Efficient and Reliable Broadcast in Intervehicle Communication Networks: A Cross-Layer Approach

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***Abstract*—Broadcast transmission is an effective way to disseminate safety-related information for cooperative driving in intervehicle communication (IVC). However, it is fraught with fundamental challenges such as message redundancy, link unreliability, hidden terminals, and broadcast storms, which greatly degrade network performance. In this paper, we introduce a cross-layer approach to design an efficient and reliable broadcast protocol for emergency message dissemination in IVC systems. We first propose a novel composite relaying metric for relay selection by jointly considering geographical locations, physical-layer channel conditions, and moving velocities of vehicles. Based on the relaying metric, a distributed relay-selection scheme is proposed to assure that a unique relay is selected to reliably forward the emergency message in the desired propagation direction. We further apply IEEE 802.11e enhanced distributed coordination access (EDCA) medium-access control (MAC) to guarantee quality-of-service (QoS) provisioning to safety-related services. In addition, an analytical model is developed to study the performance of the proposed cross-layer broadcast protocol (CLBP) in terms of the relay-selection delay and the emergency message access delay. Network Simulator (NS-2) simulation results are given to validate our analysis. It is shown that the CLBP not only can minimize the broadcast message redundancy but can quickly and reliably deliver emergency messages in IVC as well.**

***Index Terms*—Broadcast protocol, cross-layer design, intervehicle communication (IVC), relaying metric.**

I. Introduction

COOPERATIVE driving can improve safety and efficiency by enabling vehicles to exchange emergency messages to each other in the neighborhood. In vehicular ad hoc networks (VANETs), vehicles transmit traffic and safety-related information, including traffic congestion-avoidance messages, accident warnings, accident reports, etc., which assist drivers in making proper decisions to avoid vehicle collisions and congestion. Compared with vehicle-to-infrastructure communications, intervehicle communication (IVC) is more flexible for deployment with low cost [2], and research on IVC has recently attracted great attention from academia, industry, and governments. The U.S. Federal Communications Commission has approved 75-MHz (5.850–5.925 GHz) bandwidth for dedicated short-range communication systems in support of intelligent transportation system applications [3]. Industry manufacturers have launched several projects to study cooperative driving in IVC, such as advanced driver-assistance systems (ADASE2) [4], the Crash Avoidance Metrics Partnership [5], CarTALK2000 [6], FleetNet [7], Partners for Advanced Transit and Highways [8], etc.

Broadcast transmission is a frequently used approach to advertise information in VANETs. Nevertheless, effectively broadcasting emergency messages to other vehicles in IVC is extremely challenging, particularly due to high mobility and a hostile wireless environment. First, as no acknowledgment (ACK) mechanism is applied for broadcast messages in the medium-access-control (MAC) layer, message loss due to packet collisions or poor channel conditions cannot be easily detected. Since life-critical emergency messages have to be delivered to other vehicles as fast and reliable as possible [9], the traditional broadcasting scheme without an ACK mechanism is not suitable for emergency message delivery in IVC. Second, due to the limited transmission range, message relaying from intermediate nodes[1] is required to reach remote vehicles. However, without an effective broadcast control mechanism, multiple copies of the broadcast messages may be delivered among nodes, which could result in a broadcast storm problem [10] and degrade the network resource utilization. Some research works propose to reduce message redundancy and prevent broadcast storm by selecting a subset of neighboring nodes to forward the broadcast message. However, it is a nontrivial task to determine a proper subset of nodes that can simultaneously guarantee the message reliability and achieve efficient resource utilization.

To address the aforementioned issues, several broadcasting protocols have been proposed in the literature. Some protocols make use of network-layer broadcast-control algorithms to reduce the message redundancy [12]–[16], but they cannot guarantee the MAC layer reliability. Other protocols aim at improving the transmission reliability by repeatedly broadcasting

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[1]The terms “node” and “vehicle” are interchangeably used throughout this paper.

messages [17] or selecting the farthest node to relay messages [20]–[22]. However, repeated broadcast cannot completely guarantee the transmission reliability but degrades the resource utilization. The farthest node may suffer from a high packet error rate (PER) and is not an ideal relay candidate, particularly in high-speed vehicle networks. In this paper, we propose the CLBP for emergency message dissemination in IVC, aiming to improve the transmission reliability, minimize the message redundancy, and reduce the link delay. We first design a novel relaying metric, which is composed of geographical locations, physical-layer channel conditions, and moving velocities of vehicles. Based on the metric, we apply a revised request-to-send/clear-to-send (RTS/CTS) scheme to distributedly select an appropriate relaying node. Specifically, after receiving a broadcast RTS (BRTS) frame, each relay candidate starts its back-off timer to reply a broadcast CTS (BCTS) frame based on the calculated relaying metric in a distributed manner. After a successful BRTS/BCTS handshake, one node is successfully selected as the next hop relay to forward the broadcast message in the desired propagation direction. Furthermore, to support different services with various quality-of-service (QoS) requirements in IVC, we adopt the priority-based enhanced distributed channel access (EDCA) of the IEEE 802.11e MAC to support safety services. The emergency messages are served with the highest priority, and thus, the minimum channel-access delay can be achieved.

Different from previous work, the proposed CLBP jointly takes the special characteristics of the vehicle networks into consideration, i.e., mobility, channel conditions, etc., and aims to guarantee the QoS requirements of the safety-related applications in IVC. Specifically, it has the following features: 1) The CLBP adopts a cross-layer approach to select only one relaying node at each hop, which not only can reduce the broadcast message redundancy but can alleviate the hidden terminal problem and increase the message reliability as well; 2) the CLBP includes a composite relaying metric adapting to the IVC environment, which enables the broadcast message to be delivered as quickly as possible and avoids message retransmissions due to the hostile channel conditions; and 3) by service differentiation, the broadcast emergency message can quickly access the channel resource and, thus, achieves a shorter link delay.

The main contributions of this paper are threefold. First, we design a novel metric for selecting a proper relaying node to forward the emergency message. Second, based on the derived metric, we propose a cross-layer approach to efficiently broadcast emergency messages in the desired propagation direction. Third, we analyze the network performance in terms of the PER of the emergency message, the relay selection delay, and the emergency message-access delay. Analytical and simulation results with the Network Simulator (NS-2) demonstrate that the proposed cross-layer approach can quickly and reliably deliver emergency messages while minimizing the broadcast message redundancy.

The remainder of this paper is organized as follows. We briefly review the related work in Section II. The proposed CLBP is described in Section III. An analytical model is developed to study the performance of the CLBP in Section IV. The simulation results are given to demonstrate the efficiency of the CLBP in Section V, followed by conclusions in Section VI.

II. Related Work

Broadcast protocols in mobile ad hoc networks can be classified into four categories [11]:

1) simple flooding [12], [13], in which a node rebroadcasts a new message until it reaches all connected nodes in the network;
2) probability-based methods [14], in which protocols can be further divided into two subclasses:
   a) a node rebroadcasts a message according to a predefined probability, and this scheme becomes a simple flooding one if the probability is set to 1;
   b) a node decides whether to rebroadcast a message based on the number of the received copies during a certain interval;
3) an area-based method [14], in which a node that can cover more additional area is selected to forward the received message;
4) a neighbor knowledge method [15], [16], in which a node makes a forwarding decision according to the knowledge of its one-hop or two-hop neighbors.

All these aforementioned broadcast protocols aim to reduce the number of redundant messages at the network layer, without considering the MAC layer hidden terminal problem, collisions, link reliability, etc. It is well known that broadcast transmission is not reliable due to the lack of the ACK scheme in the MAC layer. However, some emergency messages are life critical, the delivery of which should be guaranteed. Therefore, previous works on the network-layer broadcast protocol design cannot be directly applied to IVC.

Recently, some protocols have been proposed for emergency message delivery in IVC. In [28], a distributed MAC protocol for emergency message dissemination is presented. A node reserves the data channel for emergency message broadcast by sending a pulse signal through the control channel. A MAC protocol that is designed for emergency message broadcasting is studied in [17], where a node broadcasts emergency messages several times to increase the transmission reliability. However, repeatedly broadcasting messages cannot guarantee the successful reception of broadcast messages but may increase the contention level in a distributed vehicle network and waste the scarce wireless network resources. A black-burst-based [18], [19] ad hoc multihop broadcast (AMB) protocol is proposed for emergency message dissemination in [20]. A neighboring node sends a channel jamming signal (black burst) with the time duration that is proportional to its distance. Thus, the farthest neighboring node sending the longest jamming signal wins the contention and becomes the next hop-relaying node. Nevertheless, the largest jamming duration that is used by the relay candidate causes a long delay for emergency messages. In the position-based multihop broadcast protocol [21], the farthest neighboring node waits the shortest time duration to reply the broadcast node. However, the farthest node usually suffers from a large path loss and a high PER, which may cause MAC layer retransmissions and, thus, a longer link delay. In [22], each node maintains a list of neighboring nodes and always selects the farthest neighboring node as the next hop relay. However, the network topology of IVC dynamically changes due to the high mobility of vehicles; therefore, effectively updating the list of neighbors is not a trivial task.

To reduce the link delay and improve the throughput, many relaying and routing metrics have been proposed in cooperative relaying schemes and routing protocols. In [23], the expected transmission count (ETX) is proposed to measure the expected number of transmissions that a node attempts until a packet is successfully delivered to the next relaying node. The routing scheme based on the ETX assures that the selected path achieves the minimum link delay. Similar routing metrics such as expected transmission time (ETT) and weighted cumulative ETT [24] also consider channel conditions and link reliability in the metric design. In [25], the enhanced interior gateway routing protocol adopts a composite metric, which uses weight factors to decide the impacts of the minimum link bandwidth, traffic load, link delay, and reliability on path selection. The cooperative MAC is proposed in [26], in which each node maintains a table of relays that can improve the link throughput and selects the relay with better channel conditions and a higher data rate. A cross-layer routing and MAC design for millimeter-wave wireless networks is studied in [27], which uses geographic position to maximize the channel resource utilization. However, all these schemes select paths or relays based on channel conditions or geographic information, and they do not consider the specific characteristics of VANETs, i.e., high mobility. In this paper, we jointly consider the geographical locations, the channel conditions, and the relative velocities of vehicles to make a relay decision in IVC.

III. Proposed Cross Layer Broadcast Protocol

We consider a highway with M lanes, and half of the lanes are used for vehicles driving to one direction, whereas the other half are used for vehicles driving to the opposite direction. A vehicle's velocity is randomly distributed among a discrete set $V = \{V_i | V_{i-1} < V_i, i \in (1, P]\}$, and the velocity is directional since vehicles may move to two different directions. Each vehicle is equipped with a half-duplex transceiver and a Global Positioning System, by which it can acquire its position information, moving velocity, and moving direction. As shown in Fig. 1, the transmission range of a vehicle R_t is divided into a number of blocks, and the length of each block is ϕ, which should be the minimum safety distance for two adjacent moving vehicles. Therefore, there are $Q = \lfloor R_t/\phi \rfloor$ blocks within R_t, and their distances to the broadcast vehicle are represented as $\{B_i | B_i = i \cdot \phi, i \in [1, Q]\}$. We use the carrier sense multiple access with collision avoidance (CSMA/CA)-based 802.11e MAC for channel access and service differentiation among multiple nodes. To provide reliable transmissions of broadcast messages, BRTS/BCTS frames are exchanged before emergency messages. In addition, in the proposed CLBP, one relaying node is selected to forward the emergency message in the desired propagation direction based on a novel relaying metric that is designed for IVC.

