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Safety Message Transmission in Vehicular Communication Networks

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Abstract

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SAFETY MESSAGE TRANSMISSION IN VEHICULAR COMMUNICATION NETWORKS

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ABSTRACT

Emerging vehicular safety applications require low latency communications and reliable packet dissemination for life saving safety messages. Significant developments have taken place over the past few years. IEEE WAVE and ISO CALM have been developed as international standards for ITS applications. Both WAVE and CALM support multi-channel operations and use CSMA/CA as channel access mechanism. WAVE may impose a latency of 54 milliseconds for enabling multi-channel operations. CSMA/CA method can experience unpredictable delay and packet drop when channel is congested. In this paper, we propose an innovative technique to increase channel coverage and reduce latency for safety messages in multi-channel vehicular environments. We also propose an efficient congestion control protocol for vehicular communication networks that use CSMA/CA channel access mechanism. The proposed congestion control protocol guarantees that safety messages gain channel access while contending with other messages. Technologies presented in this paper improve reliability of the safety message dissemination and reduce latency for safety message transmission.

INTRODUCTION

Governments and manufactures are cooperating to develop intelligent traffic systems (ITS) for vehicle safety and traffic condition improvement. North America, Europe and Asia have allocated the dedicated bandwidth for ITS applications. In the United States, the Federal Communications Commission (FCC) has allocated a 75 MHz bandwidth at 5.9 GHz band for ITS applications. The bandwidth is exclusively allocated for vehicle-to-vehicle communications and vehicle-to-infrastructure communications. The bandwidth is partitioned into multiple channels, typically seven 10 MHz channels including one control channel (CCH) and six service channels (SCH) as shown in Figure 1. CCH is only used for control purpose and public safety. No private services are allowed on CCH. The SCHs are used for public safety and private services.

IEEE has been developing the Wireless Access in Vehicular Environments (WAVE) standards for ITS applications. WAVE standards consist of IEEE 802.11p and IEEE P1609 standard family. The PHY and MAC layer specifications are defined in 802.11p

[1]. The multi-channel operation is specified in P1609.4 [2]. Rest of the P1609 standards deals with upper layer specifications. With 802.11p as the basis, ISO has been developing another set of the ITS standards, namely, Communications Access for Land Mobiles (CALM).

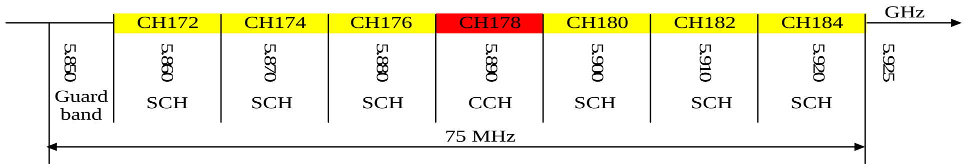

Figure 1. Frequency Channel Layout of 5.9 GHz Band

For channel coordination and synchronization, WAVE partitions time into periodic Sync Intervals as shown in Figure 2. Each Sync Interval is 100 milliseconds long and is further partitioned into a 50 milliseconds control channel interval (CCHI), and a 50 milliseconds service channel interval (SCHI). A 4 milliseconds guard interval (GI) at the beginning of each channel interval accommodates variations in timing. The GI must be treated as busy. No transmission is allowed during the GI. WAVE requires that all devices must monitor CCH during CCHI. Control messages, high priority safety messages and the service announcement messages are transmitted on CCH during CCHI while all devices monitor CCH. Multi-mode devices may monitor CCH and transmit on SCH simultaneously during CCHI. The devices can remain on CCH or switch to any SCH during SCHI. The messages can be transmitted on any channel during SCHI.

