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Medium Access Control for QoS Provisioning in Vehicle-to-Infrastructure Communication Networks

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Abstract The emerging vehicular networks are targeted to provide efficient communications between mobile vehicles and fixed roadside units (RSU), and support mobile multimedia applications and safety services with diverse quality of service (QoS) requirements. In this paper, we propose a busy tone based medium access control (MAC) protocol with enhanced QoS provisioning for life critical safety services. By using busy tone signals for efficient channel preemption in both contention period (CP) and contention free period (CFP), emergency users can access the wireless channel with strict priority when they compete with multimedia users, and thus achieve the minimal access delay. Furthermore, through efficient transmission coordination on the busy tone channel, contention level can be effectively reduced, and the overall network resource utilization can be improved accordingly. We then develop an analytical model to quantify the medium access delay of emergency messages. Extensive simulations with Network Simulator (NS)-2 validate the analysis and demonstrate that the proposed MAC can guarantee reliable and timely emergency message dissemination in a vehicular network.

Keywords medium access control · quality of service · emergency service · vehicular network

1 Introduction

Vehicular communication networks have been considered as a promising technology to enable mobile multimedia services, e.g., mobile television, online gaming, and content sharing, etc., and safety services, e.g., collision avoidance, lane changing notification, etc.. There are two types of communications in a vehicular communication network. Moving vehicles can communicate with a roadside unit (RSU), referred to as vehicle to infrastructure (V2I) communications, or with other moving vehicles in an ad hoc mode, referred to as vehicle-to-vehicle (V2V) communications. Compared with mobile relaying vehicles, a RSU can provide higher communication capacity at an extended communication coverage, and thus the V2I network is more suitable for multimedia applications with stringent quality of service (QoS) requirements. In addition, when mobile vehicles need to establish a route and exchange information with other users multiple hops

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away, V2I communications can provide a more reliable path for message forwarding due to the infrastructure support.

In an infrastructure based vehicular network, a RSU usually serves as Point Coordinator (PC), and controls the medium access of vehicles in a basic service set (BSS). With high deployment and maintenance fees, base stations (BS) in cellular networks are not considered to be suitable to provide extensive connectivity for moving vehicles, and many research works propose to adopt flexible and cost-effective Wi-Fi access points (AP) to connect mobile vehicles in a V2I network [1–5]. A traditional Wi-Fi AP uses IEEE 802.11e medium access control (MAC) protocol which specifies contention-based enhanced distributed channel access (EDCA) for asynchronous traffic and contention-free hybrid coordination function controlled channel access (HCCA) for multimedia applications [6]. Depending on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) medium access mechanism, EDCA is fully distributed and can only provide statistical priority to multimedia users [7]. In HCCA, the PC usually polls users in a round robin fashion according to a predefined polling list in the contention free period (CFP). This approach is designed for general multimedia applications, and is especially suitable for media streaming services which require bandwidth allocation in a regular mode [8, 9]. However, some safety related emergency messages are life critical and may generate randomly when an emergency event occurs [10]. In such case, if an emergency user is not included in the polling list, it may need to wait for the end of the current CFP, and attempt to transmit the emergency message in the following contention period (CP). Due to the inefficient priority provisioning for emergency traffic, an emergency user may experience excessive medium access delay for message delivery. On the other hand, busy tone is considered as an efficient approach for QoS enhancement and collision avoidance [11, 12]. However, how to apply busy tone to enhance QoS provisioning of HCCA and guarantee the reliable and timely dissemination of life-critical emergency messages is still an open issue in vehicular networks.

In this paper, we propose a busy tone based enhanced MAC protocol to provision QoS for safety services. Specifically, we design two channel preemption mechanisms, taking into account an emergency message arrived in the CFP and the CP, respectively. With the proposed protocol, users with emergency messages are able to coordinate message disseminations by the busy tone signal and attempt to transmit the messages in the same superframe, and finally achieve a low access delay. Users with other multimedia traffic also need to sense the busy tone channel before their transmissions during either CP or CFP. As a result, other users can yield the transmission opportunity to users with emergency messages. In addition, through medium access coordinations via the busy tone channel, packet collisions can be effectively avoided, which achieves efficient resource utilization.

The main contributions of the paper are three-fold. We first apply busy tone signaling in the MAC design to provide strict priority to emergency users and achieve the minimal access delay of emergency messages. We then develop a mathematical model to analyze the network performance in terms of the access delay of emergency messages. Finally, we implement the proposed MAC in Network Simulator (NS-2) and show that it can guarantee a desirable lower delay for emergency messages while maintaining high QoS performance for other applications.

The remainder of this paper is organized as follows. The related work is summarized in Section 2. We present the system model in Section 3. A busy-tone based MAC protocol is proposed in Section 4. An analytical model is developed to study the performance of the proposed MAC in Section 5. Numerical results are given in Section 6, followed by concluding remarks in Section 7.

2 Related work

The IEEE 802.11p/WAVE task group [13] has issued the physical (PHY) and MAC layer specifications for communications in mobile vehicular environment. IEEE 802.11p physical layer operates in the Dedicated Short Range Communication (DSRC) frequency band of 5.85–5.925 GHz, which is divided into one control channel (CCH) and six service channels (SCHs). IEEE 802.11p MAC layer adopts CSMA/CA mechanism for channel access, and the time is divided into superframes. A superframe consists of a CCH interval during which transporting system control messages and safety messages are delivered, and a SCH interval during which non-safety messages can be exchanged. Even though a separate CCH is dedicated for emergency message transmissions, the channel access delay could be highly variable and may exceed the maximum delay requirements of emergency applications due to the contention nature of the IEEE 802.11p protocol.