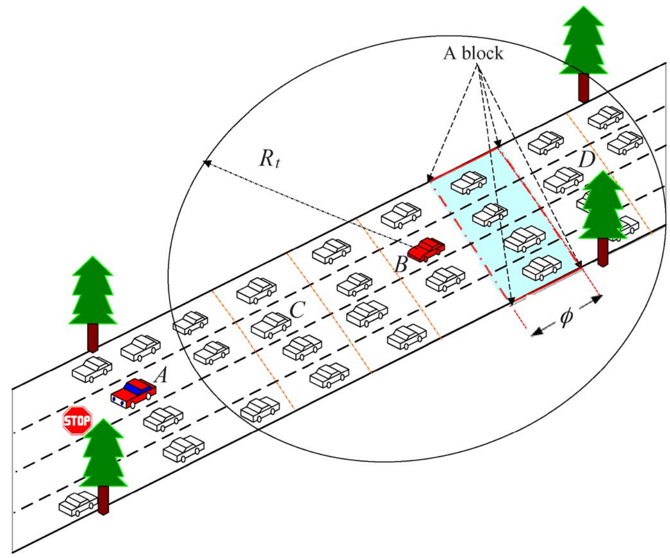

Fig. 1. Blocks on the highway.

A. BRTS/BCTS Handshake

The structure of a BRTS frame is shown in Fig. 2. Compared with the traditional RTS frame, five fields are added in the BRTS frame: *em_info*, *t_direction*, *t_velocity*, *r_x*, and *r_y*. The field *em_info* takes the information of the source node, which initially transmits the emergency message, and it contains 1) the source node address *init_addr*; 2) the position information of the source nodes *init_x* and *init_y*; 3) the sequence number of the emergency message *em_seq*; and 4) the weight factors α_1, α_2, and α_3 that are used for relaying metric calculation and relaying node selection. *t_direction* is the message propagation direction, *t_velocity* is the moving velocity of the current broadcast node, and *r_x* and *r_y* indicate the position of the broadcast node.

When a node has an emergency message for transmission, it first broadcasts a BRTS frame based on the CSMA/CA mechanism and starts a retransmission timer whose value is set to be $t_{\mathrm{brts\_}r} = t_{\mathrm{brts}} + t_{\mathrm{difs}} + t_{\mathrm{bcts}}$, where t_{brts} and t_{bcts} are the transmission times of a BRTS frame and a BCTS frame, respectively, and t_{difs} is the time duration of a Distributed Coordination Function (DCF) interframe space (DIFS). If there is no BCTS response within $t_{\mathrm{brts\_}r}$, the node contends for channel access to immediately rebroadcast a BRTS frame until a BCTS frame is successfully received. The broadcast node sets its *duration* field in the BRTS frame such that any node that hears the BRTS frame but is not eligible for replying a BCTS frame will set its Network Allocation Vector (NAV) and defer its own transmissions accordingly.

After receiving a BRTS frame, a node decides whether it is eligible for replying a BCTS frame based on the direction information or the position information of the received BRTS frame. If *init_addr* in the received BRTS frame is the same as the address of the current broadcast node, it implies that this is the first hop emergency message dissemination, and the node will decide whether to reply a BCTS frame based on propagation direction *t_direction*. Otherwise, if its own position is between the original source node and the current broadcast node, it will not reply a BCTS frame since there is no distance

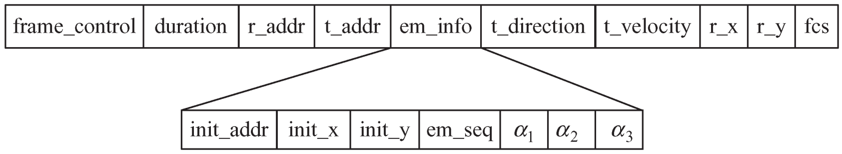

Fig. 2. Format of the BRTS frame.

gain along the propagation direction. In this case, the node updates its NAV according to the *duration* field in the received BRTS frame. Otherwise, it starts a back-off timer for replying a BCTS frame and keeps sensing the channel in the mean time. As shown in Fig. 1, A is the source node that initiates an emergency message, and B is the current broadcast node. Node C will not reply a BCTS frame to B since it locates between A and B, whereas D is eligible for relaying the message and starts a back-off timer upon receiving a BRTS frame. This guarantees that the emergency message will be efficiently forwarded along the desired propagation direction.

Each eligible relaying node that locates at (x, y) and moves at velocity v will start a timer for replying a BCTS frame according to the following metrics: 1) the distance from the current broadcast node to itself; 2) the received SNR and PER, which can be estimated from the received BRTS frame; and 3) the velocity difference from the current broadcast node. Based on the three metrics, the relay candidate evaluates the composite relaying metric $\mathcal{F}$ that is used for relay selection, which is given by

$$\mathcal{F} = \alpha_1 \cdot \left(1 - \frac{\Delta d}{B_Q}\right) + \alpha_2 \cdot \frac{e}{E_{\max}} + \alpha_3 \cdot \frac{\Delta v}{2V_P} \tag{1}$$

where

$$\Delta d = \left\lfloor \frac{\sqrt{(x - r\_x)^2 + (y - r\_y)^2}}{\phi} \right\rfloor \cdot \phi$$

$$\Delta v = |\overrightarrow{v} - \overrightarrow{t\_velocity}|.$$

Δd is the transmission distance, e is the PER of the emergency message that is calculated based on the measured SNR, Δv is the relative velocity, B_Q is the distance of the farthest block in the transmission range, $E_{\max}$ is the maximum tolerable PER defined in [29], V_P is the maximum velocity, and α_1, α_2, and α_3 $(\alpha_1 \geqslant 0, \alpha_2 \geqslant 0, \alpha_3 \geqslant 0)$ are weight factors and usually configured by users. For instance, if a user wants the messages to be delivered over a fewer number of hops or with a reduced PER, he can accordingly set a larger α_1 or α_2. Moreover, if the topology is relatively steady, a small α_3 can be set.

The main objective of the proposed CLBP is to deliver the emergency message to other vehicles as fast and reliable as possible. Δd is a metric to determine the number of hops, i.e., the message will be forwarded over a fewer number of hops with a larger Δd. In addition, the MAC layer delay of the message highly depends on the PER e. A higher PER may result in retransmissions that lead to a longer link delay. Finally, a small relative speed Δv is usually desirable in high-speed vehicle networks to guarantee that the channel between two moving nodes is relatively stationary. The proof in [30] verifies that if two routing metrics are bounded, their additive composite metric is also bounded. As $\Delta d \in [B_1, B_Q]$, $\Delta v \in [0, 2V_P]$, and $e \in [0, 1]$, the composite metric $\mathcal{F}$ is consequently bounded. The maximum and minimum values of $\mathcal{F}$ are expressed as $\mathcal{F}_{\max}$ and $\mathcal{F}_{\min}$, respectively.

To avoid interruptions to the BRTS/BCTS handshake from other flows, the CLBP requires the selected relaying node to reply a BCTS frame within the DIFS interval. Applying the concept of minislot in [31] and [32], we further divide the DIFS interval into a number of minislots. The length of a minislot τ and the number of minislots W_n can be calculated as

$$\tau = 2 \cdot \rho + t_{\text{swith}} \tag{2}$$

$$W_n = \lfloor t_{\text{difs}}/\tau \rfloor \tag{3}$$

where ρ is the maximum channel-propagation delay within the transmission range R_t, and t_{swith} is the time duration that a transceiver switches between the receiving mode and the transmitting mode. To map the relaying metric $\mathcal{F}$ to a number of minislots, we further partition the value between $\mathcal{F}_{\min}$ and $\mathcal{F}_{\max}$ into W_n segments, and each segment is $\epsilon_0 = (\mathcal{F}_{\max} - \mathcal{F}_{\min})/W_n$. After evaluating the relaying metric $\mathcal{F}$, an eligible relay candidate sets its timer to i minislots if its $\mathcal{F}$ is within $[\mathcal{F}_{\min} + (i-1) \cdot \epsilon_0, \mathcal{F}_{\min} + i \cdot \epsilon_0)$, where $i \in [1, W_n]$. The relay candidate with a minimum $\mathcal{F}$ value will reply a BCTS frame first and, thus, will be accordingly selected as a relaying node. In other words, a node with a longer distance, better channel conditions, and a smaller velocity difference is more preferable for relaying the emergency message.

After the transmission of a BCTS frame, which also takes fields *init_addr* and *em_seq*, if another relay candidate overhears a BCTS frame replying the same BRTS frame before its own timer expires, the node will stop its own back-off timer and update its NAV according to the value of the *duration* field that is included in the received BCTS frame. Note that the *duration* fields in the BRTS and BCTS frames are set to be $t_{\text{brts\_}d} = t_{\text{difs}} + t_{\text{bcts}} + t_{\text{sifs}} + (L/r_b) + t_{\text{sifs}} + t_{\text{ack}}$ and $t_{\text{bcts\_}d} = t_{\text{brts\_}d} - t_{\text{difs}} - t_{\text{bcts}}$, where t_{sifs} is the time duration of a short interframe space (SIFS), t_{ack} is the transmission time of an ACK frame, L is the payload size of the emergency message, and r_b is the basic rate. $t_{\text{brts\_}d}$ is conservative because the receiver waits at most one DIFS to reply to a BCTS in the CLBP. Whenever a node receives or overhears other BRTS/BCTS frames, it will accordingly update its NAV.

