A Distributed MAC Scheme for Emergency Message Dissemination in Vehicular Ad Hoc Networks

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***Abstract*— The successful dissemination of emergency messages in vehicular ad hoc networks can make a difference between life and death. To achieve the life-saving goals, emergency message dissemination needs timely and lossless medium access in vehicular ad hoc networks. Although in the literature there are existing medium access control (MAC) protocols that support priority medium access, these protocols focus on providing statistical priority for unicast flows instead of strict priority for individual packets. This paper proposes a new MAC scheme to address this issue. With its novel pulse-based control mechanism, the proposed MAC scheme realizes strict, packet-level priority scheduling for emergency packets in a fully distributed way. With the same mechanism, the proposed scheme supports multiple levels of strict priority for emergency packets. The comprehensive simulation results in the paper show the effectiveness of the proposed MAC scheme in serving emergency messages in vehicular ad hoc networks.**

Keywords: vehicular communications networks, vehicular ad hoc networks, medium access control (MAC), priority, hidden terminals, quality of service (QoS)

I. INTRODUCTION

Emergency message dissemination will be an important type of application in vehicular ad hoc networks as vehicles become more and more intelligent [3], [4]. For example, in battleground, if a fighting vehicle detects mines, poisonous gases, or other killing substances, the vehicle may want all other units in the platoon to be aware of the detection as soon as possible. On highways, future intelligent vehicles will form wireless ad hoc networks and share safety information to improve highway safety [5]. For example, if a vehicle detects dangerous stuff such as a sharp object fallen from a construction truck on the road, it will notify other vehicles behind to avoid the object. In these cases, emergency messages need to be delivered to each node nearby with almost no delays. A single *delayed* or *lost* message could result in loss of life.

A vehicle that detects an emergency event usually only needs to broadcast its emergency message to other vehicles in a short range, such as a range of several hundred meters. A single-hop delivery may therefore be adequate for this type of application, which makes routing for emergency packets less relevant. In such a case, medium access control becomes the most critical segment in the delivery process of an emergency packet. Medium access control for emergency message dissemination is, however, a challenging problem in vehicular ad hoc networks. The reason is that medium access control in a typical vehicular ad hoc network needs to be fully distributed due to the constantly moving and changing nodes in the network.

With fully-distributed medium access control, packets may experience unpredictable delays in media access due to deferrals and backoffs. Long medium access delay is, however, intolerable for emergency message dissemination in vehicular ad hoc networks because of the short lifetimes[1] of emergency messages in such networks. Moreover, different types of emergency messages usually have different lifetimes (i.e., different levels of emergency). In a fully distributed way, a MAC scheme for emergency message dissemination must be able to ensure that a message with a longer lifetime yields to other messages with shorter lifetimes.

Besides delay, packet loss is also a serious problem for emergency message dissemination in vehicular ad hoc networks. The neighbors of a node in a vehicular ad hoc network usually change all the time. A node in such a case can hardly have precise neighbor information. Some techniques such as automatic repeat request (ARQ), therefore, cannot ensure reliability for broadcast packets in such a case. Being lossless in medium access thus becomes critical for emergency packets in vehicular ad hoc networks. By lossless medium access we mean that the emergency packets have a negligible rate of loss caused by collisions in the network. One well-known source of packet losses in medium access in ad hoc networks is hidden terminals [6]. Basically, two nodes that cannot sense each other may still interfere with each other at their receivers and consequently cause packet losses.

Although in the literature there are existing MAC protocols supporting priority access, such as [7], [8], [9], [10], [11], these protocols focus on providing statistical priority for flows instead of strict priority for individual packets. In addition, these protocols do not fully address the hidden terminal problem. There are some other protocols in the literature that have been designed for addressing the hidden terminal problem, such as [12], [13], [14], [6], [15], [16], [17]. These protocols are, however, mainly for unicast traffic and thus are not suitable

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[1]The lifetime of an emergency message is defined in this paper as the time span in which the message can still be useful for its receivers to avoid a damaging situation.

for emergency message dissemination in vehicular ad hoc networks. There is also existing work such as [18], [19], [20], [21] that addresses specific MAC issues for broadcast traffic in vehicular networks. These proposed protocols, however, do not support strict, packet-level priority scheduling in a fully distributed way. Therefore, existing MAC protocols do not have the full capabilities to support emergency message dissemination in vehicular ad hoc networks.

The major contribution of this paper is its proposal of a new MAC scheme that effectively supports emergency message dissemination in vehicular ad hoc networks. The basic approach of the proposed MAC scheme is the intelligent use of a single control channel for multiple purposes. The proposed MAC scheme realizes low and stable medium access delays for *individual* emergency packets and does not have the hidden terminal problem. Moreover, the proposed scheme is fully distributed but able to provide multiple levels of strict priority scheduling for emergency packets. The comprehensive simulation results in the paper show the effectiveness of the proposed protocol in supporting emergency message dissemination in vehicular ad hoc networks.