To avoid the random medium access delay, a time coordinated MAC protocol named WAVE point coordination function (WPCF) is presented in [14]. Complied with the IEEE 802.11p standard, WPCF adopts the multi-channel structure and partitions a superframe into a contention free access period and a contention based access period. During either the CCH interval or the SCH interval, a user initiates a request frame to the RSU when it requires a contention free channel access. After receiving the requests, the RSU transmits a broadcast frame which contains a list of MAC addresses of users, and the sequence of user addresses reflects the urgency of users' messages, i.e., the most important safety message will be listed first. The listed users then can sequentially access the channel in the contention free access period. In order to support safety applications in RVC networks, a position-based data traffic prioritization scheme [15, 16] is proposed to reintroduce the CFP which is not present in IEEE 802.11p standard. The collision free CFP is coordinated by the RSU that is responsible for scheduling the traffic and polling the mobile users. After connecting to a neighboring RSU, a mobile user waits to be polled for data transmissions by the RSU. The polling sequence is determined by the positions of users, and the user closer to the hazard zone will have a higher priority to be polled in the CFP.

The solutions in [14–16] provide deterministic medium access delay and guarantee the transmission reliability of safety messages. However, an emergency message usually arrives in a random fashion, and it has to wait to be scheduled for transmission in the next contention free access period, which may result in a long access delay. Different from the aforementioned MAC protocols based on IEEE 802.11p multi-channel structure, a novel MAC protocol [17] is proposed using dual frequency channels, one of which operates on DSRC 5.8 GHz frequency band as a data channel, and the other uses VHF/UHF band as a control channel. When a user has an emergency message, it will transmit a resource allocation request to the RSU who will then inform the time slot allocation to the user on the control channel, and the user sends emergency message in the informed slot on the control channel and simultaneously transmits the message on the data channel according to CSMA/CA mechanism. The two way handshaking may increase the reliability of the emergency messages, but it may also prolong the channel access delay. In addition, dual frequency channel transmissions are not resource efficient.

In IVC networks, the download and upload requests to RSUs need to compete on the same channel. A scheduling mechanism [18, 19] is introduced to provision service scheduling in vehicle-roadside data access. It is called $D * S$ to consider both service deadline and data size, and uses $DS\_value = Left\_Time * Data\_size$ as its service priority weight. The request with the minimum DS_value will be served first, which means the message with an earlier deadline and a smaller packet size has a higher priority to be delivered. However, the scheduling scheme can not be applied to RVC since deadline and packet size can not be used to characterize safety messages.

3 System model

We consider a vehicular network that consists of multiple RSUs and moving vehicles, as shown in Fig. 1. RSUs are connected to wireline networks, and communicate with mobile vehicles within their coverages over the wireless channel. Vehicles move on the road with two opposite directions, and associate themselves to the closest RSUs to download Internet multimedia services or upload road traffic safety information. However, due to the high deployment and maintenance costs, RSUs can not achieve seamless coverage along the road, which means only the vehicles successfully connecting to a RSU can access Internet services, and the vehicles that fail to connect to a RSU can not initiate any data transmissions until they successfully associate themselves with next RSUs. Nevertheless, the issues of associations and handovers between two neighboring RSUs are not the focus of this paper, and we only consider the data communications when a link connection has been set up.

Each vehicle can simultaneously access two frequency channels, i.e., transmit channel jamming signals (busy tone) on a busy tone channel and data messages on a data channel, and there is no signal interference

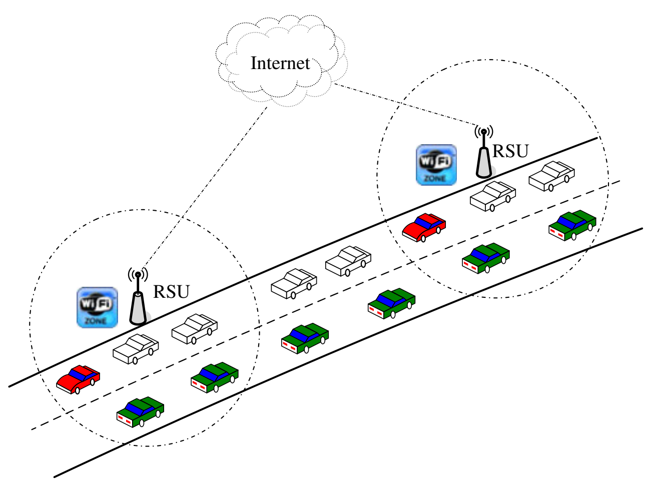

Fig. 1 The system architecture

between these two channels. Within the coverage of a RSU, different types of services share the common data channel resource, and the channel jamming signal is only used to coordinate the data channel access among multiple users. Vehicles may carry two types of services, including the multimedia traffic that has high bandwidth requirement, and the safety related emergency service that is delay-sensitive and has very stringent latency requirement. Furthermore, we employ the basic service differentiation mechanisms specified in IEEE 802.11e for QoS provisioning, and adopt the CSMA/CA mechanism of EDCA for medium access of multimedia services during the random contention interval, which means a higher priority service will have more opportunity to access channel resource over other lower priority services. However, in order to migrate the random access delay and provide fast emergency message delivery, an enhanced MAC protocol is introduced detailedly to guarantee the QoS of safety services during both CFP and CP in the following section.

4 Busy-tone based MAC protocol

In this section, we propose a busy tone based enhanced MAC protocol to support reliable and timely emergency message dissemination in V2I network. The proposed MAC is compatible with the HCCA MAC specified in IEEE 802.11e, based on the time slotted superframe structure that consists of a CFP and a CP. To achieve the minimal access latency of emergency messages, we propose two enhanced MAC protocols for emergency messages arriving in the CFP and CP, respectively.