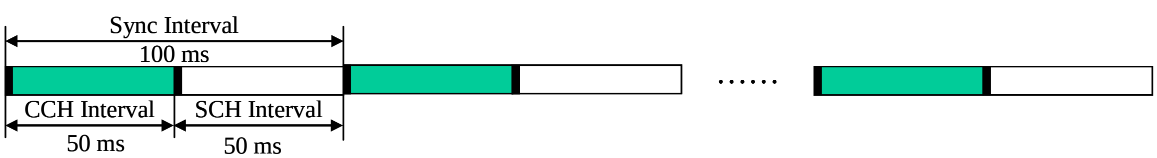

Figure 2. WAVE Sync Interval Partitioning

In multi-channel wireless environments, it is more difficult to reliably deliver packets than in single channel environments, where all devices monitor a common channel all the time. For example, a packet transmitted on a particular channel can not be heard by the devices on different channels. Due to the existence of the SCHI and the GI, WAVE may impose a latency of 54 milliseconds for life saving alert messages. If an accident is detected near the beginning of the SCHI, it takes at least 54 milliseconds to hear the corresponding alert if the alert is transmitted in next CCHI. Even if the alert is transmitted immediately on the operation channel by the vehicle that has detected the event, the latency can still be at least 54 milliseconds for vehicles using different channels. A vehicle moving at 100 km/h travels 1.5 meters in 54 milliseconds, which is long enough to cause an accident. Therefore, a latency of 54 milliseconds is unacceptable. In fact, the SAE J2735 standard, which defines formats for WAVE messages, requires that high priority safety messages, such as crash-pending notification, hard brake, and control loss, can only have a latency of up to 10 milliseconds. Other warning messages such emergency vehicle approaching can have a latency of up to 20 milliseconds. The messages, such as probe and general traffic information, can have latency greater than 20 milliseconds.

WAVE and CALM use common Enhanced Distributed Channel Access (EDCA) as medium access method. EDCA is defined in IEEE 802.11-2007 standard and uses the carrier sense multiple access with collision avoidance (CSMA/CA) as channel access mechanism [3]. CSMA/CA can experience unpredictable delay and packet drop when channel is busy. It has been shown that a WAVE channel becomes congested with 50 or more devices operating [4]. On a six lane high way, if a destination vehicle is 150 meters away from a source vehicle, the latency is greater than 50 milliseconds when WAVE channel usage reaches 50%. It has also been shown that 802.11p MAC does not provide predictable support for low delay communications [5], [6]. CSMA/CA punishes certain devices, the difference between the best device and the worst device is 50%. CSMA/CA becomes unfair when the network load increases and thus unbounded access delay and packet drop become more frequent. To control congestion and reduce latency for high priority packets in vehicular communication networks, the congestion control algorithms through manipulating transmission queues have been proposed in [4] and [7]. The disadvantage of the congestion control mechanisms via transmission queue manipulation is that each device can only prevent its own low priority packet from contending for channel access with its high priority packet, but it can not prevent other device's low priority packet from contending for channel access with its high priority packet. Instead, the self-organizing time division multiple access (STDMA) algorithm was proposed in [5] and [6] to replace CSMA/CA mechanism. Even though STDMA provides predictable delay, it can not satisfy the 10 milliseconds latency requirement when network is loaded. Since there cannot be any restrictions on the number of participating vehicles in vehicular communication networks, new methods must be provided to handle overload situations.

To achieve latency requirements for WAVE messages defined in SAE J2735 standard and enhance the reliability of the high priority safety message dissemination, this paper proposes a technique to increase channel coverage and reduce latency in multi-channel vehicular communication networks. This paper also proposes a congestion control scheme for vehicular communication networks that use EDCA channel access mechanism. The proposed scheme guarantees life saving alert messages transmitted prior to other messages.

SAFETY MESSAGE TRANSMISSION IN MULTI-CHANNEL VEHICULAR COMMUNICATION NETWORKS

In vehicular communication networks that employ WAVE standards, safety alert detected in CCHI can be immediately transmitted on CCH. All devices within radio range of transmitting device can receive the alert since all devices monitor the CCH during CCHI. However, WAVE allows devices to operate on different channels during the SCHI. The length of a SCHI plus a GI is 54 milliseconds. The alert message latency for devices on different channels can be 54 milliseconds or even longer. This kind of latency is much longer than the 10 milliseconds demanded by the SAE J2735 standard. Therefore, the delay in WAVE networks must be reduced.

We propose a neighbor assistant technique to increase channel coverage and reduce latency in multi-channel vehicular communication networks. The technique is illustrated in Figure 3. In Figure 3(a), an accident occurs at time Ta during a SCHI. A source vehicle detects the accident. In response to detecting an event during the SCHI, the source vehicle immediately transmits an alert message on channel CHa, on which source vehicle currently operates. The message has a high priority, thus, latency can not be longer than 10 milliseconds. The message also needs to be delivered to as many vehicles as possible.

