in the same ring, and $t_s = 2t_{sifs} + L_{em}/R_b + t_{ack}$, $t_r = t_{sifs} + L_{em}/R_b$. Where L_{em} is the packet size of the emergency message. In the following, we focus on the emergency message broadcasting in step (3), which is transmitted in contention mode on CH178. For a node i, we further define F_i as the set of the neighboring RFNs within its transmission range, D_i is the set of DNs and SDNs operating on the same channel within its transmission range, N_i is the set of RMNs in the same ring with node i, and $|\mathsf{F}_i|$, $|\mathsf{D}_i|$, $|\mathsf{N}_i|$ are the numbers of nodes in F_i, D_i, N_i respectively. We define γ_i as the probability that a node i randomly selects a time slot, and θ_i is the probability that at least one neighboring node selects the same time slot. From [19]:

$$\gamma_i = \frac{2(1-2\theta_i)}{(1-2\theta_i)(cw_{\min}+1) + \theta_i cw_{\min}(1-2\theta_i^{T_{retry}})}, \tag{11}$$

$$\theta_i = 1 - (1-\gamma_i)^{|\mathsf{F}_i|+|\mathsf{D}_i|}, \tag{12}$$

where $cw_{\min}$ is the minimum contention window size, and T_{retry} is the maximum retry limit. Let

τ_i denote the probability that no other nodes choose the same time slot, and node i transmits a packet successfully, consequently it can be represented as:

$$\tau_i = \frac{\gamma_i(1-\gamma_i)^{|\mathsf{F}_i|+|\mathsf{D}_i|}}{\theta_i + \gamma_i(1-\gamma_i)^{|\mathsf{F}_i|+|\mathsf{D}_i|}}. \quad (13)$$

Let Z denote the number of neighboring nodes that send their packets successfully during the backoff period of node i. Assuming equal transmission probability of each node, the mean of Z can be obtained as $E(Z) = (|\mathsf{F}_i| + |\mathsf{D}_i|) \cdot \tau_i$. Each data transmission will occupy the channel for the interval t_p, which is given by

$$t_p = t_{difs} + t_{rts} + 4\varphi + 3t_{sifs} + t_{cts} + L_d/R_d + t_{ack}, \quad (14)$$

where t_{difs} is the DIFS interval, t_{rts}, t_{cts} and t_{ack} are the time for transmitting a RTS, a CTS and an ACK packet, respectively, φ is the propagation delay. L_d is the size of a data packet, R_d is the data transmission rate. Accordingly, the delay t_b which includes the frozen time due to neighboring nodes' transmissions and the backoff time can be given by $t_b = E[Z]\cdot t_p + E[CW]\cdot\rho$, where $E[CW]$ is the average contention window size, and ρ is the slot duration. t_m is the sum of t_{difs}, the delay t_b, and the emergency message transmission time, which is denoted as $t_m = t_{difs} + t_b + L_{em}/R_b$.

C. Average Ring Throughput

Since a node can transmit its intra-ring data packets only when it holds a token in the T_d interval, the ring throughput depends on how long a node holds the token. A THN is in *saturated* state if it always has data packets in its IADB to transmit during the T_{MTH} interval, and being in *unsaturated* state if it holds the token only for partial T_{MTH} interval. Let ϕ_d and ϕ_t denote the transmission time of the data and the token, respectively, which are given by

$$\phi_d = t_{sifs} + L_d/R_d + \varphi + t_{sifs} + t_{ack} + \varphi \quad (15)$$

$$\phi_t = t_{sifs} + L_T/R_b + \varphi + t_{sifs} + t_{ack} + \varphi \quad (16)$$

The average throughput S during the period T can be obtained as

$$S = \frac{|\mathsf{N}_f| \cdot \frac{T_{MTH}-\phi_t}{\phi_d} \cdot L_{\mathsf{D}} + \sum_{i\in\overrightarrow{\mathsf{N}_f}} n_i \cdot L_{\mathsf{D}}}{T}, \quad (17)$$

where n_i is number of packets that an *un-saturated* node i transmits within its token holding time, N_f is the set of *saturated* nodes during the period T, $\overrightarrow{\mathsf{N}_f}$ is the set of *un-saturated* nodes during the period T. $|\mathsf{N}_f|$ is the number of nodes in N_f. A special case arises when all RMNs are in *saturated* state, leading to the average ring throughput:

$$S = \frac{|\mathsf{N}_f| \cdot (T_{MTH} - \phi_t) \cdot L_{\mathsf{D}}}{T \cdot \phi_d} \tag{18}$$