4.1 The preemption protocol in contention-free period

In IEEE 802.11e, when a packet is generated for transmission, a user[1] needs to send a request to the PC and starts the transmission only when PC polls or allocates time slots for its contention free transmissions. In other words, the current CFP has been scheduled for data transmissions requested in the previous superframes, and a user with data arriving in this CFP needs to wait until the current CFP ends before it attempts data transmissions. This is not desirable for emergency message dissemination in vehicular networks, which demands the minimal transmission latency. To provision strict QoS for emergency messages and achieve minimal delay, we apply an out band busy tone channel in the MAC protocol design and propose a novel channel preemption mechanism in the CFP.

When an emergency message is generated in a CFP, the user with the message will first sense the data channel. If the data channel is sensed idle for a shortest interframe space (SIFS), which implies that no other user is scheduled for transmission at this time, the user can transmit the emergency message immediately. If the channel is sensed busy when another user occupies the channel for data transmissions, the user with the emergency message will keep sensing the data channel. In the mean time, the user will sense the busy tone channel and initiate a busy tone signal transmission if the busy tone channel is idle. The duration of the busy tone signal is determined by the busy duration on the data channel. In other words, when the user overhears an acknowledgment message on the data channel, which indicates that the ongoing transmission completes, the user will stop the busy tone signal and transmit the emergency message on the data channel after a SIFS interval.

When multiple users with emergency messages arrive in the same CFP, they will compete for channel access. For example, as shown in Fig. 2, users *B* and *C* arrive at time t_0 and t_1, respectively. Since the data channel is occupied by the data transmission, both *B* and *C* will defer their emergency message transmissions and sense the busy tone channel in the mean time. As *B* first senses the busy tone channel and initiates a busy tone signal, *C* will find the channel is busy when it starts to sense the busy tone channel. In this case, *C* will keep sensing the busy tone channel until the channel is released by *B*, and then *C* can immediately initiate its own busy tone signal on the busy tone channel for a duration. After sensing the busy tone channel idle for SIFS interval, C will retransmit the busy tone signal until B releases the data channel. It is also possible that both *B* and *C* find the busy tone channel is busy, which means another user, e.g., user *A*, has sent a busy tone signal and waits to transmit an emergency message. Then both *B* and *C* will initiate their busy tone signals on the busy tone channel after *A*'s busy tone completes. Suppose *B* sets a longer busy tone signal than *C*, *C* will find the busy tone channel is still busy when its busy tone signal ends. In this case, *B* wins competition and will transmit its emergency message first on the data channel when the channel is free, as shown in Fig. 3. A user can start its emergency transmission on the data channel and stop its own busy tone signal only when the data channel is released by other users.

[1] Vehicle and user are used inter-changeably in this paper.

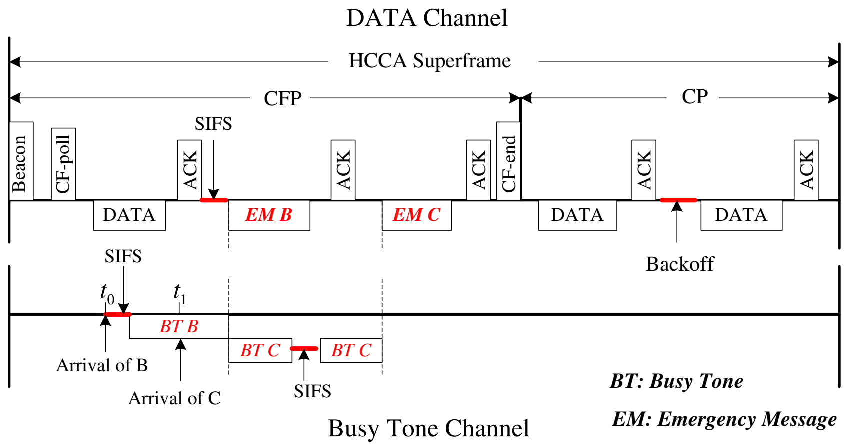

Fig. 2 The channel preemption procedure

For emergency messages with stringent delay requirement, a short busy tone signal is desirable since the message should be transmitted as soon as possible when the channel is available. When a user i competes with other users on the busy tone channel after the channel is released, denote t_i as the duration of its busy tone signal, and we have

$$t_i = \tau \cdot n_i, \tag{1}$$

where τ is the duration of a mini-slot [20–22], and n_i is the number of mini-slots for user i transmitting the busy tone signal, where $0 < n_i \leqslant W$, and it can be denoted by

$$n_i = \frac{w_i}{w_{\max}} \cdot W, \tag{2}$$

where W is given by

$$W = \left\lfloor \frac{D_e}{\tau \cdot R_d} \right\rfloor, \tag{3}$$

where $\lfloor \frac{D_e}{\tau \cdot R_d} \rfloor$ is the floor function that gives the largest integer less than or equal to $\frac{D_e}{\tau \cdot R_d}$, D_e is the size of an emergency message, R_d is the data rate, w_i is the waiting time that user i has experienced on the busy tone channel, and $w_{\max}$ is the maximum duration an user may wait on the busy tone channel, which can be denoted as

$$w_{\max} = T_m + (N_e - 1)T_e, \tag{4}$$

where N_e is the number of users with emergency messages within the coverage of a RSU, T_m and T_e are the successful transmission times of a multimedia message and an emergency message, respectively, and they can be represented by

$$\begin{aligned} T_m &= 2t_{sifs} + \frac{D_m}{R_d} + \frac{D_{\text{ack}}}{R_b}, \\ T_e &= 2t_{sifs} + \frac{D_e}{R_d} + \frac{D_{\text{ack}}}{R_b}, \end{aligned} \tag{5}$$