It is possible that multiple relay candidates may choose the same minislot to reply BCTS frames, which causes collisions. When a collision occurs, the relay candidates that have started their back-off timers but have not replied to BCTS frames will sense the channel busy, and they will accordingly stop their own timers. If a relay candidate that has replied to a BCTS

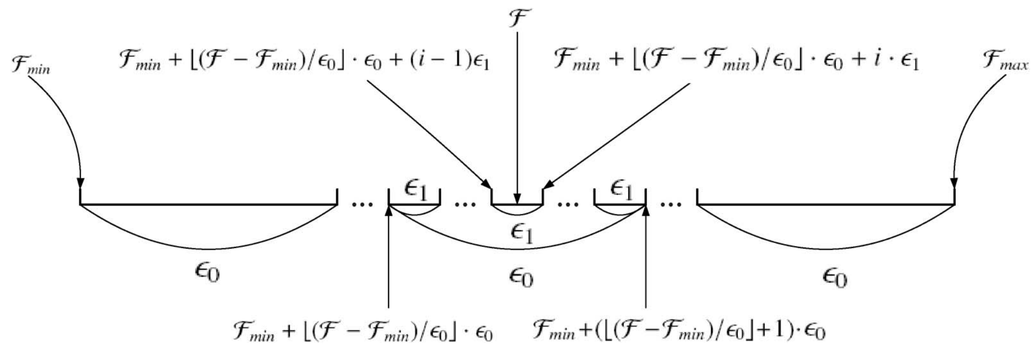

Fig. 3. Minislot reselection process.

frame receives a rebroadcast BRTS frame, it will divide ϵ_0 into W_n segments, each of which is $\epsilon_1 = \epsilon_0/W_n$. It then chooses a minislot and enters the back-off stage again. As an example shown in Fig. 3, the relay candidate who has the $\mathcal{F}$ value divides the value between $[\mathcal{F}_{\min} + \lfloor(\mathcal{F} - \mathcal{F}_{\min})/\epsilon_0\rfloor \cdot \epsilon_0, \mathcal{F}_{\min} + (\lfloor(\mathcal{F} - \mathcal{F}_{\min})/\epsilon_0\rfloor + 1) \cdot \epsilon_0]$ into W_n subsegments and waits i $(i \in [1, W_n])$ minislots to reply to a BCTS frame again if

$$\mathcal{F}_{\min} + \lfloor(\mathcal{F} - \mathcal{F}_{\min})/\epsilon_0\rfloor \cdot \epsilon_0 + (i-1)\epsilon_1 \leqslant \mathcal{F}$$
$$\mathcal{F} < \mathcal{F}_{\min} + \lfloor(\mathcal{F} - \mathcal{F}_{\min})/\epsilon_0\rfloor \cdot \epsilon_0 + i \cdot \epsilon_1. \quad (4)$$

The procedure continues until retransmissions due to BCTS collisions reach $r_{\max}$ times, which implies that some nodes have very close $\mathcal{F}$ values. Then, from the $r_{\max}$ round, the relay candidates that were collided in the last round will randomly select a minislot to reply a BCTS frame until a relay is successfully selected. In the CLBP, the relaying metric consists of three variables, and it is less likely that two nodes have exactly the same $\mathcal{F}$. Therefore, the proposed collision resolution scheme is very efficient for selecting a unique relaying node. The pseudocode of the relay selection process is presented in Algorithm 1.

Algorithm 1 Relay Selection Algorithm

1: A node j received a BRTS frame.
2: **if** $t\_addr = init\_addr$ **then**
3: **if** j receives the BRTS frame at the first time **then**
4: Check *t_direction*.
5: **if** j is in the propagation direction **then**
6: Go to line 1.
7: **else**
8: Set the NAV.
9: **end if**
10: **else**
11: Go to line 1.
12: **end if**
13: **else**
14: **if** j receives the BRTS frame at the first time **then**
15: **if** j has distance gain in the propagation direction **then**
16: Go to line 1.
17: **else**
18: Set the NAV.
19: **end if**
20: **else**
21: Go to line 1.
22: **end if**
23: **end if**
24: Compute $\mathcal{F}_{\min}$, $\mathcal{F}_{\max}$, ϵ_0, distance, relative velocity, and PER.
25: Map $\mathcal{F}$ of j to minislots.
26: Start the back-off timer, and go to line 1.
27: **if** $0 < t\_retry < r_{\max}$ **then**
28: Compute $\epsilon_{t\_retry} = \epsilon_0/(W_n)^{t\_retry}$.
29: Map $\mathcal{F}$ of j to minislots.
30: Start the back-off timer, and go to line 1.
31: **else**
32: Randomly select a minislot from W_n.
33: Start the back-off timer, and go to line 1.
34: **end if**
35: **while** the back-off timer $\neq 0$ **do**
36: **if** j receives BCTS frames replying the same BRTS frame **then**
37: Stop the timer and set the NAV.
38: break.
39: **end if**
40: **end while**
41: **if** the back-off timer $= 0$ **then**
42: Reply a BCTS frame, and *t_retry*++.
43: **end if**
44: return.

B. Emergency Message Broadcast

After a successful BRTS/BCTS handshake, the current broadcast node that successfully receives a BCTS frame will broadcast the emergency message after one SIFS interval. The selected relaying node will acknowledge the reception of the emergency message if the transmission is successful. To avoid message redundancy, each node in the system maintains a list to keep records of all received emergency messages. Each entry in the list records the address of the source node and the sequence number of the emergency message, and entries with out-of-date messages will be deleted. A node that receives an emergency message will check the list and drop this message if it has already been recorded. Otherwise, it will receive the message and update the list. After successfully replying an ACK, the

TABLE I
PARAMETERS FOR DIFFERENT SERVICES

AC	CWmin	CWmax	AIFSN	PF
0	CW_MIN	CW_MAX	7	2
1	CW_MIN	CW_MAX	3	2
2	(CW_MIN+1)/2-1	CW_MIN	2	2
3	(CW_MIN+1)/4-1	(CW_MIN+1)/2-1	2	2
4	(CW_MIN+1)/4-1	(CW_MIN+1)/4-1	2	1

selected relay becomes the next broadcast node and repeats the BRTS/BCTS handshake again in the MAC layer.

C. Priority

To provide safety-related services with satisfactory delay guarantee in IVC, we use the priority-based IEEE 802.11e EDCA for service differentiation. We include the safety services and divide all services into five classes. Different classes of services have different priorities to access the channel based on access category (AC), as shown in Table I. The settings of arbitration interframe space (AIFS) and contention window (CW) are the same as those specified in IEEE 802.11e [29], i.e.,

$$\text{AIFS[AC]} = t_{\text{sifs}} + \text{AIFS}N\text{[AC]} \cdot \sigma \tag{5}$$

$$\text{CW[AC]} = \min((\text{CW[AC]}+1)\text{PF[AC]}, \text{CWmax[AC]}) \tag{6}$$

where σ is the time slot, and PF is the persistence factor, which is set to 1 for safety services and 2 for other services. In other words, a node always selects a back-off counter from the minimum CW for emergency message delivery, whereas it doubles its CW after each collision for other services. This way, emergency messages have the highest service priority.

IV. PERFORMANCE ANALYSIS

Here, we develop an analytical model to analyze the performance of the proposed CLBP. To make the proposed scheme tractable, we make the following assumptions.

1) Nodes are randomly distributed, and the node density is λ per R_t.
2) All nodes are saturated, i.e., the nodes always have data packets in their buffers for transmissions, and data packets of the same access category AC $[i]$ have the same transmission probability p_i and collision probability q_i that can be obtained by [33].
3) All the data packets of the same access category AC$[i]$ have the same payload size D_i that is larger than *rts_threshold*.
4) The PERs of BRTS, BCTS, and ACK frames are negligible due to the small packet size.
5) The retransmission times due to BCTS collisions are not larger than $r_{\max}$.

In our proposed protocol, a node starts a timer (in terms of minislots) and contends to send a BCTS frame based on the composite relaying metric $\mathcal{F}$ in (1). Δd and Δv can be evaluated from the received BRTS frame, and PER e is dependent on the channel conditions. To the best of our knowledge, there is no consensus on fading and shadowing models for VANETs so far [34]. In our analytical model, we adopt the Friis free-space model [35] to determine the received signal power. Over an additive white Gaussian noise channel, the bit error rate of the emergency message with binary phase-shift keying modulation is $Q(\sqrt{(2\varepsilon_b/N_0)}) = Q(\sqrt{2P_r/(r_b N_0)})$ [36], where $Q(x) = (1/\sqrt{2\pi})\int_x^\infty e^{-t^2/2}dt$, ε_b is the received energy per bit, N_0 is the noise power spectral density, P_r is the received power, and r_b is the basic rate. Since $e = 1-(1-Q(\sqrt{2P_r/(r_b N_0)}))^L = 1-(1-Q(I/\Delta d))^L$ [37], (1) can be rewritten as

$$\mathcal{F} = \alpha_1 \cdot \left(1 - \frac{\Delta d}{B_Q}\right) + \frac{\alpha_2}{E_{\max}} \cdot \left[1 - \left(1 - Q\left(\frac{I}{\Delta d}\right)\right)^L\right] + \alpha_3 \cdot \frac{\Delta v}{2V_P} \tag{7}$$

where $I = \sqrt{(2P_t G_t G_r (c/f_c)^2)/(r_b N_0 (4\pi)^2)}$, P_t is the transmitted power, G_t and G_r are the transmitter and receiver antenna gains, respectively, c is the speed of light, and f_c is the carrier frequency. $\mathcal{F}$ is a function of Δd and Δv, given the parameters α_1, α_2, α_3, B_Q, V_P, P_t, G_t, G_r, c, f_c, r_b, N_0, and L. The derivations of $\mathcal{F}_{\min}$ and $\mathcal{F}_{\max}$ are given in Appendix A. Therefore, the selection of minislots is dependent on the distance and the relative velocity to the broadcast node.

Emergency message access delay T is defined as the time interval from an emergency message arriving at the head of the queue until it is successfully acknowledged, which includes 1) an AIFS; 2) T_b consisting of the back-off time, the frozen time due to other transmissions, the retransmission time due to BRTS collisions, and a successful BRTS transmission time; 3) T_c consisting of the retransmission time caused by BCTS collisions and a successful BCTS transmission time; and 4) T_d, which is the sum of delay due to retransmissions caused by the emergency message errors, a successful emergency message transmission, and its acknowledgement. Thus, we have

$$T = \text{AIFS}[4] + T_b + T_c + T_d. \tag{8}$$

Relay-selection delay T_{rs} is defined as the time duration from a broadcast node attempting to transmit the BRTS frame until a relay is successfully selected, and we have $T_{rs} = \text{AIFS}[4] + T_b + T_c$. Denote w as the average time that a back-off timer of a broadcast node reaches 0, and we have

$$T_b = \sum_{m=0}^{\infty} q_4^m (1-q_4)\left[(w + t_{\text{brts}}) + m(w + t_{\text{brts\_r}})\right] \tag{9}$$

where $q_4^m(1-q_4)$ is the probability that the broadcast node successfully delivers a BRTS frame at back-off stage m, and $(w + t_{\text{brts}}) + m(w + t_{\text{brts\_r}})$ is the corresponding delay. Denote $w|j$ $(j \in [0, \text{CW}[4]])$ as the value of w given that the jth time slot is selected. Since the broadcast node uniformly selects a time slot from $[0, \text{CW}[4]]$, we have

$$w = \sum_{j=0}^{\text{CW}[4]} (w|j) \cdot \frac{1}{\text{CW}[4]+1} \tag{10}$$

where

$$w|j = \begin{cases} \sum_{k=1}^{j} \overline{Y_k}, & j \in [1, \text{CW}[4]] \\ 0, & j = 0 \end{cases} \tag{11}$$

and $\overline{Y_k}$ is the mean of Y_k, which denotes the time delay in the kth slot of CW[4]. Y_k can be one idle time slot or the frozen