D. Access Delay

The access delay measures how long a RMN needs to wait from the THN to obtain the token for intra-ring data communications. We denote n_{ij} as the number of total nodes from the current THN i to another RMN j in the token circulation direction. There will be $n_{ij} \cdot |\mathsf{N}_f|/(|\mathsf{N}_f| + |\overrightarrow{\mathsf{N}_f}|)$ *saturated* nodes from i to j. If nodes i and j are in the same T_d period, node j will not wait T_s and T_c interval, and the waiting time t_{ij} which represents the latency for node j obtaining the token from i is given as

$$t_{ij} = n_{ij} \cdot |\mathsf{N}_f|/(|\mathsf{N}_f| + |\overrightarrow{\mathsf{N}_f}|) \cdot T_{MTH} + \sum_{i \in \overrightarrow{\mathsf{N}_f}} (n_i \cdot \phi_d + \eta + \phi_t) \tag{19}$$

where η is the value set by token passing timer, meaning that an *un-saturated* state node must pass the token to its successor if there are no packets in IADB to transmit for a period of η. If nodes i and j are in successive T_d period, the access delay is expressed as

$$t_{ij} = T_s + T_c + n_{ij} \cdot |\mathsf{N}_f|/(|\mathsf{N}_f| + |\overrightarrow{\mathsf{N}_f}|) \cdot T_{MTH} + \sum_{i \in \overrightarrow{\mathsf{N}_f}} (n_i \cdot \phi_d + \eta + \phi_t) \tag{20}$$

VI. Numerical Results

Extensive simulations are conducted with ns-2 [20] to evaluate the performance of MCTRP. We consider the scenario where vehicles are running on a 10m width highway, and they move at the speed between 10m/s and 30m/s to the same direction. All the vehicles are randomly distributed and within each other's transmission range at the beginning. To the best of our knowledge, how to model wireless fading channel in a VANET is still an open issue. In this paper, we use the wireless channel model in NS-2, where Friis free-space model for short distance and the two-ray model for long distance are used to determine the received power, and no pass loss due to shadowing is considered. We repeat every simulation for 100 times, each of which takes 50 seconds, and calculate the average value. The parameters used in the simulations are listed in Table II.

Average full ring delay – Fig. 7 shows the average *full* ring delay versus the number of inter-ring flows in the network. As mentioned in Sec. V-A, it is desirable that DNs should be quickly organized into rings. It can be observed that average *full* ring delay increases as the number of inter-ring flows increases, which takes 0.6 ~ 0.8 s, for 2 to 10 flows at the constant bit rate (CBR) of 100 packets/s. Since we bound the speed difference between RMNs and their RFNs to $[0, v_d]$, the topology of the ring is relatively stable, and a ring can quickly reach *full* state after it is created given a sufficient number of DNs. However, with the number of inter-ring flows increasing, JAMs and CNMs may be lost due to collisions, which makes the joining process aborted.

Average emergency message delay – In MCTRP, the RFN contends for channel access with neighboring inter-ring flows in order to broadcast the emergency message to neighboring RFNs, DNs. Inter-ring flows in this simulation are transmitted at the rate of 100 packets/s. Fig. 8 shows the average emergency message delay under different numbers of inter-ring flows in both inter-ring and intra-ring communications. It can be seen that even for the high node density, e.g., 10 flows, the emergency message delays in both inter-ring and intra-ring communications are less than 20ms, which is much less than the common accepted requirement (100ms) for safety applications in VANET [21]. Furthermore, the delay of intra-ring is always less than that of inter-ring, and is independent of the number of inter-ring flows. This is because the emergency message exchange within a ring takes place on the dedicated SCH during the T_s interval when only a limited number of nodes contend in the ring, and consequently the delay is not sensitive to the increase of the number of inter-ring flows in the network. While inter-ring emergency messages are delivered by the RFN contending with a number of DNs, SDNs, RFNs on the channel CCH178. This is an important advantage of MCTRP over the purely use of contention-based MAC protocols in vehicular communications, as intra-ring nodes close to the accident site have a higher chance to quickly receive the warning message.