The rest of the paper is organized as follows. Section II presents in detail the proposed MAC scheme for emergency dissemination in vehicular ad hoc networks. Section III evaluates the proposed scheme with extensive simulations. Finally, Section IV concludes the paper.

II. The Proposed Medium Access Control Scheme

A. Approach and Outline

The basic approach of the proposed MAC scheme in this paper is to use "pulses" in a single control channel to achieve multiple goals. "Pulses" in the proposed scheme are basically single-tone waves with pauses of *random* lengths, which will be introduced in detail in Section II.B. In the proposed scheme, the control channel carries *only* pulses and pulses *only* appear in the control channel. The control channel is monitored by all nodes all the time except when they are transmitting in the channel (note that an antenna usually cannot transmit and receive at the same time). A node that is generating pulses in the control channel still monitors the channel when its pulses pause. There is usually a transition delay of a couple of microseconds when an antenna switches its state. This delay, however, is small as compared with the duration of a pulse in the proposed scheme, which is usually at least several tens of microseconds.

In addition, with the proposed scheme, the application layer determines the emergency level of a message and put this information in the packet header. The application layer also determines the number of duplicate copies to send for each emergency message. The purpose of sending duplicate copies of an emergency message is to deal with the problem that ARQ is not practical for emergency message dissemination in a typical vehicular ad hoc network. Additionally, the proposed scheme assumes that there is a co-existing media access control protocol such as IEEE 802.11 for normal packets, i.e., non-emergency packets. Emergency packets access the medium through the proposed MAC protocol, while normal packets access the medium through the co-existing protocol.

Basically, the proposed scheme works in the following way. As soon as an emergency packet[2] in a node arrives at the MAC sub-layer from the upper layer, the node starts a backoff timer if the control channel has been sensed idle for a specified amount of time. Otherwise, the node keeps monitoring the control channel. The delay of the backoff timer is random but in a range determined by the emergency level of the message to be disseminated. When its backoff timer expires, the node starts to transmit pulses in the control channel. Shortly after starting to transmit pulses, the node starts to broadcast the emergency packet in the data channel. However, if the node detects a pulse before its backoff timer expires, it cancels its timer and returns to monitor the control channel. The pulses in the control channel are called "*priopulses*" in this paper and will be introduced in detail in the next subsection. When a node detects a priopulse in the control channel at any time, it aborts its transmissions to release both channels. For example, when a node is generating priopulses but detects a priopulse of another node during one of its own priopulse pauses, the node releases both channels. In addition, a node that is receiving an emergency packet in the data channel "relays" priopulses in the control channel to suppress hidden terminals (details in Section II.C). However, the proposed scheme does not require such a node to forward the emergency packet, since the proposed scheme is a MAC scheme working at the MAC sub-layer.

The above description is for a simplified scenario where there is only a single level of priority for emergency messages. In a more realistic scenario, there are multiple levels of priority for emergency packets. In such a case, an emergency message source may still contend for the data channel even if it senses the control channel busy. Particularly, if a node intends to disseminate a message of an emergency level of L_x but detects a busy control channel, it compares L_x with L_r, which is the emergency level of the message in transmission and obtained by "measuring" the priopulses in the control channel. If $L_x > L_r$, the new source starts a process to contend for the data channel as soon as the priopulse in the control channel pauses, as detailed in Section II.B. Otherwise, the node keeps monitoring the control channel.

B. Priopulses and Priority-Ensured Medium Access

When a node is using the data channel for disseminating emergency packets, it continuously transmits priopulses in the control channel, as shown in Fig. 1. The node stops its priopulses only after its transmission of emergency packets is finished or other emergency message sources interrupt it. Priopulses play key roles in the proposed scheme. Not only do priopulses ensure that an emergency packet receives the actual priority that it deserves for its level of emergency, but also they suppress the hidden terminals when the emergency message is in transmission.

Each priopulse consists of an active part of a fixed length and a pause part of a *random* length, as shown in Fig. 2. In the active part, single-frequency waves are transmitted in

[2]"Message" and "packet" are used equivalently for emergency messages in this paper because an emergency message is usually short enough to be included in one packet.