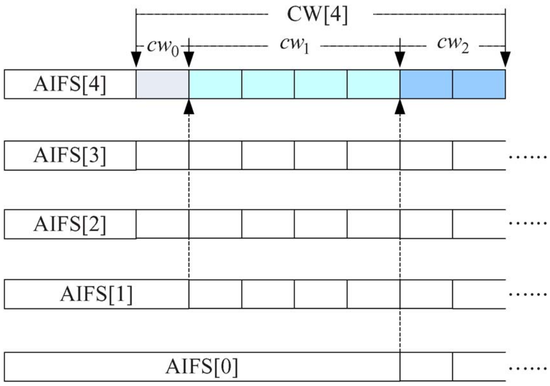

Fig. 4. Contention windows.

time due to a successful data transmission or collisions. Let E_{ks}, E_{kc}, and E_{ki} denote the events that a node successfully transmits a message in slot k, a collision occurs in slot k, and no node transmits in slot k, respectively. We have

$$pr(E_{ki}) = \prod_{i=0}^{4}(1-p_i)^{n_i \cdot x_{i,k}}$$

$$pr(E_{ks}) = \sum_{i=0}^{4} x_{i,k} \cdot \binom{n_i}{1} \cdot p_i \cdot (1-p_i)^{n_i-1} \cdot \prod_{\mathbb{i}\in[0,4],\mathbb{i}\neq i} (1-p_{\mathbb{i}})^{n_{\mathbb{i}}}$$

$$pr(E_{kc}) = 1 - pr(E_{ik}) - pr(E_{ks}) \tag{12}$$

where

$$x_{i,k} = \begin{cases} 1, & \text{if } AIFS[i] \leqslant AIFS[4]+k \\ 0, & \text{otherwise} \end{cases} \tag{13}$$

n_i is the number of contending neighboring nodes belonging to AC$[i]$, and $x_{i,k}$ denotes whether the neighboring nodes of AC$[i]$ will contend for channel access with the broadcast node in the kth slot of CW[4]. As shown in Fig. 4, CW[4] is divided into three subwindows cw_0, cw_1, and cw_2. If the broadcast node selects time slot 0, it only contends with neighboring nodes of AC[3] and AC[2], and $x_{3,0}=1$, $x_{2,0}=1$, $x_{1,0}=0$, and $x_{0,0}=0$. Similarly, if the node chooses a time slot k from cw_1, it must contend with the neighboring nodes of AC[3], AC[2], and AC[1], and $x_{3,k}=1$, $x_{2,k}=1$, $x_{1,k}=1$, and $x_{0,k}=0$.

We denote $\overline{S}$ as the average frozen time that the broadcast node experiences for one successful packet transmission and denote S_i as one successful transmission time of AC$[i]$. For AC$[i]$ $(i\in[0,3])$, $S_i = 3\cdot t_{\text{sifs}} + t_{\text{rts}} + t_{\text{cts}} + D_i/r_d + t_{\text{ack}} + \text{AIFS}[4]$, whereas for safety services, S_4 is approximately equal to $2\cdot t_{\text{sifs}} + t_{\text{difs}} + t_{\text{brts}} + t_{\text{bcts}} + L/r_b + t_{\text{ack}} + \text{AIFS}[4]$. Since the successful transmission probability of AC$[i]$ is $\binom{n_i}{1}\cdot p_i \cdot (1-p_i)^{n_i-1}\cdot \prod_{\mathbb{i}\in[0,4],\mathbb{i}\neq i}(1-p_{\mathbb{i}})^{n_{\mathbb{i}}}$, we obtain

$$\overline{S} = \sum_{i=0}^{4}\binom{n_i}{1}\cdot p_i \cdot (1-p_i)^{n_i-1}\cdot \prod_{\mathbb{i}\in[0,4],\mathbb{i}\neq i}(1-p_{\mathbb{i}})^{n_{\mathbb{i}}}\cdot S_i. \tag{14}$$

Let $\overline{C}$ represent the average frozen time that the broadcast node experiences owing to one packet collision, and $\overline{C}$ is approximately equal to $t_{\text{rts}} + \text{AIFS}[4]$. Finally, we have

$$\overline{Y_k} = \sigma \cdot pr(E_{ki}) + \overline{S}\cdot pr(E_{ks}) + \overline{C}\cdot pr(E_{kc}). \tag{15}$$

With (10)–(12) and (15), T_b can be obtained.

T_c, which denotes the time interval from the successful reception of a BRTS frame to the successful reception of a BCTS frame, is a variable and depends on how long the broadcast node can successfully receive a BCTS frame from its relay candidates. In the CLBP, a relay candidate starts its back-off timer to reply a BCTS frame after receiving a BRTS frame from the broadcast node. To capture the activities of the back-off timer of a relay candidate, the back-off process is illustrated by a 3-D diagram with the state space (m,n,l), as shown in Fig. 5, where m $(m\in[0,r_{\max}))$ is the back-off stage, n $(n\in[1,W_n])$ is the initial value of the back-off timer, and l $(l\in[0,W_n])$ is the number of minislots that elapsed since the start of the timer.

The state transitions of a back-off timer are given in Appendix B1, and therefore, we have

$$T_c = S_0\cdot t_0 + \sum_{m=1}^{r_{\max}}\left(\prod_{j=0}^{m-1} C_j\right)\cdot S_m \cdot t_m \tag{16}$$

where S_m, C_m, and t_m are the successful transmission probability of a BCTS frame, the collision probability of a BCTS frame, and the average time taken for a relay candidate successfully replying a BCTS frame at back-off stage m, respectively, the derivations of which are given in Appendix B2. Finally, T_d, which denotes the time spent on emergency message transmission, can be represented as

$$T_d = \sum_{m=0}^{\infty} e^m\cdot(1-e)\cdot[t_{\text{sifs}} + L/r_b + t_{\text{sifs}} + t_{\text{ack}} + m\cdot(T_b + T_c + t_{\text{sifs}} + L/r_b + t_{\text{sifs}} + t_{\text{ack}})] \tag{17}$$

where $e^m\cdot(1-e)$ is the successful transmission probability of the emergency message after m retransmissions, and $t_{\text{sifs}} + L/r_b + t_{\text{sifs}} + t_{\text{ack}} + m\cdot(T_b + T_c + t_{\text{sifs}} + L/r_b + t_{\text{sifs}} + t_{\text{ack}})$ is the corresponding time taken in the retransmission process.

V. Simulation Results

Here, we evaluate the performance of the proposed CLBP in terms of the PER of the emergency message, the relay-selection delay, and the emergency message access delay via NS-2 simulations. For performance comparison, we also implemented the AMB [20] since it also uses a cross-layer approach to select one relaying node to forward the broadcast message and addresses QoS issues in IVC. In the simulations, vehicles are randomly distributed over a two-lane highway with two opposite directions, and a vehicle is selected as the broadcast node. The velocity of a vehicle is randomly distributed among the discrete set $V=\{(20+5*i)m/s | i\in[0,6]\}$. As the default setting,

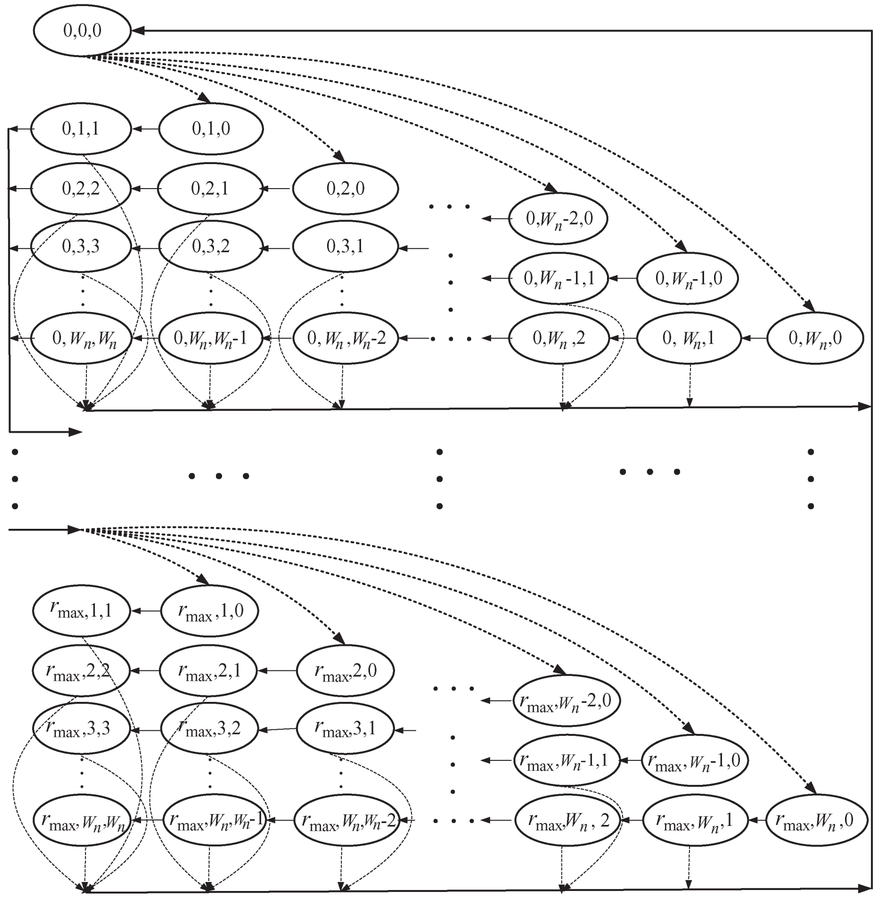

Fig. 5. State transitions of the back-off timer.

TABLE II
PARAMETERS IN SIMULATIONS

Parameter	Value	Parameter	Value
t_{sifs}	10 μs	PLCP&preamble	192 μs
σ	20 μs	RTS	20byte
E_{max}	8%	CTS	14byte
r_b	1M	BRTS	37byte
r_d	2M	BCTS	17byte
R_t	250m	L	1024byte
ϕ	25m	Data packet	512 byte
CW_MIN	31	CW_MAX	1023
f_c	2.4G	P_t	15dBm
G_t	1	G_r	1
B_1	25m	B_Q	250m
V_1	20m/s	V_P	50m/s
ρ	1 μs	t_{swith}	1 μs
α_1	1	α_2	1
α_3	1	r_{max}	7

five data flows are set up with the rate of 100 packets/s. Other simulation parameters are listed in Table II.