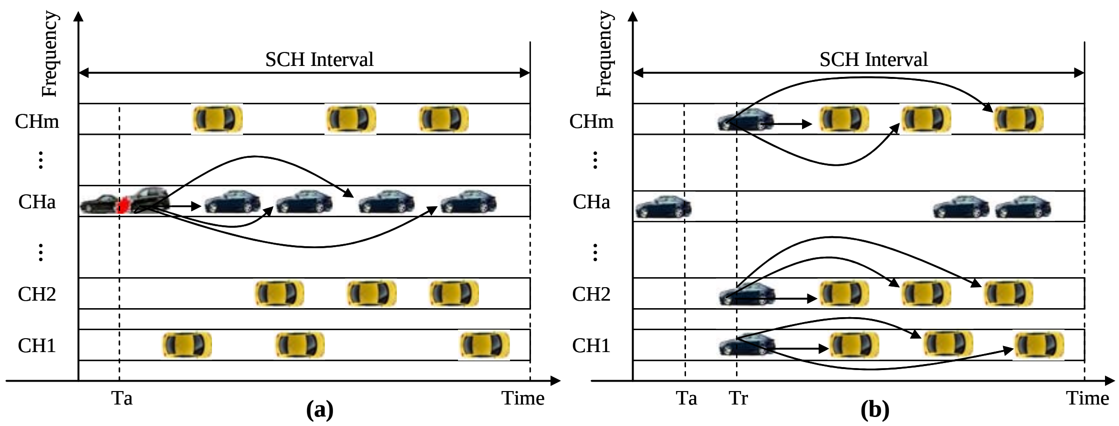

Figure 3. Safety Message Transmission in Multi-Channel Vehicular Communication Networks

A set of vehicles operating on channel CHa receive the message. It is understood that the set of vehicles are within radio range of the source vehicle. However, other vehicles not monitoring channel CHa can not hear the message. To cover all channels, the neighbor vehicles received message switch on other channels and retransmit the message on those channels at time Tr as shown in Figure 3(b).

Figure 4 shows the format of the high priority safety message transmitted in SCHI. The message includes source identification (ID), source location, sequence number, current channels, next channels, and content of the message.

Source ID	Source location
Sequence Number	
Current channels	Next channels
Message content	

Figure 4. Safety Message Format Transmitted in SCHI

The source ID uniquely identifies the source vehicle that generates the message. The source location is the geometric position of the source vehicle and used by receivers to determine the distance to the source, presuming the receivers can determine their locations. The sequence number specifies the sequence identifier for the message, and can be used to determine if a particular message was received previously. The current channels indicate the channels used by the source vehicle to transmit the message first. The next channels indicate the channels used by the source vehicle to transmit the message next. The receivers use current channels and next channels fields to determine the channels not covered by source vehicle. Since a multi-mode device can operate on multiple channels simultaneously, the current channels and next channels fields may include one or more channels.

Source vehicle first transmits the message on channels specified in current channels field. Then, the source vehicle immediately transmits the message on channels specified in next channels field. In this way, less relay vehicles are needed to cover all channels. Therefore, channel usage is more efficient.

The current channels are the channels on which source vehicle currently operate when the event is detected. The selection of next channels may depend on various factors, such as the number of vehicles monitoring the current channels as determined, e.g., from channel load information provided in WAVE standard [8]. Since WAVE allows different transmission power limits on different channels the next channels can also be selected to have higher transmission power limits so that the message can be transmitted as far as possible. An optimization process can be used by considering all relevant factors to select next channels.

Figure 5 shows the procedure for transmitting the message in response to detecting the event during the SCHI. The source vehicle determines if the transmission of the message can be completed by the end of this SCHI. If false, the source vehicle waits for next CCHI. If true, the source vehicle constructs the message, and transmits the message on the current channels. After transmitting the message on the current channels, the source vehicle selects next channels and determines if the transmission can be completed on the next channels by the end of this SCHI. If false, the source vehicle has completed message transmission in this SCHI. If true, the source vehicle switches to the next channels, if necessary, and transmits the message on channels specified by the next channels field.