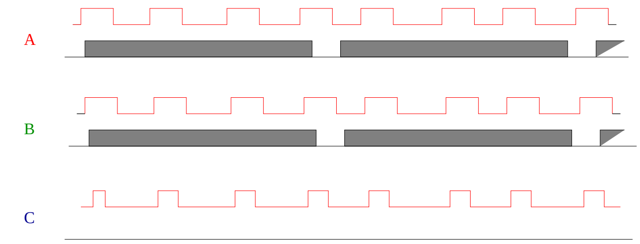

Fig. 1. Emergency Packets and Their Accompanying Priopulses. Node A is the emergency message source; node B is a neighbor of node A; node C is a hidden terminal to node A. The signals in the control and data channels are shown, respectively, in the figure for the three nodes (see Section II.C for the details about the priopulses in node C's control channel).

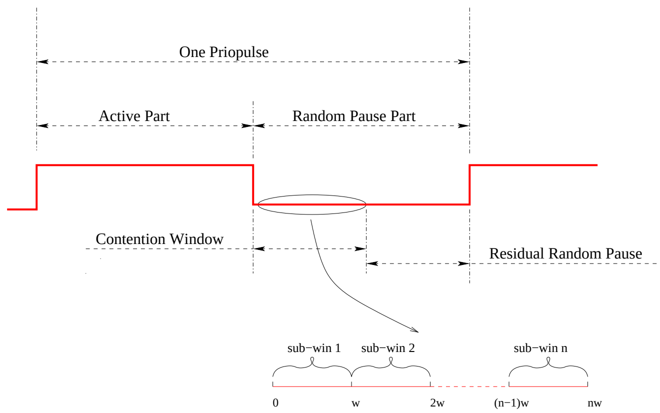

Fig. 2. The Structure of a Priopulse. A priopulse consists of an active part of a fixed length and a pause part of a *random* length. The random pause part is composed of a contention window and a residual random pause. Furthermore, the fixed-size contention window is cut into sub-windows.

the control channel, while there is no wave transmitted in the pause part. The random pause part is further divided into two parts, a contention window of a fixed size and a residual pause of a random length. Moreover, the contention window is cut into equal-size sub-windows.

The active part of a priopulse plays two roles. One is to suppress hidden terminals: any node hearing a priopulse aborts its transmissions. The other role is to deliver the emergency level information for the message in transmission. In particular, the length, P_a, of the active part of a priopulse indicates the emergency level, L, of the message in transmission: a longer active part indicates a higher level of emergency for the message in transmission, i.e.,

$$L_1 > L_2 \quad if \ P_{a1} > P_{a2}.$$

The encoding of emergency level information in the priopulses is more robust against loss than placing the emergency level information in the emergency message itself. In the proposed scheme, priopulses and thus the embedded priority information exist in the control channel as long as an emergency message is in transmission. Emergency level information in an message, however, can only have a single and short presence in the data channel. Moreover, priopulses are more tolerant to interference than bit-based messages.

The random pause part of a priopulse is to support multiple levels of priority for emergency messages. When emergency message sources S_1 to S_n detect a busy control channel but find that the emergency levels L_1 to L_n of their messages are higher than the emergency level L_r of the message currently in transmission, each of these sources starts a random backoff timer as soon as the current priopulse in the control channel pauses. The random backoff delay d_i of the emergency source i is drawn from a contention sub-window in the priopulse in the control channel. The specific sub-window is determined by the emergency level, L_i, of the message to be transmitted. Basically, a source with a higher level of emergency acquires a lower sub-window in the priopulse and thus draws a shorter random delay, i.e.,

$$d_j < d_k \quad if \ L_j > L_k.$$

The source with the shortest backoff delay (i.e., of the highest level of emergency) usually acquires the medium before other sources do, and this source becomes the winner source S_v in this round of contention.

As soon as the backoff timer of the winner source S_v expires, source S_v starts to transmit priopulses in the control channel. All the other competing sources back off after detecting S_v's priopulse. Meanwhile, the emergency message source S_o then owning the channels is still in its pause in the control channel because random backoff delays d_1 to d_n are drawn in the contention window of S_o's priopulse and there is still a residual random pause behind the window in its priopulse. Source S_o can, therefore, detect the priopulse of the winner source S_v and releases both channels.

However, two sources of the same level of emergency, such as sources i and j, may draw similar delays in the same contention sub-window, which may result in a collision between the two sources. The random length of the residual pause of a priopulse is designed to deal with this problem. If sources i and j draw similar backoff delays in contending for the medium, the active parts of their first priopulses are synchronized with each other and neither node will be aware of the other. However, the random-length pauses in their priopulses will desynchronize the active parts in their priopulses. After the desynchronization, one source will detect the other (i.e., hear its priopulse) and back out to wait for the next chance to contend for the medium. An emergency message is usually transmitted multiple times with the proposed scheme, as introduced earlier. Therefore, after one source backs out, the surviving source will be able to successfully disseminate its remaining copies of the message.