A. PER of the Emergency Message

We first compare the PER performance of the CLBP with that of the AMB proposed under various N_0. For a smaller N_0, both the CLBP and the AMB achieve a low PER. When N_0 increases, the PER of the AMB increases, whereas that of the CLBP does not change much. In the CLBP, the broadcast node jointly considers the distance, the channel conditions, and the relative velocity to select the next hop-relaying node. Under ideal channel conditions, the farthest relay candidate has the lowest $\mathcal{F}$ and is selected as the relaying node, whereas under poor channel conditions, the received SNR at the farthest relay candidate decreases, and accordingly, the achieved PER increases, in which case, a closer relay candidate with a lower PER may be selected with the CLBP. As shown in Fig. 6(a), the PER of the CLBP slightly decreases when N_0 increases from -174.6 to -173.88 dBw/Hz. Therefore, the CLBP assures the PER performance of the emergency message and, thus, is more suitable for IVC with variant channel conditions.

B. Relay-Selection Delay

Relay-selection delay is defined as the interval from the time that the broadcast node attempts to deliver a BRTS frame to the time it successfully receives a BCTS frame. In Fig. 6(b), we compare the relay selection delays of the CLBP and the AMB. By applying service differentiation in the CLBP, the emergency messages are served with the highest priority. On the other hand, the AMB adopts a basic CSMA/CA mechanism, which neglects the requirements of delay-sensitive traffic, and all packets have the same priority to access the channel [38]. Therefore, the AMB has a longer access delay compared with that of the CLBP. In addition, the node sending the longest channel jamming signal becomes the relaying node in the AMB, whereas a node waiting the shortest time to reply a BCTS frame becomes the relaying node in the CLBP. As shown in Fig. 6(b), the relay-selection delay of the CLBP is much shorter

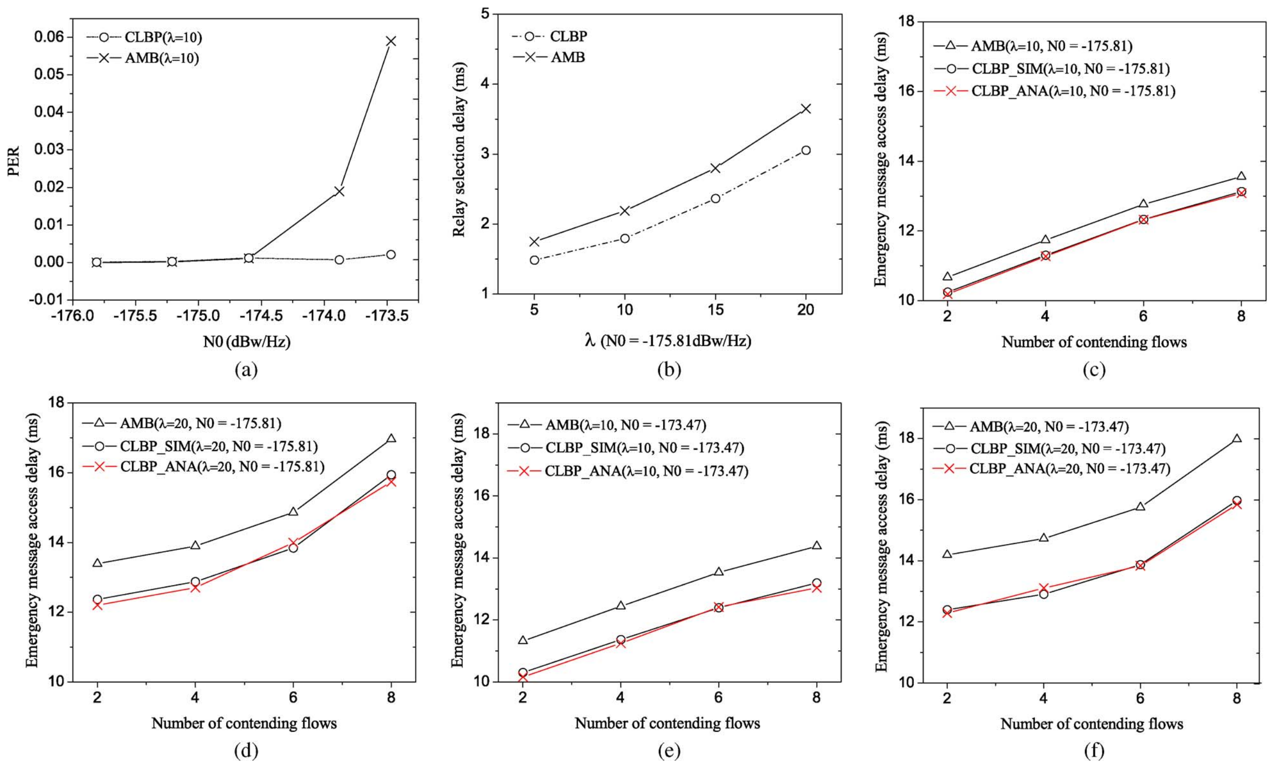

Fig. 6. Performance comparisons between the CLBP and the AMB. (a) PER. (b) Relay selection delay. (c)–(f) Emergency message access delay.

than that of the AMB. However, both relay-selection delays of the CLBP and the AMB go up with the increase in the node density due to severe packet collisions.

C. Emergency Message Access Delay

Finally, we show the emergency message access delay under various node densities and background noise levels in Fig. 6(c)–(f). It can be seen that the emergency message access delays of the AMB are higher than those of the CLBP, and their differences increase with the increase of node densities and background noise levels. This is because, first, the CLBP gives the highest priority for safety services by adjusting AIFSN, PF, CWmin, and CWmax, which results in a smaller access delay, whereas in the AMB, emergency messages have to contend with other services with the same priority. Second, in the CLBP, the selected relaying node waits the minimum number of minislots to reply a BCTS frame, whereas in the AMB, the selected relaying node sends the longest black-burst signal to win the opportunity to reply a clear-to-broadcast frame. Third, under poor channel conditions, the broadcast node in the CLBP chooses an appropriate node with reasonable PER performance to relay the emergency message. In the AMB, the broadcast node always selects the farthest relay candidate, which incurs retransmissions under a high PER.

VI. Conclusion

In this paper, we have developed a composite relaying metric to select an appropriate relaying node, considering the special characteristics of vehicle networks. Based on the relaying metric, we have proposed a CLBP to efficiently disseminate emergency messages in IVC. Analytical and simulations results with NS-2 have shown that the CLBP can quickly disseminate emergency messages and achieve high resource utilization. In our future work, we will further study reliable broadcasting with user cooperation in both urban and rural environments, incorporating various mobility models and road traffic conditions. We will also analyze the end-to-end QoS performance of the proposed broadcasting protocol.

Appendix A
Derivation of $\mathcal{F}_{\min}$, $\mathcal{F}_{\max}$, and ϵ_0

Consider the continuous function $z(x,y)=\alpha_1\cdot(1-(x/B_Q))+(\alpha_2/E_{\max})\cdot[1-(1-Q(I/x))^L]+\alpha_3\cdot y/(2V_P)$, where $x\in[B_1,B_Q]$, $y\in[0,2V_P]$, and its partial differential coefficient $z'_x(x)$ and $z'_y(y)$ can be expressed as

$$z'_x(x) = -\frac{\alpha_1}{B_Q}+\frac{\alpha_2\cdot L\cdot I\cdot\left[1-Q\left(\frac{I}{x}\right)\right]^{L-1}}{\sqrt{2\pi}\cdot E_{\max}\cdot x^2\cdot e^{I^2/2x^2}} \quad \text{(A.1)}$$

$$z'_y(y)=\frac{\alpha_3}{2V_P}. \quad \text{(A.2)}$$

Thus, z is a monotonic increasing function of x if $z'_x(x)>0$ and a monotonic decreasing function of variable x if $z'_x(x)<0$, where $x\in[B_1,B_Q]$. Let $X_*=\{x_i|z'_x(x_i)=0, z''_x(x_i)>0, |x_i\in[B_1,B_Q]\}$ and $X^*=\{x_i|z'_x(x_i)=0, z''_x(x_i)<0, |x_i\in[B_1,B_Q]\}$. Let $Z_*=\{z(\lfloor x_i/\phi\rfloor\cdot\phi,V_1)|x_i\in X_*\}\bigcup\{z(\lceil x_i/\phi\rceil\cdot\phi,V_1)|x_i\in X_*\}$ and $Z^*=\{z(\lfloor x_i/\phi\rfloor\cdot\phi,V_1)|x_i\in X^*\}\bigcup\{z(\lceil x_i/\phi\rceil\cdot\phi,V_1)|x_i\in X^*\}$. Similarly, z is a monotonic increasing function of y since $z'_y=\alpha_3/(2V_P)\geqslant 0$.

Therefore, the minimum value $\mathcal{F}_{\min}$ and the maximum value $\mathcal{F}_{\max}$ of the discrete function $\mathcal{F}$ can be expressed as

$$\mathcal{F}_{\min} = \begin{cases} z(B_Q, V_1), & z'_x(x) \leqslant 0, x \in [B_1, B_Q] \\ \min(Z_*), & Z_* \neq \emptyset \\ z(B_1, V_1), & z'_x(x) \geqslant 0, x \in [B_1, B_Q] \end{cases}$$

$$\mathcal{F}_{\max} = \begin{cases} z(B_1, V_P), & z'_x(x) \leqslant 0, x \in [B_1, B_Q] \\ \max(Z^*), & Z^* \neq \emptyset \\ z(B_Q, V_P), & z'_x(x) \geqslant 0, x \in [B_1, B_Q] \end{cases} \tag{A.3}$$

and $\epsilon_0 = (\mathcal{F}_{\max} - \mathcal{F}_{\min})/W_n$ is obtained.

Appendix B
Derivations of Transition Probabilities and T_c

Let random variables $\{\mathcal{F}_1, \mathcal{F}_2, \ldots, \mathcal{F}_N\}$ denote the relaying metrics of N relay candidates, and $\mathcal{F}_t = \alpha_1 \cdot (1-(\Delta d_t/B_Q)) + (\alpha_2/E_{\max}) \cdot [1 - (1 - Q(I/\Delta d_t))^L] + \alpha_3 \cdot \Delta v_t/(2V_P)$ is the relaying metric of node t. Notice that the distances between the broadcast vehicle and other vehicles are not independent variables because two vehicles cannot locate in the same position. Consequently, as functions of distances, the routing metrics $\{\mathcal{F}_1, \mathcal{F}_2, \ldots, \mathcal{F}_N\}$ are not independently distributed either. In a highway consisting of M lanes, at most M vehicles can choose the same block. Let events $A_1 = \{\Delta d_1 = B_1 \cap \Delta d_2 = B_1 \cap \cdots \cap \Delta d_M = B_1 \cap \Delta d_{M+1} = B_2, \ldots\}$, $A_2 = \{\Delta d_1 = B_1 \cap \Delta d_2 = B_1 \cap \cdots \cap \Delta d_M = B_2 \cap \Delta d_{M+1} = B_2, \ldots\}, \ldots, A_{\binom{M\cdot Q}{N}} = \{\Delta d_1 = B_Q \cap \Delta d_2 = B_Q \cap \cdots \cap \Delta d_M = B_Q \cap \Delta d_{M+1} = B_Q - 1, \ldots\}$. Denote $v_{t,i}(y)$ as the relative velocity between node t and the broadcast node when $\mathcal{F}_t = y$ and event A_i occurs. For example, $\Delta d_1 = B_1$ in event A_1, and therefore, $v_{1,1}(y) = (2V_P/\alpha_3) \cdot (y - \alpha_1 \cdot (1-(B_1/B_Q)) - (\alpha_2/E_{\max}) \cdot [1 - (1 - Q(I/B_1))^L])$. Letting $\psi_{t,m}$ $(m \in [0, r_{\max} - 1])$ represent the number of minislots that t backs off, we have

$$\psi_{t,m} = \begin{cases} \lfloor (\mathcal{F}_t - \mathcal{F}_{\min})/\epsilon_0 \rfloor + 1, & \text{if } m = 0 \\ \left\lfloor \left[\mathcal{F}_t - \mathcal{F}_{\min} - \sum_{k=0}^{m-1} (\psi_{t,k} - 1) \cdot \epsilon_k \right] \Big/ \epsilon_m \right\rfloor + 1, & \text{otherwise} \end{cases} \tag{B.1}$$

where $\epsilon_m = \epsilon_0/(W_n)^m$.