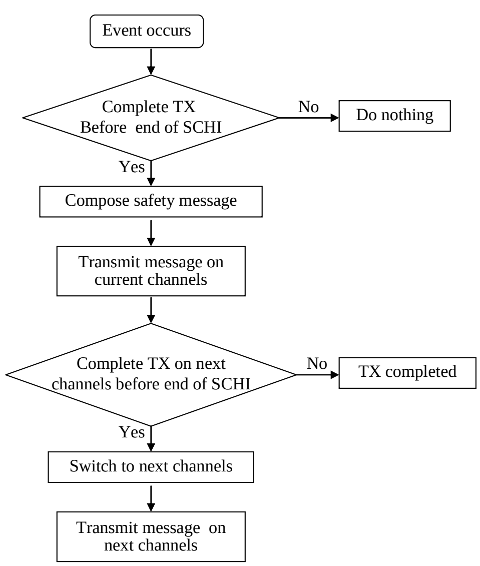

Figure 5. Source Vehicle Safety Message Transmission in SCHI

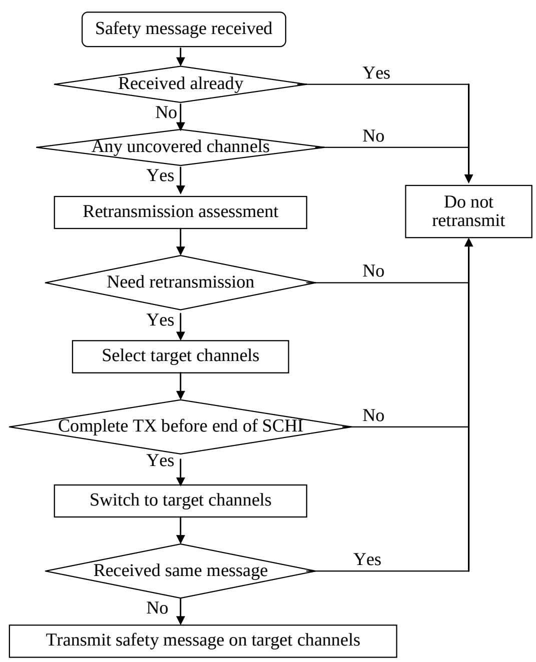

Figure 6. Neighbor Vehicle Safety Message Relay in SCHI

Figure 6 shows the procedure for retransmitting the received message during the same SCHI. The receiver determines if this particular message has already been received, based on the source ID and sequence number. If true, the receiver does not retransmit. If false, the receiver determines if there are any channels not specified in current channels and next channels fields. If false, the receiver does not retransmit. If true, the receiver performs the retransmission assessment procedure to determine if retransmission is necessary. If false, the receiver does not transmit. If true, the receiver randomly selects one or more unspecified channels as target channels to reduce the probability of collision and duplication. A multi-mode receiver may first select channels that correspond to the channels currently monitored by the receiver so that no channel switching is required. The receiver determines if the retransmission on the selected channels can be completed by the end of this SCHI. If true, the receiver switches to the selected channels, if necessary. The receiver determines if the message is received on the selected channels. If true, the receiver does not retransmit, and otherwise the message is retransmitted.

To reduce collision and duplication, each receiver performs the retransmission assessment to determine if it should retransmit the received message. It is ideal that only vehicles near to source vehicle retransmit the message since the safety messages, such as crash notification and control loss, are of the most interest to nearby vehicles and the vehicles nearest the source vehicle have a greater probability to decode and retransmit message successfully. The area around the source vehicle are partitioned into zones, Z_1, Z_2, …, Z_n, as shown in Figure 7. The principle of the zone partitioning is that the receiver closer to source vehicle has a greater probability to retransmit message. If a receiver is located in Z_1 it is most likely to retransmit the received message. However, if a receiver is in Z_n it has very little probability to retransmit the message.