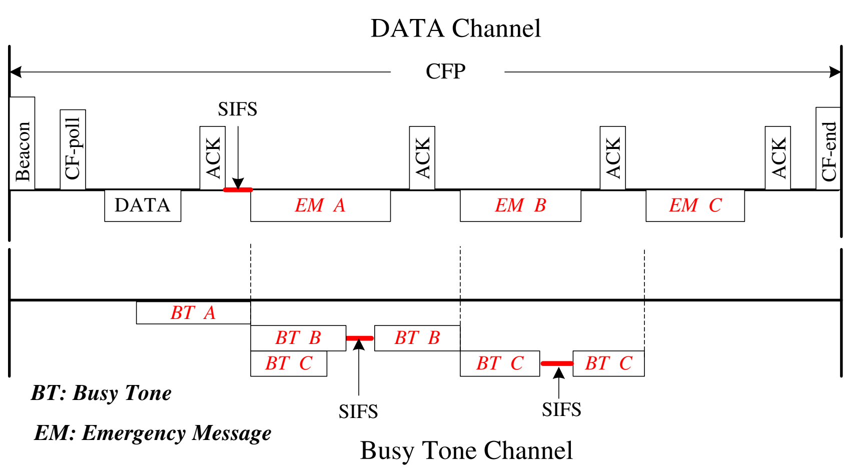

Fig. 3 Competition of multiple users

where t_{sifs} is the duration of a SIFS, R_b is the basic transmission rate, D_m and D_{ack} are the packet payload sizes of a multimedia message and an acknowledgement packet.

The duration of a mini-slot is usually several microseconds, and the transmission time of an emergency message will be divided into a large number of mini-slots, from which a user selects its number of mini-slots for busy tone signal transmission based on its waiting time on the busy tone channel. Therefore, the duration of busy tone signal is smaller than the transmission time of an emergency message. After transmitting a busy tone signal with duration t_i, user i will sense the busy tone channel. If the channel is busy for a SIFS, which indicates that other users also have emergency messages for transmission, user i will stop the busy tone signal, and re-initiate a signal after the busy tone channel is released. Otherwise, user i will transmit busy tone signal, and sense the data channel simultaneously. The procedure repeats until emergency messages are transmitted successfully. Note that, according to Eq. 2, the user waiting for the longest duration of the busy tone channel will select the largest number of mini-slots, and transmit the longest busy tone signal to win the competition for data channel access. The channel preemption procedure with multiple users competing on the busy tone channel is shown in Fig. 3.

By applying busy tone signals to preempt data channel access from other users, a user can disseminate emergency messages with a high priority and achieve a low access delay. As users need to sense the busy tone channel before initiating a busy tone signal, the multiuser collisions are also reduced. With efficient collision avoidance on the busy tone channel, the access delay on the data channel is also mitigated accordingly. The pseudo codes of the channel preemption procedure in a CFP is described in Algorithm 1.

Algorithm 1 Channel preemption Mechanism in CFP

```
1:  User i has an emergency message in CFP
2:  User i senses the data channel
3:  if Data channel is idle for a SIFS then
4:      User i transmits the emergency message
5:  else
6:      User i senses both data and busy tone channels
7:      if Busy tone channel is idle then
8:          User i transmits a busy tone signal
9:          while Data channel is busy do
10:             if i overhears an ACK frame on data channel then
11:                 break
12:             end if
13:         end while
14:         User i stops busy tone signal
15:         User i transmits the emergency immediately
16:     else
17:         while Busy tone channel is sensed busy do
18:             Continue to sense the channel;
19:         end while
20:         User i computes n_i ∈ (0, W]
21:         User i initiates a busy tone signal for duration t_i
22:         After t_i, User i senses the busy tone channel for SIFS

23:         if Busy tone channel is busy then
24:             User i keeps sensing the channel, and go to line 17
25:         else
26:             User i initiates a busy tone signal, and go to line 9
27:         end if
28:     end if
29: end if
```

4.2 The channel preemption protocol in CP

Due to the random initiation of emergency messages, a message may arrive at the MAC layer during a contention period using the distributed EDCA MAC. In this case, the user with emergency messages must compete for data channel access with other users carrying different traffic flows. Similarly, if the data channel is sensed idle, a user can transmit the emergency message immediately. If the data channel is sensed busy, a user can use a similar procedure to compete for channel access on the busy tone channel as that in CFP. To assure the highest priority of safety services, users with emergency messages only sense the channel for a duration that equals a SIFS plus a slot time, while other users use a larger AIFS which is at least a distributed interframe space (DIFS),[2] based on the categories of the multimedia traffic. In other words, if a user has an emergency message during the CP, it can attain a higher probability to access the channel compared with users carrying other multimedia applications by waiting for a smaller duration before transmitting.

4.3 Collision avoidance

By adopting busy tone channel for channel access preemption, we can not only mitigate the channel access delay of emergency messages and provision satisfactory QoS for safety services, but also improve the network resource utilization by reducing collisions among

[2] A DIFS equals a SIFS plus two slots.

different users. Generally, all users with multimedia traffic for transmission need to sense the busy tone channel before attempting to transmit in both CFP and CP. If the busy tone channel is busy, which indicates that some users want to disseminate emergency messages, users with other traffic should postpone their own transmissions until emergency messages are successfully delivered and the busy tone channel is released. Therefore, by sensing the busy tone channel, collisions between emergency messages and other categories of traffic can be efficiently migrated, and the transmission efficiency can be improved accordingly.