Average ring throughput – The throughput of MCTRP, IEEE 802.11, and OTRP [13] are compared, as shown in Fig. 9. All nodes are within each other's transmission range, and a RMN starts intra-ring data exchange after it receives the token. We consider different traffic load by varying the CBR rate. Fig. 9(a) shows the number of data flows versus the throughput of MCTRP, IEEE 802.11, and OTRP with nodes in *saturated* scenario, which means all the transmitters always have data packets to send in their buffers. As the number of flows increases, the throughput of IEEE 802.11 decreases greatly, while the throughput of MCTRP and OTRP do not vary much, and are higher than that of IEEE 802.11 eventually. However, the throughput of OTRP is much lower than that of MCTRP all the time. These observations can be explained as follows. In IEEE 802.11, packet collisions are serious in dense nodes scenario, which degrades the channel utilization. OTRP can reduce collisions by incorporating nodes into different rings. But it can not eliminate collisions among different rings. In MCTRP, the token holding time for a saturated THN consists of two parts: 1) the data transmission time; and 2) the token exchange time. There are no RTS/CTS control packets for intra-ring data communications, which boosts the utilization of channel resource dramatically and thus increases the throughput. Furthermore, taking the advantage of multi-channel structure in MCTRP, different rings set up in dense node scenario, and adopt different SCHs. As a result, the whole network throughput will increase since there are no co-channel interference within the transmission range.

Fig. 9(b) shows the throughput comparison among MCTRP, IEEE 802.11, and OTRP with nodes in *unsaturated* state. It is observed that IEEE 802.11 performs better than MCTRP and OTRP for a small number of flows. With the node density increasing, the throughput of IEEE 802.11 decreases significantly as compared to that of MCTRP and OTRP. Similar to throughput comparison in *saturated* state, throughput of OTRP is much lower than that of MCTRP. MCTRP makes use of the multi-channel structure in conjunction with the token for intra-ring communications, which significantly reduce the contentions among neighboring nodes, and consequently the ring throughput of MCTRP does not change much as the node density increases, which makes it suitable for the VANET with a dense vehicle network. Even packet collision in light traffic load is not extensive, OTRP may not fully utilize the channel because each node is required to hold the token for a constant period of time without adapting to the dynamic change of traffic load.

Access delay – Fig. 10 shows the access delay for a RMN j to receive the token from the current THN i. Firstly, we can observe that the access delay increases with a larger number of intermediate nodes between j and i. Moreover, the access delay increases sharply when the number increases from 7 to 9 with traffic load 100 packets/s. It is because that j can not receive the token at the end of T_d, and it must wait $T_s + T_c$ time interval for next T_d. Secondly, the traffic load also has a direct impact on the access delay. For a fixed number of intermediate nodes, j takes much longer time to receive the token when the traffic load of intermediate nodes is higher, and the maximum access delay is reached when all intermediate nodes are *saturated*. In MCTRP, the token holding time varies according to the node's traffic load. If there is no packet in IADB for a time interval set by the token passing timer, the THN must deliver the token to its successor. It prevents a node which has no data packets to transmit from holding the token for the whole T_{MTH} interval, while a node with a heavy traffic load has to wait the token for intra-ring data communications.

VII. Conclusion

We have proposed a multi-channel token ring protocol for achieving efficient inter-vehicle communications based on the channel structure specified in IEEE 802.11p. By combining the notion of virtual rings and distributed multi-channel management, the proposed protocol has the following features: i) The emergency messages are quickly delivered to nearby vehicles; ii) The network throughput is significantly improved especially in dense vehicle scenarios by dynamic SCHs allocation; and iii) MCTRP reduces the channel access time of each node by adjusting the token holding time of nodes according to their traffic load. In addition, an analytical model has been developed to evaluate the performance of MCTRP, and simulation results have been given to demonstrate that MCRTP can guarantee QoS requirements for both safety related applications and non-safety multimedia applications in IVC. In our future work, we will extend MCTRP to integrate RVC and IVC communications environment. We will further study the performance of proposed protocol in the presence of different fading and shadowing scenarios in VANET.