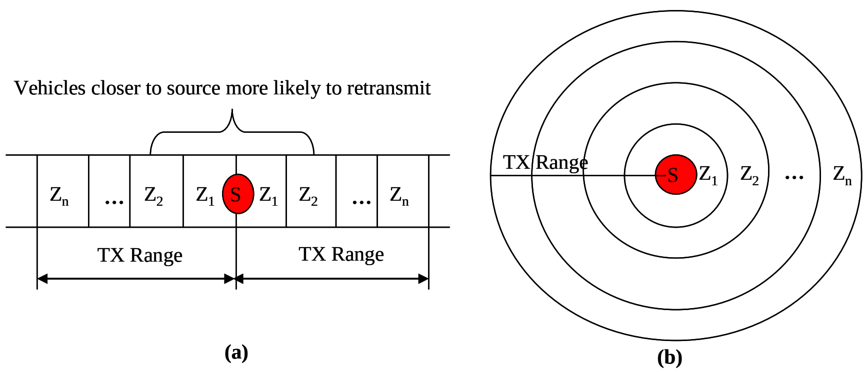

Figure 7. Safety Message Retransmission Zone Partitioning

Zone partitioning depends on the distance to the source vehicle, the number of channels not covered by source vehicle, the vehicle density, vehicle mobility, etc. In the WAVE networks, the vehicle can use the heartbeat messages to estimate the vehicle density. The size of the zone is proportional to the number of channels not covered by source vehicle, and inversely proportional to the vehicle density near the source vehicle. In a high mobility environment, the size of the zone should be larger since the messages need to be received by more vehicles. Each receiver uses source vehicle location and its own location to identify the zone in which it is located.

A probability function can be defined such that vehicles in the zones close to source vehicle have greater probability to retransmit the message. For example, vehicles in Z_1 must perform retransmission, vehicles in Z_2 have a 1/2 probability to retransmit, vehicles in Z_3 have a 1/3 probability to retransmit, and so on. Optimally, the message is retransmitted on each uncovered channel by exactly one vehicle. The sizes of the zones and probability functions control the number of relay vehicles. To enhance the reliability of safety message dissemination, more relay vehicles can be allowed. The relay vehicle uses the probability functions and its zone location during the retransmission assessment.

CONGESTION CONTROL FOR SAFETY MESSAGE TRANSMISSION IN VEHICULAR COMMUNICATION NETWORKS

In wireless communication networks, a major cause of packet drop and long latency is channel congestion. Channel congestion is an issue to be addressed by ITS standards, IEEE WAVE and ISO CALM. The reason is that both WAVE and CALM use EDCA as medium access method. EDCA is a contention based channel access method using the CSMA/CA mechanism for channel access. EDCA can experience unpredictable channel access delay and packet drop due to its nondeterministic characteristics. When a higher priority packet contends for channel access with a lower priority packet, EDCA does not guarantee that the higher priority packet gain channel access first. The higher priority packet only has a higher probability to win contention. A WAVE channel becomes congested with 50 or more devices. There is no control on the number of participating vehicles in vehicular communication networks. New mechanisms must be provided for safety message transmission in overload situation. This paper proposes a signaling scheme for safety message transmission in vehicular communication networks and an adaptive CCHI method to reduce safety message latency in WAVE networks.

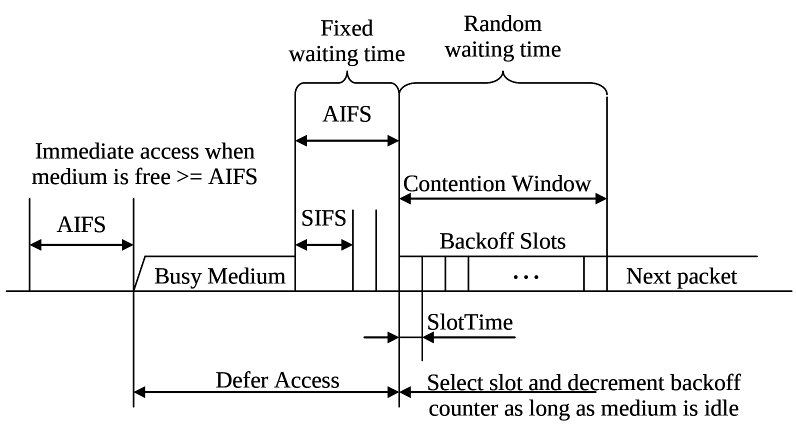

Figure 8. EDCA Channel Access Illustration

Figure 8 shows the EDCA channel access mechanism. EDCA supports four access categories (AC): AC_BK for background, AC_BE for best effort, AC_VI for video and AC_VO for voice. Each message packet is mapped to one access category according to the priority level (WAVE has 8 levels and CALM has 256 levels). A set of EDCA parameter is defined for each AC to contend for the channel access. An EDCA backoff time includes a fixed length waiting time and a random length waiting time. The fixed waiting time is a number of time slots given by arbitration interframe space (AIFS). The random waiting time is a random number of time slots within contention window (CW). Both AIFS and CW are different for each AC. AIFS is defined using two basic EDCA time parameters, short interframe space time (SIFSTime) and a slot time (SlotTime):