5 Performance analysis

In this section, we develop an analytical model to study the performance of the proposed MAC protocol. We consider two categories of services in a vehicular network, the multimedia service and the emergency service. Denote the duration of a superframe as S, a proportion of which, $S \cdot \alpha$ is assigned for CFP, and the remaining $S \cdot (1-\alpha)$ is used for CP. An emergent user generates emergency messages at an average rate of $\lambda_e = 1/S$ with the arrival times randomly distributed in a superframe. A Non-emergency user generates CBR traffic at the rate λ_m, and it is saturated, which means it always has multimedia traffic in the buffer for transmission. We use the saturation case for the worst case performance analysis of emergency traffic because the delay performance can be improved under non-saturation case. We assume an error-free wireless channel so that transmitted messages are successfully received if there are no packet collisions. As emergency messages are randomly generated and the arrival times are uniformly distributed over a superframe S, the probability that an emergency user has an emergency packet to transmit during T_e is thus given by $p_e = T_e/S$. Similarly, an emergency user may deliver an emergency packet during T_d with probability $p_d = T_d/S$.

For time critical safety applications, the most crucial performance metric is the emergency message access delay [23]. Define the access delay as the duration from the time instant an emergency message arrives at the head of the MAC layer until it is successfully transmitted. As emergency message collisions are avoided by efficient transmission coordinations on the busy tone channel, a message will be transmitted successfully when the data channel is available. Therefore, emergency message access delay is comprised of two parts: (i) the waiting time for medium access at the MAC layer; and (ii) the message transmission time. In order to compute the average emergency message access delay, we tag an emergency message, and there are three possibilities when the tagged emergency message arrives at the head of the MAC layer:

(1) The data channel is idle, and the tagged emergency message can be transmitted directly. Its emergency message access delay is

$$T_1 = T_e. \tag{6}$$

(2) The data channel is occupied by a data packet transmission, and the transmission of the tagged emergency message has to be postponed. In the mean time, the user with this emergency message turns to sense the busy tone channel. In this case, the tagged emergency message access delay is

$$T_2 = X + (m+1)T_e, \tag{7}$$

where X is the remaining time of the current data packet transmission since the tagged emergency message arrives, and m is the number of the emergency messages that arrive during the current data packet transmission but before the arrival of the tagged emergency message. According to Eq. 2, the emergency messages waiting for data channel access form a First Come First Serve (FCFS) queue. Therefore, the tagged emergency message has to wait until the current data packet and the previous m emergency message transmissions complete.

(3) The data channel is occupied by an emergency message. Similar to the second case, the user with the tagged emergency message can not transmit and has to sense the busy tone channel. In this case, the access delay of the tagged emergency message is

$$T_3 = X + (M+m+1)T_e, \tag{8}$$

where M is the number of emergency messages that arrive before the current multimedia packet transmission but wait for data channel access in the FCFS queue. Consequently, the tagged emergency message can not initiate data channel access until the current multimedia packet and the previous $M+m$ emergency message transmissions finish.

In each of the three cases, the average emergency message access delay is the expectation of T_i ($i = 1, 2, 3$). In the first case $E(T_1) = T_e$. However, in the second case, m is the number of emergency messages that arrive during the current data packet transmission but before the arrival of the tagged emergency message. Let $\lambda_1 = N_e\lambda_e$, $\lambda_2 = N_m\lambda_m$, $\lambda = \lambda_1 + \lambda_2$, $\rho = \lambda_1 \cdot T_e + \lambda_2 \cdot T_m$, where N_m is the number of nodes with multimedia traffic. We have

$$m = \lambda_1 \cdot (T_d - X), \tag{9}$$

and consequently the expectation of T_2 is expressed as

$$\begin{aligned} E(T_2) &= E(X + (m+1)T_e) \\ &= E(X) + (E(m)+1)T_e \\ &= E(X) + [\lambda_1 \cdot (T_d - E(X)) + 1]T_e \\ &= T_d/2 + [\lambda_1 \cdot (T_d - T_d/2) + 1]T_e \\ &= T_d/2 + (\lambda_1 \cdot T_d/2 + 1)T_e. \end{aligned} \tag{10}$$

In order to derive the expectation of T_3, we first consider the average number of emergency messages to be served in the FCFS queue. We denote $N_{e,i}$ and $N_{m,i}$ as the numbers of emergency messages and multimedia packets waiting for transmissions at the beginning of the i'th transmission, and $A_{e,i}$ and $A_{m,i}$ represent the numbers of emergency messages and multimedia packets that arrive during the i'th transmission on the data channel. Since the departure probability of an emergency message is equal to the probability of a message arriving to the FCFS queue in a steady state, we have

$$\begin{aligned} P(N_{e,i} > 0) &= \rho \cdot \frac{\lambda_1}{\lambda}, \\ P(N_{e,i} = 0, N_{m,i} > 0) &= \rho \cdot \frac{\lambda_2}{\lambda}, \\ P(N_{e,i} = 0, N_{m,i} = 0) &= \rho \cdot \frac{(\lambda - \lambda_1 - \lambda_2)}{\lambda}. \end{aligned} \tag{11}$$