C. Pulse Relay

In the proposed scheme, priopulses are "relayed" by nodes to suppress the hidden terminals of the message source. We use the term "relay" to distinguish priopulse spreading from packet forwarding. Unlike a packet that is to be forwarded, a priopulse that is to be relayed triggers its relaying nodes to regenerate it as soon as it emerges in the control channel; relaying nodes do not wait for the reception of the whole priopulse before regenerating it. Ideally, only neighbors of an emergency message source should "relay" priopulses. However, priopulses, unlike packets, cannot contain address or hop-count information. Before introducing the mechanism used in the scheme for approaching the ideal situation of priopulse relay, we first introduce how a node "relays" a priopulse.

Basically, a "relayed" priopulse has a shorter active part than the original priopulse and the active parts of the relayed priopulse and the original priopulse are "loosely synchronized". We first consider the case where a node has the legitimate information L_r and thus the legitimate information P_a of the priopulses in the control channel. In such a case, a relayed priopulse has an active length close to P_a. As soon as the relaying node senses the emergence of the active part of the original priopulse, it starts its own relayed priopulse. However, the relaying node ensures that the active part, p_a, of its relayed priopulse is shorter than that of the original priopulse, which is demonstrated in Fig. 1. The shorter active part of the relayed priopulse is to make sure that the source of the original priopulse will not hear the relayed priopulse (note that when the source is transmitting in the control channel, it cannot hear any other transmissions in the channel.). The difference between p_a and P_a needs to be big enough to compensate for propagation delays, delay spreadings, and other factors that may affect either the size or the starting time of the relayed priopulse (the difference is 20μs in our simulations).

The other case is that a node has no legitimate information of P_a. In such a case, a priopulse is only relayed as a pulse of a short active length. Although the short-active-length pulse does not carry any emergency level information, it is generated to suppress hidden terminals. An example of emergency packets accompanied by priopulses is shown in Fig. 1. Note that the first relayed priopulse is a short pulse.

To approach the ideal situation of priopulse relay introduced earlier, a node in the proposed scheme relays a priopulse only in the following two cases. The first case is that the node is busy receiving in the data channel *and* the priopulse is the first one detected after the control channel became idle last time. The second case is that the node has the knowledge that it is receiving an *emergency* packet in the data channel.

The priopulse relay in the first case is to clear the data channel for the incoming emergency packet. After an emergency message source acquires the medium, it starts to transmit priopulses. When the source's first priopulse arrives at its neighbors, the neighbors cannot determine if they are the neighbors of an emergency message source, since priopulses can be relayed but carry no address or hop count information. However, if some of these neighbors are receiving any packets, they need to stop their senders so that the emergency packet will arrive at them with a clear channel shortly after. Therefore, a node with the proposed scheme always relays a priopulse if the priopulse is the first one that the node detects in an idle control channel *and* meanwhile the node is busy receiving in the data channel. If such a node receives an emergency packet shortly after, it continues to relay the following priopulses. Otherwise, the node will stop relaying.

Finally, if the coarse synchronization of the pulses between a sender and its receivers is lost for any reason such as interference or noise, the sender will detect pulses in its own pulse pauses and thus stop transmission in both channels. The nodes will then start to contend for the medium again after the interference or noise disappears. Note that the emergency packets may be corrupted by the interference or noise anyway in such a case, and thus the abortion of the dissemination process is justified.

III. Scheme Evaluation

A. Simulation Scenarios and Detailed Configurations

This section presents comprehensive simulation results for the proposed MAC scheme. The proposed scheme is named "PreempPrio-MAC" because of the preemptive priority service that it provides to emergency packets at the MAC sub-layer. The simulations were conducted with NS-2 [22] for scenarios in which vehicles move on highways.

The implemented PreempPrio-MAC scheme in our simulations supports three levels of priority for emergency packets. Table I shows the scheme parameters. As shown in the table, the active lengths of priopulses are 100, 200, and 300μs, respectively, for encoding the three levels of priority for emergency messages. The contention window in each priopulse has a size of 150μs and each sub-window is 50μs long. The residual pause window from which each priopulse draws its residual random pause is 100μs.

Another important detail of our simulations is that we used "blank" broadcast packets of small intervals to simulate priopulses in the control channel. "Blank" means that these packets carry no address or other information. When a node receives such a "blank" packet at the right power level (i.e., above the carrier sense threshold) in the control channel, it detects a priopulse signal, and the active length of the priopulse is "measured" as the time during which such blank packets are continuously flowing in. This mechanism of simulating priopulses enables our simulations to truthfully reflect how priopulses spread in the network with the proposed scheme.