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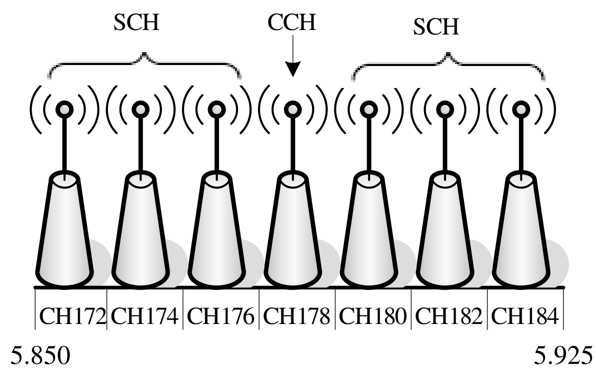


Fig. 1. Multi-channel structure.

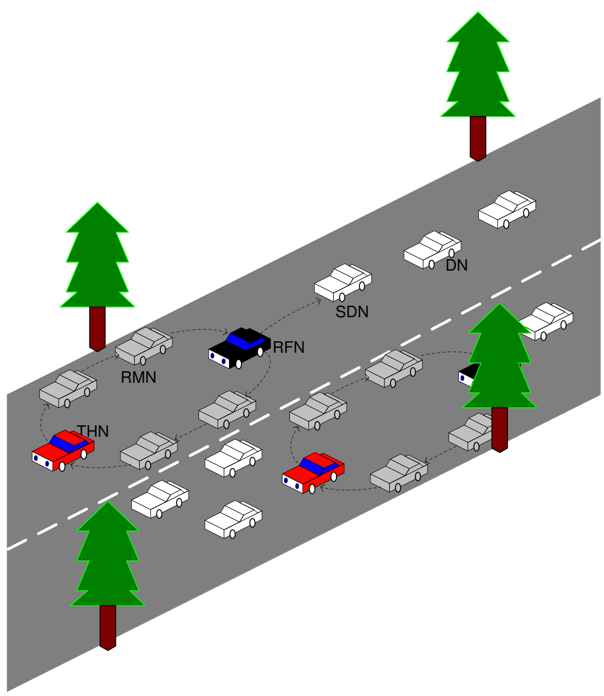


Fig. 2. Different types of vehicles in the proposed MCTRP.

TABLE I
SUMMARY OF IMPORTANT SYMBOLS

Symbol	Definition	Symbol	Definition
CCH	control channel	SCH	service channel
RFN	ring founder node	THN	token holder node
RMN	ring member node	DN	dissociative node
SDN	semi-dissociative node	EM	emergency message
RFM	ring founding message	JIM	joining invitation message
JAM	joining acknowledgement message	CNM	connection notification message
CSM	connecting successor message	CAM	connection acknowledge message
JSM	joining success message	ANM	address notification message
IADB	intra-ring data buffer	IRDB	inter-ring data buffer
T	the ring period	T_s	the safety period
T_c	the coordination period	T_d	the data exchange period
T_{MTH}	maximum token holding time	T_{retry}	maximum retransmission times
t_{sifs}	SIFS interval	t_{difs}	DIFS interval
η	the value set by token passing timer	ρ	time slot
L_{em}	size of the emergency message	L_d	size of the data packet
N_{max}	maximum number of RMNs in a ring	e_j	the steps for a ring to be full from the state j
t_s	the delay for transmitting an EM from a RMN to its RFN	t_r	the delay for a RFN broadcasting an EM to its RMNs
F_i	the set of neighboring RFNs of i	D_i	the set of neighboring DNs and SDNs of i
N_i	the set of RMNs in the same ring with node i	N_f	the set of saturated RMNs in the ring
$\overrightarrow{\mathsf{N}_f}$	the set of un-saturated RMNs in the ring	γ_i	the probability that a node i randomly selects a time slot
τ_i	the probability that node i transmits a packet successfully	φ	the propagation delay on the channel
t_m	the delay for a RFN broadcasting an EM to its neighboring RFNs, DNs and SDNs	θ_i	the probability that at least one neighboring node selects the same slot with i
p_j	the joint probability that a DN joins the ring and no RMN leaves the ring	q_j	the joint probability that one RMNs leaves the ring and no DN joins the ring