We then consider the numbers of emergency messages and multimedia packets at the beginning of the $(i+1)$'th transmission on the data channel, for $N_{e,i} > 0$

$$\begin{aligned} N_{e,i+1} &= N_{e,i} - 1 + A_{e,i}, \\ N_{m,i+1} &= N_{e,i} + A_{m,i}, \end{aligned} \tag{12}$$

and for $N_{e,i} = 0$, $N_{m,i} > 0$, we have

$$\begin{aligned} N_{e,i+1} &= A_{e,i}, \\ N_{m,i+1} &= N_{e,i} - 1 + A_{m,i}, \end{aligned} \tag{13}$$

and finally for $N_{e,i} = 0$, $N_{m,i} = 0$, we have

$$\begin{aligned} N_{e,i+1} &= A_{e,i}, \\ N_{m,i+1} &= A_{m,i}. \end{aligned} \tag{14}$$

Because the number of emergency messages waiting for transmission at the beginning of the i'th transmission is independent of the number of emergency messages arriving during the i'th transmission, we consequently have

$$\begin{aligned} E(N_{e,i+1}) &= E(N_{e,i+1}|N_{e,i} > 0) \cdot P(N_{e,i} > 0) \\ &\quad + E(N_{e,i+1}|N_{e,i} = 0, N_{m,i} > 0) \\ &\quad \cdot P(N_{e,i} = 0, N_{m,i} > 0) \\ &\quad + E(N_{e,i+1}|N_{e,i} = 0, N_{m,i} = 0) \\ &\quad \cdot P(N_{e,i} = 0, N_{m,i} = 0) \\ &= E(N_{e,i} - 1 + A_{e,i}) \cdot P(N_{e,i} > 0) + E(A_{e,i}) \\ &\quad \cdot P(N_{e,i} = 0, N_{m,i} > 0) \\ &= \rho \cdot \frac{\lambda_1}{\lambda}\left[E(N_{e,i}) - 1 + E(A_{e,i})\right] \\ &\quad + \rho \cdot \frac{\lambda_2}{\lambda} E(A_{e,i}) \\ &= \left(\rho \cdot E(A_{e,i}) - \rho \cdot \frac{\lambda_1}{\lambda}\right) \Big/ \left(1 - \rho \cdot \frac{\lambda_1}{\lambda}\right). \end{aligned} \tag{15}$$

In Eq. 15, as we assume the multimedia traffic is saturated, i.e., $N_{m,i} > 0$, consequently $P(N_{e,i} = 0, N_{m,i} = 0) = 0$. In addition, because $A_{e,i}$ is independent of $N_{e,i}$, and $E(A_{e,i}) = E(N_{e,i+1})$, the third and fourth steps are obtained. However, at the last step of Eq. 15, the expectation $E(A_{e,i})$ is the average number of emergency messages arrived during the i'th transmission on the data channel. Let E_e and E_m denote the events that the current i'th transmission is an emergency message transmission or a multimedia packet transmission, respectively, and we have

$$\begin{aligned} E(A_{e,i}) &= P(E_e)E(A_{e,i}|E_e) + P(E_m)E(A_{e,i}|E_m) \\ &= P(E_e)\lambda_1 T_e + P(E_m)\lambda_1 T_d \\ &= N_e p_e \lambda_1 T_e + (1 - N_e p_e)\lambda_1 T_d, \end{aligned} \tag{16}$$

During the period S, there are N_e emergency message transmissions, and the probability that data channel is occupied by an emergency message is $N_e p_e$. Combining Eqs. 15 and 16, we can obtain the average number of emergency messages in the FCFS queue which can be expressed by

$$\begin{aligned} &E(N_{e,i+1}) \\ &\quad = \rho\lambda_1[N_e p_e T_e + (1 - N_e p_e)T_d - 1/\lambda] \Big/ \left(1 - \rho \cdot \frac{\lambda_1}{\lambda}\right) \\ &\quad = \rho\lambda_1[N_e p_e T_e \lambda + (1 - N_e p_e)T_d \lambda - 1]/(\lambda - \rho\lambda_1). \end{aligned} \tag{17}$$

Table 1 Parameters in simulations

Parameter	Value	Parameter	Value
SIFS	10 µs	PLCP & preamble	192 µs
Time slot	20 µs	RTS	20 byte
DIFS	50 µs	CTS	14 byte
Basic rate	1 M	DATA frame	512 byte
Data rate	11 M	ACK	14 byte
Transmit range	250 m	Emergency message	1,000 byte
Retry limit	4	Superframe	50 ms
τ	10 µs	α	0.5

Next, we consider the access delay of the tagged emergency message in the third case, and the expectation of T_3 is given by

$$\begin{aligned} E(T_3) &= E(X + (M + m + 1)T_e) \\ &= E(X) + (E(M + m) + 1)T_e \\ &= E(X) + \big(E(N_{e,i+1}) + 1\big)\,T_e \\ &= T_e\rho\lambda_1[N_e p_e T_e\lambda + (1 - N_e p_e)T_d\lambda - 1] \\ &\quad /\,(\lambda - \rho\lambda_1) + T_d/2 + T_e \end{aligned} \tag{18}$$

As multimedia traffic is bandwidth intensive, we consider there are always data transmissions on the data channel, and for the first case the possibility that the channel is idle when the tagged emergency message arrives is 0. Therefore, the user with the tagged message will either find the channel is occupied by a multimedia user as the second case (event E_m) or another emergency user as the third case (event E_e). Since an emergency user generates emergency messages at an average rate of $1/S$ and there are totally N_e emergency users, the probability that the channel is occupied by another emergency user when the emergency user comes is $N_e p_e$, and consequently the probability that the channel is occupied by a multimedia user when the emergency user comes is $1 - N_e p_e$. As a result, the average access delay of an emergency message could be obtained by the equation $T = P(E_m)E(T_2) + P(E_e)E(T_3)$.