1) State Transition Probabilities of the Back-Off Timer: We denote N_m as the set of contending relay candidates at the back-off stage m, and initially, $|N_0| = N$. After receiving a BRTS frame, relay candidate t starts its back-off timer and prepares to reply a BCTS frame. The transition probability $\Pr[(0, n, 0)|(0, 0, 0)]$, which denotes that t starts a back-off timer with initial value n, can be expressed as

$$\begin{aligned} &\Pr[(0, n, 0)|(0, 0, 0)] \\ &\quad = \Pr(\psi_{t,0} = n) \\ &\quad = \Pr[\mathcal{F}_{\min} + (n-1) \cdot \epsilon_0 \leqslant \mathcal{F}_t < \mathcal{F}_{\min} + n \cdot \epsilon_0] \\ &\quad = \sum_{i=1}^{\binom{M\cdot Q}{N}} \Pr[\mathcal{F}_{\min} + (n-1) \cdot \epsilon_0 \leqslant \mathcal{F}_t < \mathcal{F}_{\min} + n \cdot \epsilon_0 | A_i] \cdot \Pr(A_i) \\ &\quad = \frac{1}{\binom{M\cdot Q}{N}} \sum_{i=1}^{\binom{M\cdot Q}{N}} \Pr[\mathcal{F}_{\min} + (n-1) \cdot \epsilon_0 \leqslant \mathcal{F}_t < \mathcal{F}_{\min} + n \cdot \epsilon_0 | A_i] \\ &\quad = \frac{1}{\binom{M\cdot Q}{N}} \sum_{i=1}^{\binom{M\cdot Q}{N}} \Pr[v_{t,i}(\mathcal{F}_{\min} + (n-1) \cdot \epsilon_0) \leqslant \Delta v_t < v_{t,i}(\mathcal{F}_{\min} + n \cdot \epsilon_0)]. \end{aligned}$$

Because the velocities of the broadcast node and relay candidate t are directional and randomly distributed, the relative velocity Δv_t is also randomly distributed among the $(2P-1)!$ relative velocities $\Delta V_1, \Delta V_2, \ldots, \Delta V_{(2P-1)!}$. In addition, since Δv_t does not depend on events $A_1, A_2, \ldots, A_{\binom{M\cdot Q}{N}}$, for specific values $v_{t,i}(\mathcal{F}_{\min} + (n-1) \cdot \epsilon_0)$ and $v_{t,i}(\mathcal{F}_{\min} + n \cdot \epsilon_0)$, we can acquire $\Pr[v_{t,i}(\mathcal{F}_{\min} + (n-1) \cdot \epsilon_0) \leqslant \Delta v_t < v_{t,i}(\mathcal{F}_{\min} + n \cdot \epsilon_0)]$, and, therefore, probability $\Pr[(0, n, 0)|(0, 0, 0)]$ is obtained.

In the proposed scheme, when node t has started the back-off timer and successfully backs off one more minislot, it means that the initial values of all other nodes' back-off timers are larger than the minislots that node t has elapsed. Therefore, the transition probability $\Pr[(0, n, l+1)|(0, n, l)]$, which represents that l minislots have elapsed and t's back-off timer can back off one more minislot, can be expressed as

$$\Pr[(0, n, l+1)|(0, n, l)] = \begin{cases} 1, & \text{if } l = 0 \\ \Pr\left(\bigcap_{j \in N_0} \psi_{j,0} \geqslant l+1\right), & \text{otherwise} \end{cases} \tag{B.2}$$

where

$$\begin{aligned} &\Pr\left(\bigcap_{j \in N_0} \psi_{j,0} \geqslant l+1\right) \\ &\quad = \sum_{i=1}^{\binom{M\cdot Q}{N}} \Pr\left(\bigcap_{j \in N_0} \mathcal{F}_j \geqslant \mathcal{F}_{\min} + l \cdot \epsilon_0 | A_i\right) \cdot \Pr(A_i) \\ &\quad = \sum_{i=1}^{\binom{M\cdot Q}{N}} \Pr\left[\bigcap_{j \in N_0} \Delta v_j \geqslant v_{j,i}(\mathcal{F}_{\min} + l \cdot \epsilon_0)\right] \cdot \Pr(A_i) \\ &\quad = \frac{1}{\binom{M\cdot Q}{N}} \cdot \sum_{i=1}^{\binom{M\cdot Q}{N}} \prod_{j \in N_0} \Pr[\Delta v_j \geqslant v_{j,i}(\mathcal{F}_{\min} + l \cdot \epsilon_0)]. \end{aligned} \tag{B.3}$$

Node t stops its back-off timer and returns to the initial state (0, 0, 0) when it or any other relay candidate successfully transmits a BCTS frame. In the former case, the number of elapsed minislots is equal to the initial value of t's back-off timer and less than the initial value of any other timer. On the other hand, in the latter case, at least one other timer's initial value is equal to the minislots elapsed, and the initial value of t's timer is larger than the minislots elapsed. Therefore, for $l = 0$, we have

$$\Pr[(0, 0, 0)|(0, n, l)] = 0 \tag{B.4}$$

for $l = n \neq 0$, we have

$$\Pr\left[(0,0,0)|(0,n,l)\right] = \Pr\left[\left(\bigcap_{j\in N_0, j\neq t} \psi_{j,0} \geqslant l+1\right) \bigcap (\psi_{t,0} = l)\right] \quad \text{(B.5)}$$

and for $l \neq n \neq 0$, we have

$$\Pr[(0,0,0)|(0,n,l)] = \Pr\left[\left(\bigcap_{j\in N_0, j\neq t} \psi_{j,0} \geqslant l\right) \bigcap (\psi_{t,0} \geqslant l+1)\right] - \Pr\left(\bigcap_{j\in N_0} \psi_{j,0} \geqslant l+1\right)$$

where

$$\Pr\left[\left(\bigcap_{j\in N_0, j\neq t} \psi_{j,0} \geqslant l+1\right) \bigcap (\psi_{t,0} = l)\right] = \frac{1}{\binom{MQ}{N}} \cdot \sum_{i=1}^{\binom{M\cdot Q}{N}} \left(\prod_{j\in N_0, j\neq t} \Pr\left[\Delta v_j \geqslant v_{j,i}(\mathcal{F}_{\min} + l\cdot\epsilon_0)\right]\right) \cdot \Pr[v_{t,i}(\mathcal{F}_{\min} + (l-1)\cdot\epsilon_0) \leqslant \Delta v_t < v_{t,i}(\mathcal{F}_{\min} + l\cdot\epsilon_0)] \quad \text{(B.6)}$$

$$\Pr\left[\left(\bigcap_{j\in N_0, j\neq t} \psi_{j,0} \geqslant l\right) \bigcap (\psi_{t,0} \geqslant l+1)\right] - \Pr\left(\bigcap_{j\in N_0} \psi_{j,0} \geqslant l+1\right) = \frac{1}{\binom{M\cdot Q}{N}} \cdot \sum_{i=1}^{\binom{M\cdot Q}{N}} \left(\prod_{j\in N_0, j\neq t} \Pr[\Delta v_j \geqslant v_{j,i}(\mathcal{F}_{\min} + (l-1)\cdot\epsilon_0)]\right) \cdot \Pr[\Delta v_t \geqslant v_{t,i}(\mathcal{F}_{\min} + l\cdot\epsilon_0)] - \frac{1}{\binom{M\cdot Q}{N}} \cdot \sum_{i=1}^{\binom{M\cdot Q}{N}} \prod_{j\in N_0} \Pr[\Delta v_j \geqslant v_{j,i}(\mathcal{F}_{\min} + l\cdot\epsilon_0)]. \quad \text{(B.7)}$$

If t's back-off timer decreases to 0, it means that the elapsed minislots are equal to the initial value of the timer. t can either successfully deliver a BCTS frame and return to the initial state (0, 0, 0) as expressed by (B.6) or simultaneously transmit a BCTS frame with other relay candidates. In the latter case, given that t's BCTS collides with those from other relay candidates, the probability that t sets its back-off timer to be n in the next back-off stage is given by

$$\Pr\left[(1,n,0)|(0,l,l)\right] = \Pr\left[\left(\bigcap_{j\in N_0, j\neq t} \psi_{j,0} \geqslant l\right) \times \bigcap \left(\left\lfloor \frac{\mathcal{F}_t - \mathcal{F}_{\min} - (l-1)\cdot\epsilon_0}{\epsilon_1} \right\rfloor = n-1\right)\right] - \Pr\left[\left(\bigcap_{j\in N_0, j\neq t} \psi_{j,0} \geqslant l+1\right) \times \bigcap \left(\left\lfloor \frac{\mathcal{F}_t - \mathcal{F}_{\min} - (l-1)\cdot\epsilon_0}{\epsilon_1} \right\rfloor = n-1\right)\right] \quad \text{(B.8)}$$

where $\Pr[(\bigcap_{j\in N_0, j\neq t} \psi_{j,0} \geqslant l) \bigcap (\lfloor(\mathcal{F}_t - \mathcal{F}_{\min} - (l-1)\cdot\epsilon_0)/\epsilon_1\rfloor = n-1)]$, and $\Pr[(\bigcap_{j\in N_0, j\neq t} \psi_{j,0} \geqslant l+1) \bigcap (\lfloor(\mathcal{F}_t - \mathcal{F}_{\min} - (l-1)\cdot\epsilon_0)/\epsilon_1\rfloor = n-1)]$ can be obtained similarly as (B.6).