To show the performance of the approach that uses in-band control messages, we also simulated with the IEEE 802.11 and 802.11e MAC protocols[3]. In IEEE 802.11e, the minimum backoff window limit for emergency packets was half of that for normal packets. Meanwhile, the Arbitration Inter Frame Space (AIFS) for emergency packets was one timeslot less than that for normal packets. Additionally, Asynchronous Fixed Repetition with Carrier Sensing (AFR-CS) proposed in [19] was also simulated for comparison. The authors of [19] showed that AFR-CS was the best of the schemes proposed in the paper.

In our simulations we used the basic highway scenario introduced in [18]. Particularly, the highway in our simulations has 4 lanes (2 lanes in each direction) and forms a circle. The lane width is 4 meters and the inner lane has a radius of 350 meters. Additionally, the cars in each lane have the same speed that is randomly drawn between 55 and 120 kilometers per hour. The distance between two adjacent cars in the same lane is 20 meters. Each car broadcasts packets at a rate of 10 packets per second and the packet size varies from 200 to 600 bytes.

[3] Although there are also existing proposals on improving the performance of IEEE 802.11e, they cannot eliminate the intrinsic shortcoming of IEEE 802.11e, which is that it only supports "statistical" priority for specific flows but not "strict" priority for individual packets.

TABLE I

SCHEME PARAMETERS

Name	Active Length 1, 2, and 3	Contention Window	Contention Sub-window	Residual Pause Window
Value (μs)	100, 200, and 300	150	50	100

B. Competition between Priority Traffic and Normal Traffic

We show in this section the simulation results for the cases where priority traffic compete with normal traffic. In our simulations, one vehicle on the circular highway disseminates emergency packets, and other vehicles disseminate normal packets. Fig. 3 shows the emergency packet reception ratio of vehicles versus their distance to the source of the emergency packets for the case where the channel model is two-ray ground and the node transmission distance is 100 meters (note that with the default ns-2 power threshold configurations, the node carrier sense distance is about 200 meters in such a case).

Several observations can be made in Fig. 3. First, the proposed scheme, PreempPrio, shows no emergency packet loss in the transmission distance, while AFR-CS shows losses at any distance. This is because AFR-CS does not fully address the hidden terminal problem. Second, packet losses increase with the propagation distance for the AFR-CS protocol. This shows that the hidden terminal problem is more serious for receivers that are located farther from the sender. Third, the IEEE 802.11e version of AFR-CS shows higher performance than the IEEE 802.11 version, which is due to the priority that emergency packets enjoy in the IEEE 802.11e case.

Fig. 4 shows the results for a similar case but in which a Rayleigh fading channel model instead of a two-ray ground channel model is used. As shown in the figure, the proposed PreempPrio protocol still maintains its lossless characteristic in a significant range from the source. Moreover, as compared with the other protocols, the proposed protocol maintains much higher reception rates for emergency packets in all cases.

With PreempPrio and AFR-CS, each emergency packet is repeated for five times in our simulations. The repetitions actually increase the performance of the protocols. Fig. 5 shows the results for the case in which no packet repetitions are used and the channel model is two-ray ground. Comparing Fig. 5 with Fig. 3, we find that the repetitions greatly improve the performance of the IEEE 802.11 protocols. However, in the PreempPrio case, the improvement is not significant because the PreempPrio protocol has almost no loss from collisions.

The situation in the Rayleigh fading case is different. Fig. 6 shows the results for the case in which no repetition is used and the channel model is Rayleigh fading. Comparing Fig. 6 with Fig. 4, we find that the repetitions improve the performance of all protocols significantly in the Rayleigh fading case, since repetitions compensate for channel losses.

In summary, PreempPrio realizes lossless medium access for emergency packets. As explained earlier, by lossless we mean that the emergency packets have a negligible rate of loss caused by collisions in the network. As shown in Fig. 3, when there is no channel loss in the two-ray ground case, emergency packets are not lost in the transmission range of the emergency message source in the PreempPrio case. When there are channel losses, the message repetitions of PreempPrio greatly compensate for the channel losses, as shown in 4. We need to emphasize here that the simulation results for the proposed protocol in the preceding sections and the following sections are self-contained in showing the effectiveness of the proposed MAC protocol in serving emergency message dissemination in vehicular ad hoc networks, and the simulation results for the IEEE 802.11e systems are just for the demonstration of the performance of in-band protocols.

Besides reception ratio, another important criterion for evaluating a MAC protocol designed for emergency message dissemination is the medium access latency for emergency packets. Fig. 7 shows the average medium access delay for emergency packets versus the size of the packets in the network in the two-ray ground case. The packet size determines the network load in our simulations. There are about forty vehicles in the carrier sense range of each vehicle in our simulations and the packet interval is 0.1 second. In such a case, the network load for a packet size of s is about $s * 8 * 40/0.1 = 3200 * s$ bits per second in our simulations. As shown in Fig. 7, PreempPrio introduces negligible medium access delays for emergency packets as compared with the IEEE 802.11 protocols. Meanwhile, IEEE 802.11e has significantly better performance than IEEE 802.11 due to its support of priority medium access.