6 Numerical results

In this section, we implement the proposed MAC in network simulator-2 [24] and evaluate its performance in terms of the average access delay of emergency messages and the average throughput of multimedia traffic. We also compare the performance of the proposed busy tone based MAC with those of IEEE 802.11e HCCA and WPCF, and add a traffic category of safety services in the CP of HCCA.

We simulate a vehicle network with multiple moving vehicles in two opposite directions, as shown in Fig. 1. A RSU can communicate with vehicles within its coverage area with a radius of 250 m. The RSU and the vehicles in its coverage form a basic service set. In each service set, we have N_e users with emergency messages and N_m users with other multimedia traffic for transmissions. The length of a MAC superframe is set $S = 50$ ms, and a portion $\alpha = 50\%$ of which is allocated for CFP while the remaining 50% is for CP using contention based EDCA MAC. The arrivals of emergency messages follow random distribution with mean $\lambda_e = 1/S$, and the initial generation time is uniformly distributed over the duration of S. The packet payload size of an emergency message is 1,000 bytes, and the multimedia traffic is modeled as a constant bit rate flow and each packet has 512 bytes. The detailed parameter setting used in the simulations is tabulated in Table 1.

6.1 Emergency message access delay

We first evaluate the access delay performance of the safety services using the proposed MAC, and compare it with that of HCCA, as shown in Fig. 4. We

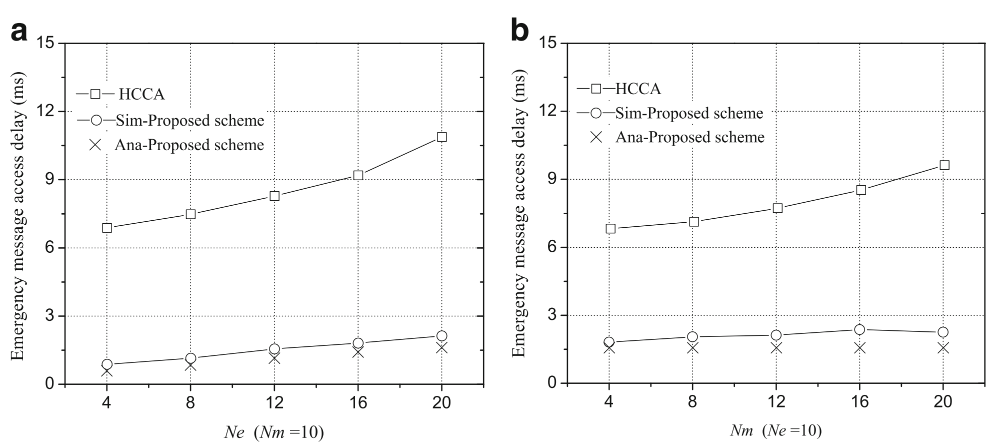

Fig. 4 Emergency message access delays of HCCA and the proposed protocol

first set $N_m = 10$, i.e., in each service set 10 saturated users carry multimedia traffic and always have data to transmit, and increase N_e, the number of users with emergency messages. It is shown in Fig. 4a that the access delay of emergency messages increases when more users compete to send emergency messages. It can also been seen that the proposed MAC achieves much lower access delay compared with HCCA, especially when N_e increases. In HCCA, when a user has an emergency message arriving during a CFP, the user needs to wait till the current CFP terminates and competes with all other users in the following CP, which results in a long access delay. In the proposed protocol, a user is able to preempt channel access by sending a busy tone signal to reserve a channel access for emergency message dissemination on the data channel, and only competes with other users with emergency messages. Therefore, a lower access delay is achieved with our proposed MAC. We also study the impacts of multimedia traffic on the access delay performance of emergency messages in Fig. 4b. We set $N_e = 10$, i.e., 10 users have emergency messages, and vary the number of saturated users with multimedia traffic. Similarly, it is shown that the access delay with our proposed protocol is much lower than that of HCCA due to efficient channel preemption on the busy tone channel. In addition, the access delay does not vary much with the number of multimedia users. This is because emergency users only compete for channel access with each other on the busy tone channel, and thus the competition level is independent of the multimedia users. As shown in Fig. 4, the analytical results approach the simulation results well.

We then compare the access delay performance of the safety services between WPCF and the proposed protocol in Fig. 5. We first set $N_m = 0$, which means no user requests to upload or download multimedia traffic and competes for channel access with emergency users, and therefore the traffic load of the system is not heavy. We increase N_e, the number of users with emergency messages, and evaluate its impact on the emergency message access delay of the two protocols under light traffic load. It is observed from Fig. 5a that both emergency message access delays slightly increase when more emergency users start to transmit messages to the RSU. The delay of our proposed protocol is much lower than that of WPCF. This is because that an emergency user has to request bandwidth allocation from the RSU in WPCF, and waits to transmit the emergency message in a following CFP period after obtaining its order in the MAC list from the RSU. Although the transmission reliability of emergency messages during the CFP period can be guaranteed, channel access delay of the emergency user could be variable. Nevertheless, in our proposed protocol a randomly arrived emergency message do not need to be scheduled by the RSU for transmission, and an emergency user can access the wireless channel directly when the medium is sensed idle, which results in a shorter access delay.