Then, from the second round of the BCTS reply $(m \geqslant 1)$, for $l = 0$, we have

$$\Pr\left[(m,n,l+1)|(m,n,l)\right] = 1$$

and for $l \in [1, W_n - 1]$, we have

$$\Pr[(m,n,l+1)|(m,n,l)] = \sum_{x_1=2}^{N} \left(\cdots \left(\sum_{x_m=2}^{x_{m-1}} \Pr\left[\left(\bigcap_{j\in N_m} \psi_{j,m} > l\right) \mid |N_m| = x_m\right] \cdot \Pr(|N_m| = x_m \mid |N_{m-1}| = x_{m-1})\right)\cdots\right) \cdot \Pr(|N_1| = x_1)$$

where $\Pr[(\bigcap_{j\in N_m} \psi_{j,m} \geqslant l+1)||N_m| = x_m]$ can be obtained from (B.3), and $\Pr(|N_m| = x_m||N_{m-1}| = x_{m-1})$ is given by (B.12). Conditioning on $|N_m|, |N_{m-1}|, \ldots, |N_1|$, we can acquire $\Pr[(0,0,0)|(m,n,l)]$ and $\Pr[(m+1,n,0)|(m,l,l)]$, respectively.

2) Calculation of T_c: Let random variable $Y = \min(\mathcal{F}_1, \mathcal{F}_2, \ldots, \mathcal{F}_N)$. Its probability mass function (PMF) is

$$\begin{aligned}
F_Y(y) &= \Pr(Y \leqslant y) = 1 - \Pr(Y > y) \\
&= 1 - \Pr(\mathcal{F}_1 > y, \mathcal{F}_2 > y, \ldots, \mathcal{F}_N > y) \\
&= 1 - \sum_{i=1}^{\binom{M\cdot Q}{N}} \Pr(\mathcal{F}_1 > y, \mathcal{F}_2 > y, \ldots, \mathcal{F}_N > y | A_i) \cdot \Pr(A_i) \\
&= 1 - \sum_{i=1}^{\binom{M\cdot Q}{N}} \Pr\left(\Delta v_1 > v_{1,i}(y), \ldots, \Delta v_N > v_{N,i}(y) | A_i\right) \cdot \Pr(A_i) \\
&= 1 - \frac{1}{\binom{M\cdot Q}{N}} \cdot \sum_{i=1}^{\binom{M\cdot Q}{N}} \prod_{j=1}^{N} \Pr\left(\Delta v_j > v_{j,i}(y) | A_i\right) \\
&= 1 - \frac{1}{\binom{M\cdot Q}{N}} \cdot \sum_{i=1}^{\binom{M\cdot Q}{N}} \prod_{j=1}^{N} \Pr\left(\Delta v_j > v_{j,i}(y)\right).
\end{aligned} \quad \text{(B.9)}$$

We represent S_m and C_m as the successful transmission probability and the collision probability of the BCTS frame at back-off stage m, respectively, and let $\psi_0 = \lfloor (Y - \mathcal{F}_{\min})/\epsilon_0 \rfloor$ and $\psi_m = \lfloor (Y - \mathcal{F}_{\min} - \sum_{i=0}^{m-1} \psi_i \cdot \epsilon_i)/\epsilon_m \rfloor$, where $m \in [1, r_{\max}]$. Without loss of generality, we consider $\mathcal{F}_t = Y$ as the minimum value among $\{\mathcal{F}_1, \mathcal{F}_2, \ldots, \mathcal{F}_N\}$; $K_{j,t,m}$ and $H_{j,t,m}$ denote the events

$$K_{j,t,m} = \begin{cases} \left\lfloor \frac{(\mathcal{F}_j - \mathcal{F}_{\min})}{\epsilon_0} \right\rfloor > \left\lfloor \frac{(\mathcal{F}_t - \mathcal{F}_{\min})}{\epsilon_0} \right\rfloor, & \text{if } m = 0 \\ \left\lfloor \frac{(\mathcal{F}_j - \mathcal{F}_{\min} - \sum_{i=0}^{m-1} \psi_i \cdot \epsilon_i)}{\epsilon_m} \right\rfloor \\ \quad > \left\lfloor \frac{(\mathcal{F}_t - \mathcal{F}_{\min} - \sum_{i=0}^{m-1} \psi_i \cdot \epsilon_i)}{\epsilon_m} \right\rfloor, & \text{otherwise} \end{cases}$$

$$H_{j,t,m} = \begin{cases} \left\lfloor \frac{(\mathcal{F}_j - \mathcal{F}_{\min})}{\epsilon_0} \right\rfloor = \left\lfloor \frac{(\mathcal{F}_t - \mathcal{F}_{\min})}{\epsilon_0} \right\rfloor, & \text{if } m = 0 \\ \left\lfloor \frac{(\mathcal{F}_j - \mathcal{F}_{\min} - \sum_{i=0}^{m-1} \psi_i \cdot \epsilon_i)}{\epsilon_m} \right\rfloor \\ \quad = \left\lfloor \frac{(\mathcal{F}_t - \mathcal{F}_{\min} - \sum_{i=0}^{m-1} \psi_i \cdot \epsilon_i)}{\epsilon_m} \right\rfloor, & \text{otherwise} \end{cases}$$

and $K_{j,t,m}(x,y,z)$ and $H_{j,t,m}(x,y,z)$ denote the events $K_{j,t,m}$ and $H_{j,t,m}$ under the conditions $\Delta d_j = x$, $\Delta d_t = y$, and $\Delta v_t = z$. Therefore, for $m = 0$, we have

$$\begin{aligned} S_0 &= \binom{|N_0|}{1} \cdot \Pr\left[\left(\bigcap_{j \in N_0, j \neq t} K_{j,t,0}\right)\right] \\ &= N \cdot \sum_{i=1}^{\binom{M \cdot Q}{N}} \Pr\left[\left(\bigcap_{j \in N_0, j \neq t} K_{j,t,0} | A_i\right)\right] \cdot \Pr(A_i) \\ &= \frac{N}{\binom{M \cdot Q}{N}} \cdot \sum_{i=1}^{\binom{M \cdot Q}{N}} \prod_{j \in N_0, j \neq t} \Pr(K_{j,t,0} | A_i) \\ &= \frac{N}{\binom{M \cdot Q}{N}} \cdot \sum_{i=1}^{\binom{M \cdot Q}{N}} \prod_{j \in N_0, j \neq t} \Pr(K_{j,t,0} | \Delta d_j = d_{j,i}, \Delta d_t = d_{t,i}) \\ &= \frac{N}{\binom{M \cdot Q}{N}} \cdot \sum_{i=1}^{\binom{M \cdot Q}{N}} \prod_{j \in N_0, j \neq t} \sum_{l=1}^{(2P-1)!} \Pr[K_{j,t,0}(d_{j,i}, d_{t,i}, \Delta V_l)] \\ &\quad \cdot \Pr(\Delta v_t = \Delta V_l) \\ &= \frac{N \cdot \sum_{i=1}^{\binom{M \cdot Q}{N}} \prod_{j \in N_0, j \neq t} \sum_{l=1}^{(2P-1)!} \Pr[K_{j,t,0}(d_{j,i}, d_{t,i}, \Delta V_l)]}{\binom{M \cdot Q}{N} \cdot (2P-1)!} \end{aligned}$$

where $d_{j,i}$ and $d_{t,i}$ denote the values of Δd_j and Δd_t in event A_i, respectively. For $m \in [1, r_{\max} - 1]$, we have (B.10), shown at the bottom of the page, where

$$\begin{aligned} \Pr&\left[\left(\bigcap_{j \in N_m, j \neq t} K_{j,t,m}\right) \mid |N_m| = x_m\right] \\ &= \frac{1}{\binom{M \cdot Q}{N} \cdot (2P-1)!} \cdot \sum_{i=1}^{\binom{M \cdot Q}{N}} \prod_{j \in N_m, j \neq t} \\ &\quad \times \sum_{l=1}^{(2P-1)!} \Pr[K_{j,t,m}(d_{j,i}, d_{t,i}, \Delta V_l)] \end{aligned} \tag{B.11}$$

$$\begin{aligned} \Pr&(|N_m| = x_m |\, |N_{m-1}| = x_{m-1}) \\ &= \binom{x_{m-1}}{x_m} \Pr\left[\left(\bigcap_{j \in N_m, j \neq t} H_{j,t,m}\right)\right. \\ &\qquad \left.\times \bigcap\left(\bigcap_{j \notin N_m, j \in N_{m-1}} K_{j,t,m-1}\right)\right] \\ &= \frac{\binom{x_{m-1}}{x_m}}{\binom{M \cdot Q}{N}} \cdot \sum_{i=1}^{\binom{M \cdot Q}{N}} \Pr\left[\left(\bigcap_{j \in N_m, j \neq t} H_{j,t,m}\right)\right. \\ &\qquad \left.\times \bigcap\left(\bigcap_{j \notin N_m, j \in N_{m-1}} K_{j,t,m-1}\right) | A_i\right] \\ &= \frac{\binom{x_{m-1}}{x_m}}{\binom{M \cdot Q}{N}} \cdot \sum_{i=1}^{\binom{M \cdot Q}{N}} \left(\prod_{j \in N_m, j \neq t} \Pr(H_{j,t,m} | A_i)\right) \\ &\qquad \cdot \left(\prod_{j \notin N_m, j \in N_{m-1}} Pr(K_{j,t,m-1} | A_i)\right) \\ &= \frac{\binom{x_{m-1}}{x_m}}{\binom{M \cdot Q}{N} \cdot (2P-1)!} \\ &\quad \cdot \sum_{i=1}^{\binom{M \cdot Q}{N}} \left(\prod_{j \in N_m, j \neq t} \sum_{l=1}^{(2P-1)!} \Pr[H_{j,t,m}(d_{j,i}, d_{t,i}, \Delta V_l)]\right) \\ &\quad \cdot \left(\prod_{j \notin N_m, j \in N_{m-1}} \sum_{l=1}^{(2P-1)!} \Pr[K_{j,t,m}(d_{j,i}, d_{t,i}, \Delta V_l)]\right). \end{aligned} \tag{B.12}$$

whereas for $m = r_{\max}$, we have (B.13), shown at the top of the next page.