$$AIFS = AIFSN \times SlotTime + SIFSTime \quad (1)$$

The Arbitration Interframe Space Number (AIFSN) is AC dependent and can have value in the range from 2 to 9. CW is an integer within a range of values CWmin and CWmax such that CWmin $\leq$ CW $\leq$ CWmax. Both CWmin and CWmax are AC dependent.

A device can immediately transmit packet if the medium is free for more than one AIFS time period. However, following busy medium, all devices have to perform a random backoff procedure for packet transmission. This indicates that random backoff is needed on congested channels. Random backoff can cause unpredictable delay and packet drop even for high priority messages.

To guarantee safety message transmission on a congested channel, this paper provides an efficient congestion control technique: signaling for safety message transmission. Vehicle with safety message to transmit sends a signal to indicate its transmission intention. Upon detecting the attention signal, all other vehicles defer access. The signal must be short enough so that its transmission can be completed in one SlotTime period. The signal must be detectable. As shown in Figure 9, the slot after SIFS time period is selected as the signal slot to transmit an attention signal.

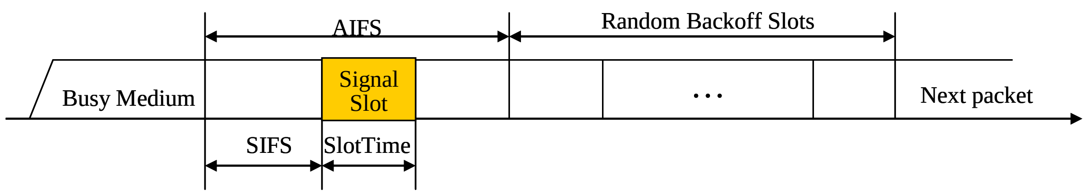

Figure 9. Signal Slot Selection

Signal slot is hardly used in WAVE and CALM. Equation (1) shows that the shortest backoff time is longer than SIFSTime. This means that no initiation of the frame exchange sequence starts at SIFSTime following the busy medium. In the IEEE 802.11 standard, SIFS is only used prior to transmission of ACK, CTS, subsequent fragment of a fragment burst and poll response. EDCA does not support polling mechanism and therefore, there is no poll response. No burst transmission is allowed by CALM. For WAVE, burst transmission is prohibited on CCH. The default EDCA parameter set indicates no burst transmission on the SCHs too. ACK and CTS are unicast packets. In fact, request-to-send and clear-to-send (RTS/CTS) are not recommended in current version of CALM.

Even though the probability of using the signal slot in WAVE and CALM is very small, to avoid standard violation, the attention signal is not transmitted in following cases:

when an immediate previous packet requires an ACK, or when the immediate previous packet is RTS, or when the immediate previous packet indicates a need to transmit a subsequent packet.

In the proposed signaling scheme, vehicle with safety message to transmit sends the attention signal in the signal slot following busy medium. The attention signal indicates intention of the vehicle to transmit a high priority safety message. The safety message vehicle performs regular random backoff procedure and transmits the safety message as if the attention signal was not transmitted. Vehicles with other messages to transmit also perform standard backoff procedure. However, the non-safety message vehicles must detect the attention signal during the signal slot. If the attention signal is detected during the signal slot, the non-safety message vehicles defer access to the medium so that safety message can be transmitted first.

Figure 10 shows an example of the proposed signaling technique. Vehicles V1 and V2 contend for channel access. V1 attempts to transmit non-safety message, and V2 contends for safety message transmission. V1 and V2 have equal AIFS. However, V1 has a shorter random backoff time. Without the attention signal by V2, V1 would transmit first. Because V1 receives the attention signal from V2, V1 defers channel access. Therefore, V2 transmits the safety message first.