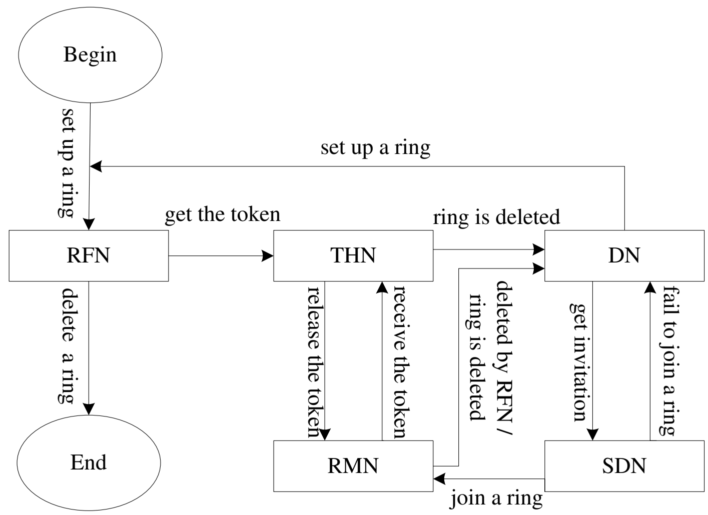


Fig. 3. State transitions diagram

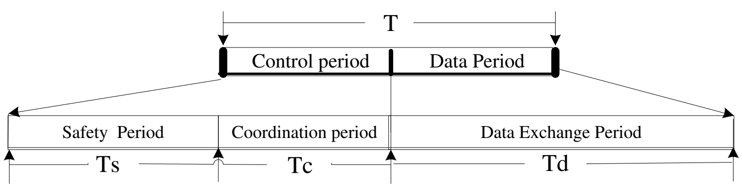


Fig. 4. Timing structure

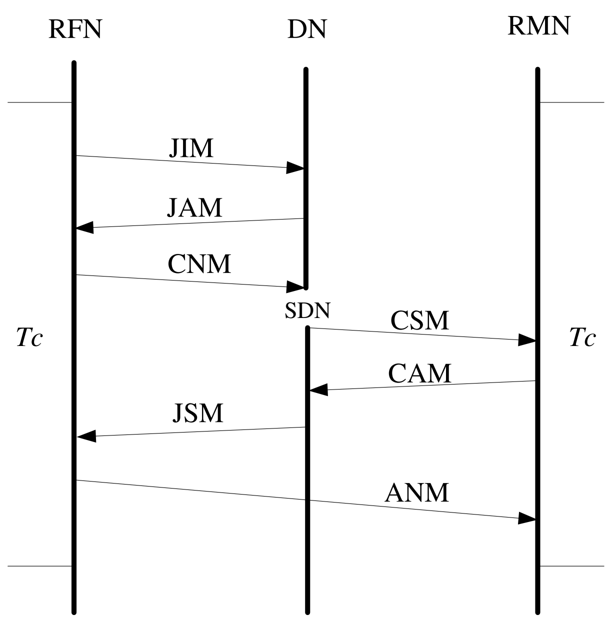


Fig. 5. Illustration of the joining process.