In the proposed scheme, if a relay candidate simultaneously transmits a BCTS frame with other relay candidates and introduces BCTS collisions, it will reply with a BCTS frame again after receiving a rebroadcast BRTS frame until the retransmission times reach $r_{\max}$. Then, it will randomly select

$$\begin{aligned} S_m = \sum_{x_1=2}^{N} \Bigg(\sum_{x_2=2}^{x_1} \Bigg(\cdots \Bigg(\sum_{x_m=2}^{x_{m-1}} \binom{x_m}{1} \Pr\left[\left(\bigcap_{j \in N_m, j \neq t} K_{j,t,m}\right) \mid |N_m| = x_m\right] \\ \cdot \Pr(|N_m| = x_m |\, |N_{m-1}| = x_{m-1}) \Bigg) \cdots \Bigg) \cdot \Pr(|N_2| = x_2 |\, |N_1| = x_1) \Bigg) \cdot \Pr(|N_1| = x_1) \end{aligned} \tag{B.10}$$

$$S_m = \sum_{x_1=2}^{N} \left(\sum_{x_2=2}^{x_1} \left(\cdots \left(\sum_{x_m=2}^{x_{m-1}} \binom{x_m}{1} \cdot \frac{1}{W_n} \sum_{k=1}^{W_n} \left(\frac{1}{W_n - k} \right)^{x_m - 1} \cdot \Pr\left(|N_m| = x_m | \, |N_{m-1}| = x_{m-1}\right) \right) \cdots \right) \cdot \Pr\left(|N_2| = x_2 | \, |N_1| = x_1\right) \right) \cdot \Pr(|N_1| = x_1) \quad \text{(B.13)}$$

a minislot to reply with a BCTS frame, and any minislot has the same probability $1/W_n$ to be chosen. If a relay candidate selects minislot k and successfully replies a BCTS frame, other relay candidates should randomly select minislots between $k+1$ and W_n, and (B.13) will be obtained. Finally, we can acquire S_m and $C_m = 1 - S_m$. Let t_m denote the average time that is taken for a relay candidate successfully replying a BCTS frame at back-off stage m, which contains the back-off time, the delay of retransmissions caused by BCTS collisions, and the BCTS successful transmission time. Therefore, it can be represented as

$$t_m = \begin{cases} \overline{\psi_m} \cdot \tau + t_{\text{bcts}} \\ \quad + m(T_b + t_{\text{difs}} + t_{\text{bcts}}), & \text{if } m \in [0, r_{\max} - 1] \\ \frac{W_n}{2} \cdot \tau + t_{\text{bcts}} \\ \quad + m(T_b + t_{\text{difs}} + t_{\text{bcts}}), & \text{if } m = r_{\max} \end{cases}$$

where

$$\overline{\psi_m} = \begin{cases} \left\lfloor \left(\overline{Y} - \mathcal{F}_{\min} - \sum_{i=0}^{m-1} \overline{\psi_i} \cdot \epsilon_i \right) / \epsilon_m \right\rfloor, & \text{if } m \in [1, r_{\max} - 1] \\ \left\lfloor (\overline{Y} - \mathcal{F}_{\min}) / \epsilon_0 \right\rfloor, & \text{if } m = 0 \end{cases}$$

is the mean of ψ_m. Given the PMF of Y in (B.9), $\overline{Y}$ and $\overline{\psi_m}$ can be obtained. At the back-off stage $r_{\max}$, a relay candidate uniformly selects a minislot to reply a BCTS, and the average number of minislots that it backs off is $W_n/2$. With S_m, C_m, and t_m, we can obtain T_c by (16).

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REFERENCES

[1] C. L. Robinson, L. Caminiti, D. Caveney, and K. Laberteaux, "Efficient coordination and transmission of data for cooperative vehicular safety applications," in *Proc. VANET*, Sep. 2006, pp. 10–19.

[2] J. Luo and J. P. Hubaux, "A survey of inter-vehicular communication," School Comput. Commun. Sci., Swiss Fed. Inst. Technol., Lausanne, Switzerland, Tech. Rep. IC/2004/24, 2004.

[3] Dedicated Short Range Communications Working Group. [Online]. Available: http://grouper.ieee.org/groups/scc32/dsrc/

[4] M. Heddebaut, J. Rioult, J. P. Ghys, C. Gransart, and S. Ambellouis, "Broadband vehicle-to-vehicle communication using an extended autonomous cruise control sensor," *Meas. Sci. Technol.*, vol. 16, no. 6, pp. 1363–1373, Jun. 2005.

[5] M. Shulman and R. K. Deering, "Third annual report of the crash avoidance metrics partnership April 2003–March 2004," Nat. Highway Traffic Safety Admin., Washington, DC, DOT HS 809 837, Jan. 2005.

[6] D. Reichardt, M. Miglietta, L. Moretti, P. Morsink, and W. Schulz, "CarTALK 2000: Safe and comfortable driving based upon inter-vehicle-communication," in *Proc. Intell. Vehicle Symp.*, Jun. 2002, pp. 545–550.

[7] R. Kruger, H. Fuler, M. Torrent-Moreno, M. Transier, H. Hartenstein, and W. Effelsberg, "Statistical analysis of the FleetNet highway movement patterns," Univ. Mannheim, Mannheim, Germany, Tech. Rep. TR-2005-004, Jul. 2005.

[8] M. Ergen, D. Lee, R. Sengupta, and P. Varaiya, "WTRP—Wireless token ring protocol," *IEEE Trans. Veh. Technol.*, vol. 53, no. 6, pp. 1863–1881, Nov. 2004.

[9] Y. Bi, K.-H. Liu, L. X. Cai, X. Shen, and H. Zhao, "A multi-channel token ring protocol for QoS provisioning in inter-vehicle communications," *IEEE Trans. Wireless Commun.*, vol. 8, no. 11, pp. 5621–5631, Nov. 2009.

[10] Y.-C. Tseng, S.-Y. Ni, Y.-S. Chen, and J.-P. Sheu, "The broadcast storm problem in a mobile *ad hoc* network," *Wireless Netw.*, vol. 8, no. 2/3, pp. 153–167, Mar. 2002.

[11] B. Williams and T. Camp, "Comparison of broadcasting techniques for mobile *ad hoc* networks," in *Proc. MobiHoc*, Jun. 2002, pp. 194–205.

[12] C. Ho, K. Obraczka, G. Tsudik, and K. Viswanath, "Flooding for reliable multicast in multi-hop *ad hoc* networks," in *Proc. DIALM*, Aug. 1999, pp. 64–71.

[13] J. Jetcheva, Y. Hu, D. Maltz, and D. Johnson, A Simple Protocol for Multicast and Broadcast in Mobile Ad Hoc Networks, Jul. 2001.

[14] S. Ni, Y. Tseng, Y. Chen, and J. Sheu, "The broadcast storm problem in a mobile *ad hoc* network," in *Proc. MobiCom*, Aug. 1999, pp. 151–162.

[15] H. Lim and C. Kim, "Multicast tree construction and flooding in wireless *ad hoc* networks," in *Proc. MSWIM*, Aug. 2000, pp. 61–68.

[16] W. Peng and X. Lu, "On the reduction of broadcast redundancy in mobile *ad hoc* networks," in *Proc. Mobihoc*, Aug. 2000, pp. 129–130.

[17] Q. Xu, T. Mak, J. Ko, and R. Sengupta, "Medium access control protocol design for vehicle-vehicle safety messages," *IEEE Trans. Veh. Technol.*, vol. 56, no. 2, pp. 499–518, Mar. 2007.

[18] J. L. Sobrinho and A. S. Krishnakumar, "Quality-of-service in *ad hoc* carrier sense multiple access wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 17, no. 8, pp. 1353–1368, Aug. 1999.

[19] P. Wang, H. Jiang, and W. Zhuang, "A new MAC scheme supporting voice/data traffic in wireless *ad hoc* networks," *IEEE Trans. Mobile Comput.*, vol. 7, no. 12, pp. 1491–1503, Dec. 2008.

[20] G. Korkmaz, E. Ekici, and F. Ozguner, "Black-burst-based multihop broadcast protocols for vehicular networks," *IEEE Trans. Veh. Technol.*, vol. 56, no. 5, pp. 3159–3167, Sep. 2007.

[21] Y. Bi, H. Zhao, and X. Shen, "A directional broadcast protocol for emergency messages exchange in inter-vehicle communications," in *Proc. ICC*, Jun. 2009, pp. 1–5.

[22] L. Briesemeister and G. Hommel, "Role-based multicast in highly mobile but sparsely connected *ad hoc* networks," in *Proc. IEEE/ACM Workshop MobiHoc*, Aug. 2000, pp. 45–50.

[23] D. S. J. D. Couto, D. Aguayo, J. Bicket, and R. Morris, "A high-throughput path metric for multi-hop wireless networks," in *Proc. MobiCom*, Sep. 2003, pp. 134–146.

[24] R. Draves, J. Padhye, and B. Zill, "Routing in multi-radio, multi-hop wireless mesh networks," in *Proc. MobiCom*, Sep. 2004, pp. 114–128.

[25] A. Zinin, *Cisco IP Routing*. Boston, MA: Addison-Wesley, 2002.

[26] P. Liu, Z. Tao, S. Narayanan, T. Korakis, and S. S. Panwar, "CoopMAC: A cooperative MAC for wireless LANs," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 2, pp. 340–354, Feb. 2007.

[27] L. X. Cai, H. Hwang, X. Shen, J. W. Mark, and L. Cai, "Optimizing geographic routing for millimeter-wave wireless networks with directional antenna," in *Proc. Broadnets*, Sep. 2009, pp. 1–8.

[28] J. Peng and L. Cheng, "A distributed MAC scheme for emergency message dissemination in vehicular *ad hoc* networks," *IEEE Trans. Veh. Technol.*, vol. 56, no. 6, pp. 3300–3308, Nov. 2007.

[29] *IEEE Standard for Information Technology—Telecommunications and Information Exchange between Systems—Local and Metropolitan Area Networks—Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, IEEE Std. 802.11-2007, 2007.

[30] G. Mohammad and S. Marco, "Maximizable routing metrics," *IEEE/ACM Trans. Netw.*, vol. 11, no. 4, pp. 663–675, Aug. 2003.

[31] A. Bletsas, A. Khisti, D. P. Reed, and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 3, pp. 659–672, Mar. 2006.

[32] H. Shan, W. Zhuang, and Z. Wang, "Distributed cooperative MAC for multihop wireless networks," *IEEE Commun. Mag.*, vol. 47, no. 2, pp. 126–133, Feb. 2009.

[33] D. Xu, T. Sakurai, and H. L. Vu, "An access delay model for IEEE 802.11e EDCA," *IEEE Trans. Mobile Comput.*, vol. 8, no. 2, pp. 261–275, Feb. 2009.

[34] T. K. Mak, K. P. Laberteaux, R. Sengupta, and M. Ergen, "Multichannel medium access control for dedicated short-range communications," *IEEE Trans. Veh. Technol.*, vol. 58, no. 1, pp. 349–366, Jan. 2009.

[35] J. W. Mark and W. Zhuang, *Wireless Communications and Networking*. Englewood Cliffs, NJ: Prentice-Hall, 2003.

[36] J. G. Proakis, *Digital Communications*, 4th ed. New York: McGraw-Hill, 2000.

[37] J. A. Roberts, "Packet error rates for DPSK and differentially encoded coherent BPSK," *IEEE Trans. Veh. Technol.*, vol. 42, no. 2–4, pp. 1441–1444, Feb.–Apr. 1994.

[38] L. X. Cai, X. Shen, J. W. Mark, L. Cai, and Y. Xiao, "Voice capacity analysis of WLAN with unbalanced traffic," *IEEE Trans. Veh. Technol.*, vol. 55, no. 3, pp. 752–761, May 2006.

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