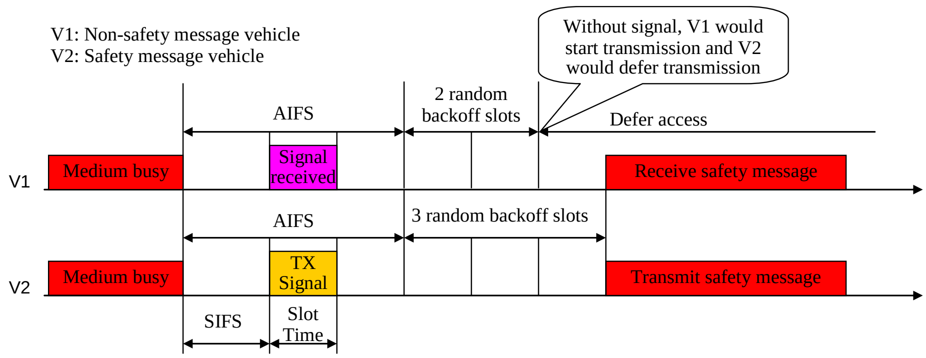

Figure 10. Example of Signalling for Safety Message Transmission

Figure 11 shows that the signaling technique avoids non-safety message collision with safety message, where V1 is non-safety message vehicle and V2 is safety message Vehicle. V1 has a longer AIFS. However, V1 has a shorter random backoff time. Without

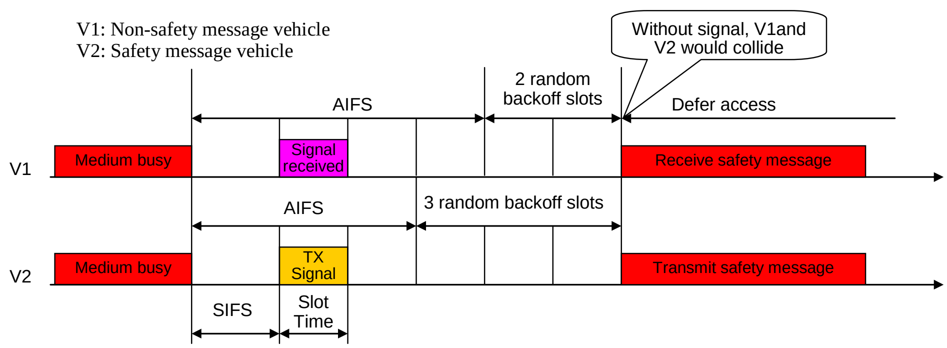

Figure 11. Example of Signalling Avoiding Collision

the attention signal by V2, V1 and V2 would collide since they have same total backoff time. Because V1 receives the attention signal from V2, V1 defers channel access and V2 transmits. Therefore, the signaling technique avoids a safety message collision and improves reliability.

Figures 12a and 12b show the signaling technique for the safety message vehicle and non-safety message vehicle, respectively. The signaling technique works on all channels specified by the various standards. It fits CCH especially well because CCH is primarily a broadcast channel.