Algorithm 1 Token Delivery Algorithm

1: **if** A node i received a token **then**
2: $t_{th} = 0$;
3: **if** $i.IADB! = NULL$ **then**
4: If the timer t_w is open, turn off it;
5: Get a packet D from i.IADB, and compute its transmission time t_d;
6: **if** $t + t_d \leq T$ **then**
7: **if** $t_{th} + t_d \leq T_{MTH}$ **then**
8: Transmit data;
9: Update the current time $t = t + t_d$ and token hold time $t_{th} = t_{th} + t_d$;
10: **if** transmission is successful **then**
11: Delete D from i.IADB, and go to line 3;
12: **else**
13: Go to line 6;
14: **end if**
15: **else**
16: Go to line 31;
17: **end if**
18: **else**
19: Wait until next data exchange period T_D and go to line 6;
20: **end if**
21: **else**
22: **if** the timer t_w is off **then**
23: Turn on the timer t_w;
24: **end if**
25: **if** the value of t_w is less than η **then**
26: Keep checking buffer status, and go to line 3 when i.IADB becomes non-empty;
27: **else**
28: Go to line 31;
29: **end if**
30: **end if**
31: Set $t_{retry} = 0$;
32: **if** $t_{retry} \leq T_{retry}$ **then**
33: **if** $t + t_{token} \leq T$ **then**
34: Attempt to pass the token to the successor;
35: Update $t = t + t_{token}$ and $t_{retry} + +$;
36: **else**
37: Wait until next data exchange period T_D to pass a token;
38: **end if**
39: **if** Token passing is successful **then**
40: Successor receives a token, go to line 1
41: **else**
42: Go to line 32;
43: **end if**
44: **else**
45: Attempt to pass the token to the next node of i's successor and go to line 31.
46: **end if**
47: **end if**

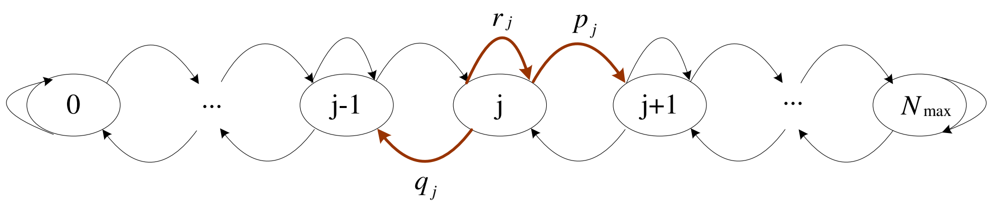


Fig. 6. State transition of a ring modeled by Markov chain.

TABLE II
PARAMETERS USED IN PERFORMANCE EVALUATION

Parameter	Value	Parameter	Value
t_{sifs}	32 μs	T_{retry}	5
t_{difs}	64 μs	RTS	21 bytes
ρ	16 μs	CTS	15 bytes
φ	1 μs	ACK	15 bytes
$cw_{\min}$	31	RFM	22 bytes
$cw_{\max}$	1023	JIM	29 bytes
T	60 ms	JAM	21 bytes
T_s	20 ms	CNM	23 bytes
T_c	10 ms	CSM	21 bytes
T_d	30 ms	JSM	22 bytes
T_{MTH}	5 ms	L_d	512 bytes
v_d	5 m/s	L_{em}	100 bytes
$N_{\max}$	10	transmission range	250m
basic rate (R_b)	1 Mbps	data rate (R_d)	11 Mbps

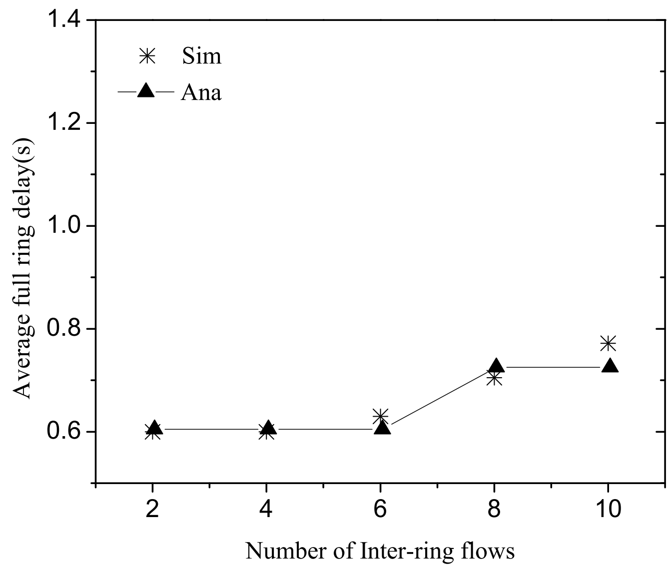


Fig. 7. Average *full* ring delay *vs.* number of inter-ring flows.