The access delay performance of the two protocols is compared under high traffic load in Fig. 5b. The number of users with multimedia traffic is set to be 10. Each user is under a saturated state, e.g., always has data for transmissions. First, we observe that the access delay of WPCF in Fig. 5b does not change compared with that in Fig. 5a even though the system traffic is saturated. Second, the access delay of the proposed protocol in Fig. 5b is slightly larger than that in Fig. 5a. Third, the access delay of WPCF is much larger than that of our proposed protocol. In WPCF, the emergency users will be scheduled first and access the wireless channel at the beginning of a CFP period, and consequently the access delay will not change with the increasing number of multimedia traffic that are scheduled after them in the CFP period. However, under high traffic load, in the proposed protocol, an emergency user needs to postpone its channel access during the transmission

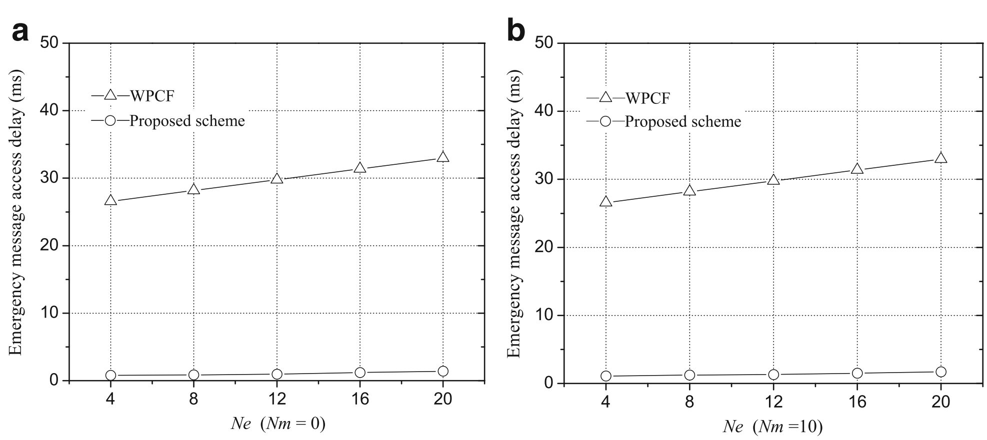

Fig. 5 Emergency message access delays of WPCF and the proposed protocol

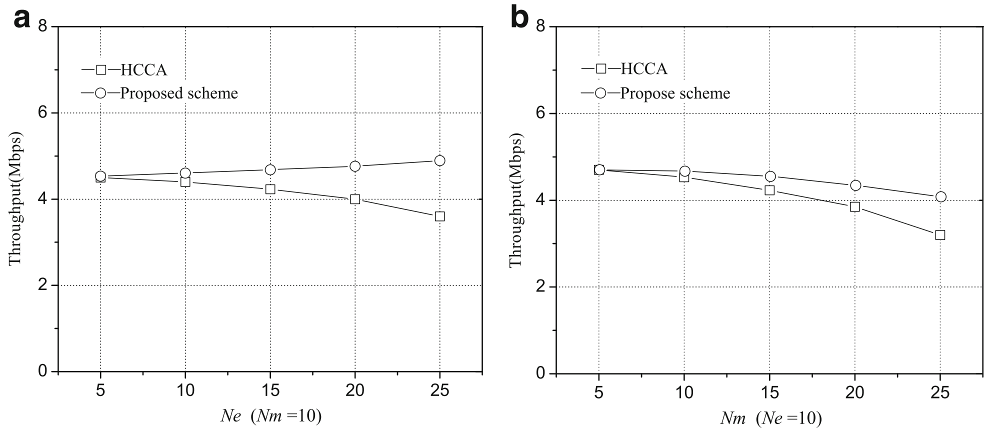

Fig. 6 Throughputs of HCCA and the proposed protocol

interval of a multimedia user, and only preempts the channel after the complete of the ongoing data transmission. Therefore, it may not be able to access the channel immediately, which results in a higher access delay compared with that under the light traffic load. Nevertheless, the access delay of our proposed protocol is still much lower than that of WPCF.

6.2 Network throughput

In Fig. 6, we compare the average network throughput of HCCA with that of our proposed protocol under different N_e and N_m. The network throughput is evaluated as the successfully transmitted messages, including safety messages and the multimedia traffic. As shown in Fig. 6a, the network throughput using the proposed protocol slightly goes up with the increasing number of emergency users, as the increasing safety traffic preempting the channel resource can prevent multimedia traffic to access the medium, and thus multimedia packet collisions are reduced. With the HCCA, more emergency users lead to a higher contention level on the data channel, which causes collisions and degrades the network throughput. In the proposed MAC, emergency users only compete on the busy tone channel, and transmit data without contentions over the data channel. Therefore, the network throughput does not drop with N_e. We then fix N_e, vary N_m, and compare the network throughput of the two protocols in Fig. 6b. It can be seen that the network throughput decreases when more multimedia users join the network due to the increased contentions between multimedia users on the data channel. However, as our proposed MAC reduces the contention level by mitigating the contentions between the emergency message and the multimedia traffic, the proposed MAC achieves a higher network throughput compared to HCCA.

7 Conclusions

In this paper, we have proposed a busy tone based MAC protocol for safety services in the V2I network. By using busy tone signals for channel preemption in both CFP and CP, our proposed MAC provides strict priority for safety services and achieves a low access delay for emergency messages. Because of efficient transmission coordinations over the busy tone channel, the channel access contention between emergency messages and multimedia traffic is also mitigated, which improves the overall resource utilization. We have also developed an analytical model to study the emergency message access delay. Simulation results have validated the analysis and demonstrated the efficiency and effectiveness of the proposed MAC. For our future work, we will jointly take into account other contending metrics when multiple emergency users compete to access data channel, in addition to consider the waiting time on the busy tone channel. For instance, an emergency user that is going to leave the coverage of the RSU should have a higher priority to deliver its emergency message since a long access delay may lead to its link break with the RSU, and furthermore the urgency of the emergency message also needs to be considered because outdated emergency messages not only waste the limited channel resource but also are useless for other users. We will also study the impact of mobile fading channel on the performance of the proposed MAC protocol.

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