Similar results have been observed in the Rayleigh fading channel case, as shown in Fig. 8. Interestingly, when the packet size is the same, the medium access delay for emergency packets is shorter in the Rayleigh fading case than in the two-ray ground case. This phenomenon occurs because signals attenuate faster over a Rayleigh fading channel than over a two-ray ground channel and thus the actual network load is lower in the Rayleigh fading channel case.

Besides the averages, the distributions of the medium access delays are also important for emergency message dissemination in vehicular ad hoc networks, since each single message delay in such a case may have serous consequences. Fig. 9 shows the medium access delay distribution for IEEE 802.11e for the case in which the packet size is 400 bytes (i.e., a medium network load). As shown in the figure, a significant amount of packets have medium access delays beyond 0.1 second. As shown in Fig. 10, however, the proposed protocol maintains a medium access delay of less than 0.05 second for every emergency packet.

The situation is similar in the Rayleigh fading case, as shown in Figs. 11 and 12. One thing that we notice is that IEEE 802.11e has a better performance in the Rayleigh fading case than in the two-ray ground case, which is because the actual network load is lower in the Rayleigh fading case, as explained earlier. However, a significant portion of the emergency packets still have excessive medium access delays in the Rayleigh fading case, as shown in Fig. 11. The proposed protocol maintains its satisfactory performance, as shown in

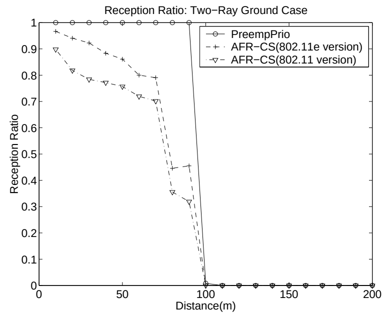

Fig. 3. Packet Reception Ratio versus Propagation Distance (Two-Ray Ground)

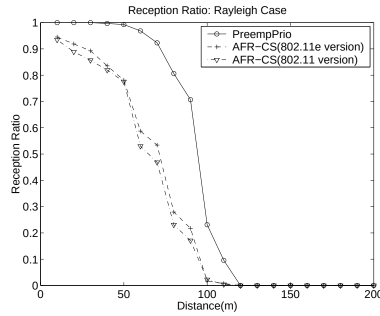

Fig. 4. Packet Reception Ratio versus Propagation Distance (Rayleigh Fading)

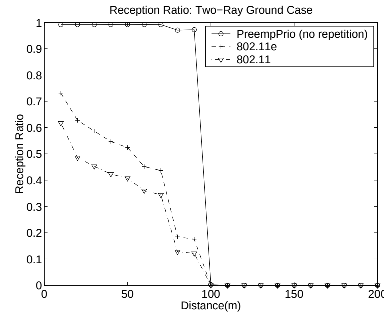

Fig. 5. Packet Reception Ratio versus Propagation Distance (Two-Ray Ground and without Packet Repetitions)

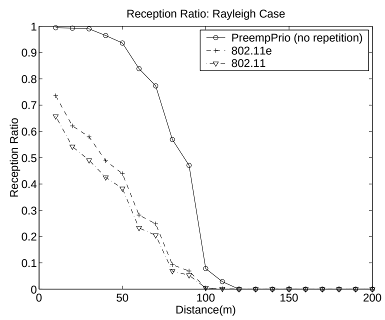

Fig. 6. Packet Reception Ratio versus Propagation Distance (Rayleigh Fading and without Packet Repetitions)

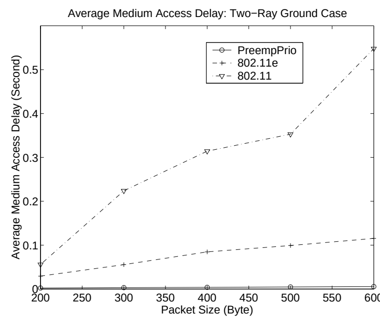

Fig. 7. Medium Access Delay versus Network Load (Two-Ray Ground)

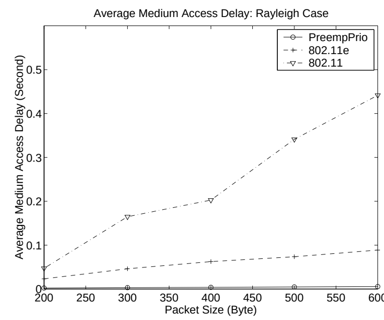

Fig. 8. Medium Access Delay versus Network Load (Rayleigh Fading)