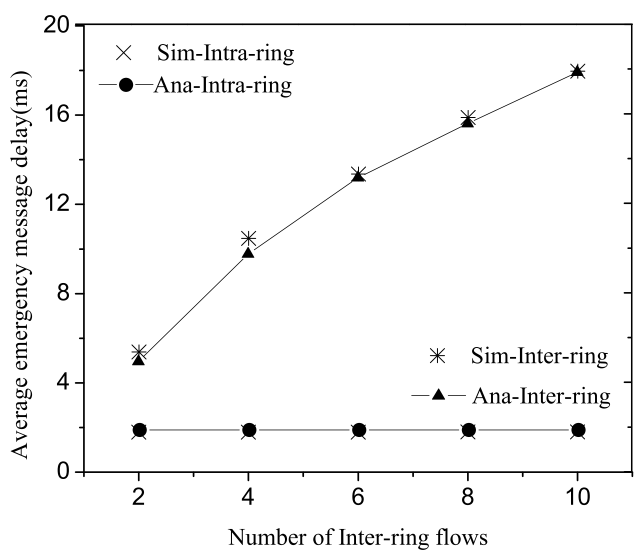
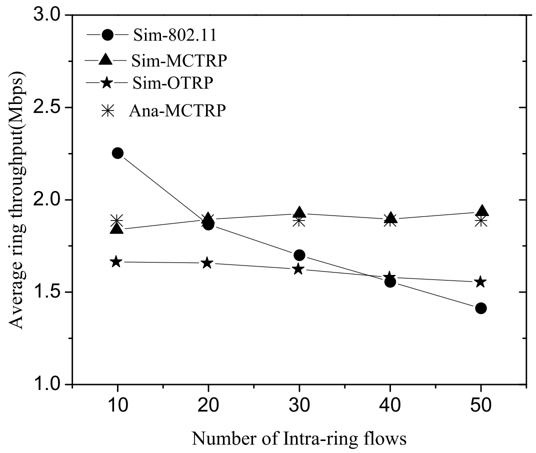
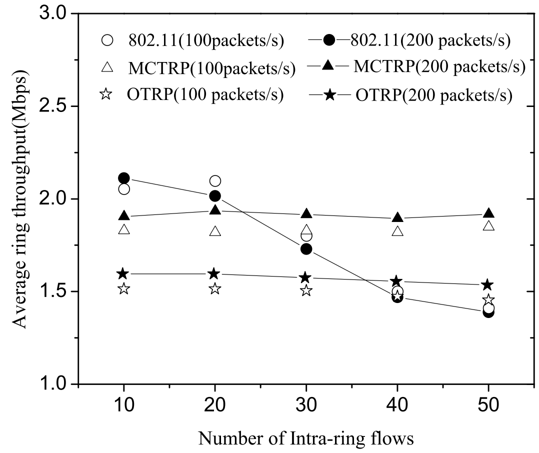


Fig. 8. Average emergency message delay *vs.* number of inter-ring flows.



(a) Saturated case



(b) Unsaturated case

Fig. 9. Comparisons of throughput between MCTRP and IEEE 802.11

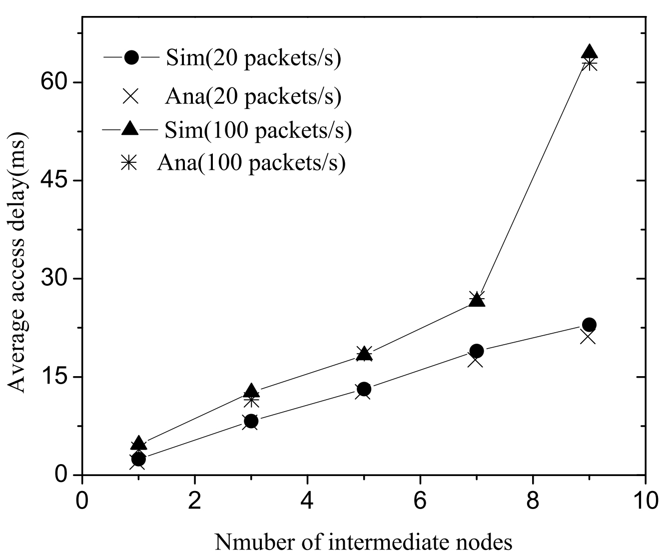


Fig. 10. Access delay for RMNs.