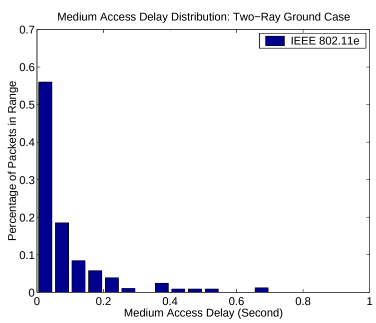

Fig. 9. Medium Access Delay Distribution (IEEE 802.11 and Two-Ray Ground)

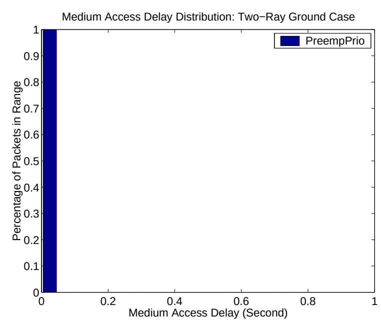

Fig. 10. Medium Access Delay Distribution (PreempPrio and Two-ray Ground)

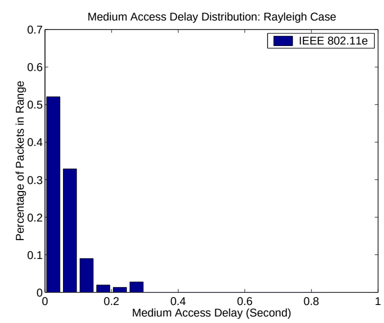

Fig. 11. Medium Access Delay Distribution (IEEE 802.11 and Rayleigh Fading)

Fig. 12.

C. Competition between Emergency Message Sources

The simulation results in the preceding subsection show that the proposed scheme achieves timely and lossless medium access for emergency packets in vehicular ad hoc networks. Another requirement for emergency message dissemination in vehicular ad hoc networks is the support of multiple levels of strict priority for emergency packets. This subsection shows how the proposed protocol performs in this aspect. We did not further investigate the performance of 802.11e and AFR-CS in supporting multiple levels of priority for emergency packets because of their unsatisfactory performance shown in the preceding subsection.

In the simulations examining the competitions between emergency message sources, five vehicles on the same segment of the circular highway were chosen to disseminate emergence messages at the same time. The events happening at these five vehicles were then recorded. Basically, There were three types of events recorded, which were successful medium access (i.e., successful expiration of the backoff timer), transmission interruption, and successful packet delivery. The three types of events are denoted by triangles, crosses, and rings, respectively, in the event maps shown in this section.

We first show the simulation results for the case in which emergency packets have a single level of priority in accessing the medium (i.e., all of them have the same priority over normal packets) and the channel model is two-ray ground. The simulation results are shown in Fig. 13 as an event map for the competing sources. In the figure, the horizontal axis shows the time, while the vertical axis shows the identification number of the node at which an event happens.

As shown in Fig. 13, the five sources successfully deliver their emergency packets in sequence. Source 3 first succeeds

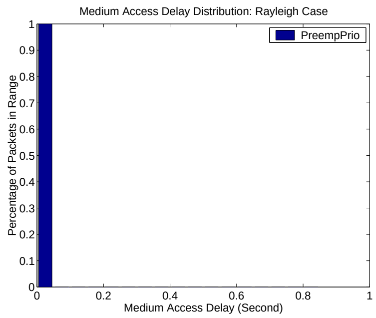

Fig. 12. Medium Access Delay Distribution (PreempPrio and Rayleigh Fading)

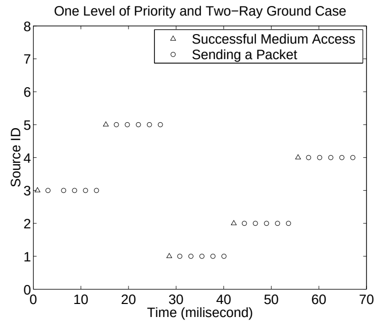

Fig. 13. Event Map for The Competing Emergency Message Sources (Single Level of Priority and Two-Ray Ground)

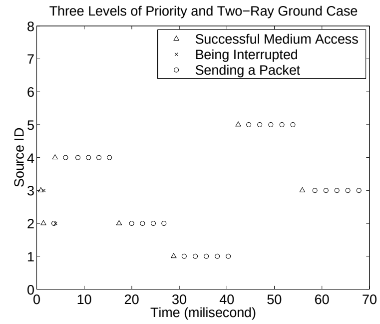

Fig. 14. Event Map for The Competing Emergency Message Sources (Multiple Levels of Priority and Two-Ray Ground)

in accessing the medium and delivers its emergency packets. After it releases the medium, source 5 succeeds in accessing the medium. After source 5 finishes transmitting its emergency packets, sources 1, 2, and 4 use the medium in sequence and succeed in delivering their emergency packets. The five sources therefore use the medium without collisions.

In the above case of same-level priority for all emergency message sources, source 4 is the last one to use the medium among the five sources, while source 2 is the next to the last. It is possible, however, that these two sources have higher levels of emergency than the other sources. In such a case, source 4 and source 2 are unduly delayed for 40 to $60ms$ in accessing the medium because of the competition from the other sources of lower emergency. Forty to sixty milliseconds are long delays for emergency packets in vehicular ad hoc networks because of the short lifetimes of emergency packets in such networks. To demonstrate how the proposed PreempPrio-MAC scheme can help in such a case, we assigned source 4 and source 2 higher levels of priority than the other sources. We assigned source 4 the highest level of priority, which is level 3. Meanwhile, source 2 was assigned a priority level of 2.

The simulation results for the new case are shown in Fig. 14. As shown in Fig. 14, source 3 successfully accesses the medium first because its emergency packets arrive at its MAC sub-layer first. However, before it finishes transmitting its first emergency packet, it is interrupted by source 2, which has the second highest possible priority. Shortly after, source 4 takes over the medium because source 4 has the highest priority among the emergency message sources. After source 4 finishes its transmissions and releases the medium, source 2 starts to use the medium. After source 2 finishes its transmissions, the other three sources of the same priority finish their transmissions in sequence. These simulation results show that the proposed MAC scheme is effective in supporting multiple levels of strict priority for emergency packets.

The above results are for the two-ray ground channel model case. Similar results have been observed for the Rayleigh fading channel case. Fig. 15 shows the results for the case in which all emergency message sources have the same level of priority and the channel is Rayleigh fading. As in the two-ray ground case, all five sources send out their emergency packets in sequence. In the Rayleigh fading case, source 3 accesses the medium last and source 1 accesses the medium the next

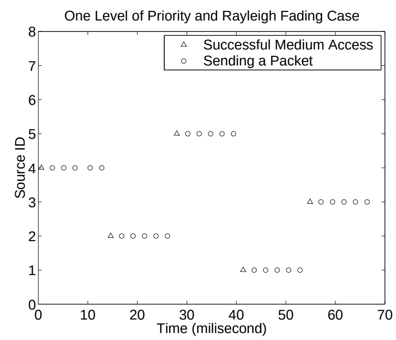

Fig. 15. The Event Map for The Competing Emergency Message Sources (Single Level of Priority and Rayleigh Fading Channel Model)

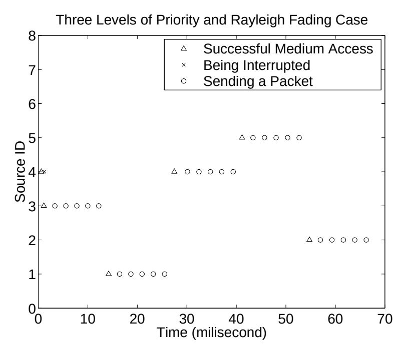

Fig. 16. The Event Map for The Competing Emergency Message Sources (Multiple Levels of Priority and Rayleigh Fading Channel Model)

to the last. Fig. 16 shows the results for the case in which source 3 and source 1 are assigned the highest priority and the next to the highest priority, respectively. As shown in Fig. 16, source 4 accesses the medium first. However, before source 4 finishes transmitting its packet, it is interrupted by source 3, which has the highest possible priority. After source 3 finishes its transmissions, source 1 accesses the medium successfully. Therefore, strict priority is still followed in the Rayleigh fading case.

IV. Conclusion

Emergency message dissemination in vehicular ad hoc networks is an important type of application and requires cross-layer assistance in the network. Although medium access is a critical part in emergency message dissemination in vehicular ad hoc networks, existing MAC protocols lack the full capabilities for supporting this type of application. In particular, existing MAC protocols do not support strict, packet-level priority scheduling and lossless medium access in a fully distributed way. This paper presents a new MAC scheme to address this issue. Using a novel pulse-based control mechanism, the proposed MAC scheme realizes timely and lossless medium access for emergency packets in vehicular ad hoc networks. In a fully distributed way, the proposed scheme introduces preemptive priority scheduling at the MAC sublayer to serve emergency packets in vehicular ad hoc networks. Moreover, it supports multiple levels of strict priority for emergency packets. The comprehensive simulation results in the paper show the effectiveness of the proposed MAC scheme in serving emergency packets in vehicular ad hoc networks.

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