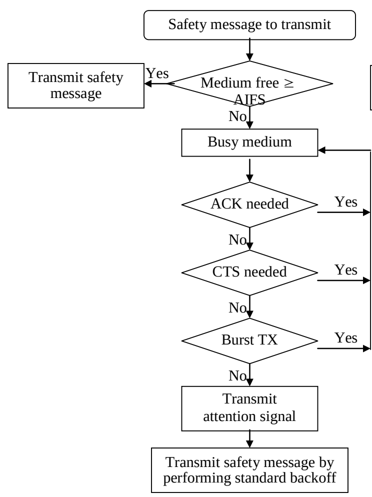

Figure 12a. Safety Message Transmission

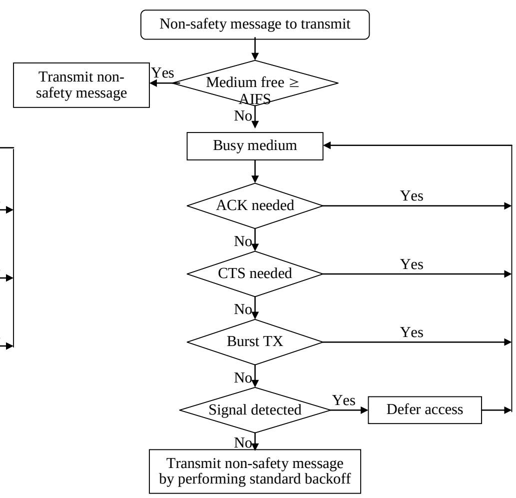

Figure 12b. Non-Safety Message Transmission

In Figure 12a, the vehicle has a safety message to transmit. The vehicle checks if the medium is free for more than one AIFS time period. If yes, the vehicle transmits safety message immediately. If not, the medium is busy, the vehicle checks if ACK is needed. If not, the vehicle checks if CTS is needed. If not, the vehicle checks if burst TX is in progress. If not, the vehicle transmits the attention signal in signal slot. It then transmits safety message by performing the standard backoff procedure as if the attention signal was not transmitted.

In Figure 12b, the vehicle has non-safety message to transmit. The vehicle checks if the medium is free for more than one AIFS time period. If yes, the vehicle transmits non-safety message immediately. If not, the medium is busy. The vehicle checks if ACK is needed. If not, the vehicle checks if CTS is needed. If not, the vehicle checks if burst TX is in progress. If not, the vehicle attempts to detect the attention signal in signal slot, and defers its access if signal is detected. Otherwise, the vehicle transmits non-safety message by performing the standard backoff procedure.

ADAPTIVE CONTROL CHANNEL INTERVAL FOR WAVE NETWORKS

As we pointed out early that safety messages may experience 54 milliseconds delay in WAVE networks due to existence of the SCHI and the GI. The 54 milliseconds latency does not satisfy the SAE's 10 milliseconds requirement. To reduce the latency in WAVE networks, this paper presents an adaptive control channel interval (ACCHI). Figure 13 shows the ACCHI, which consists of a GI, a SIFS slot, an attention signal slot, and an adaptive safety message transmission interval. The length of adaptive safety message transmission interval is variable. The length is zero if there is no attention signal transmitted in signal slot. If there is attention signal transmitted, the length depends on the time taken by the safety message transmission. All devices monitor the CCH at the beginning of the ACCHI.

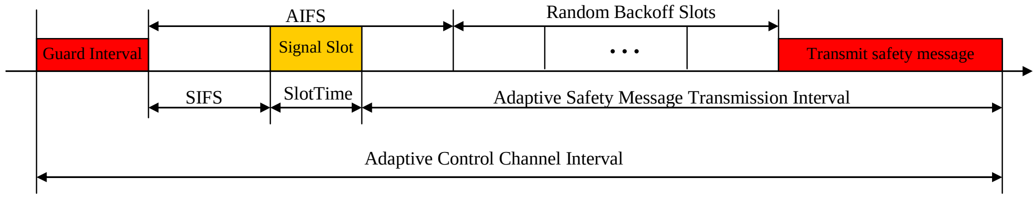

Figure 13. Structure of the Adaptive Control Channel Interval

The device with the safety message to transmit sends the attention signal in signal slot and then transmits safety message on the CCH by following the standard backoff procedure. The device can resume activities on other channel after the safety message transmission. Devices without safety message must monitor for the attention signal in the signal slot. If no attention signal is detected, the ACCHI terminates, and all devices can resume their previous activities. If the attention signal is detected, non-safety message devices monitor the CCH for up to 5 time slots following the signal slot to receive the safety message since the maximum backoff time after signal slot on CCH is 4 time slots, and the safety message transmission can start in the fifth slot. After receiving the safety message, non-safety message devices may resume their previous activities.

With the proposed ACCHI, WAVE Sync Interval can be modified to reduce safety message transmission latency in SCHI by adding ACCHIs into SCHI.

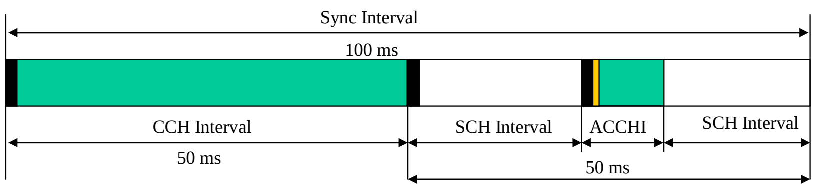

Figure 14. WAVE Sync Interval with one ACCHI Inserted in SCHI

Figure 14 shows an example of revised WAVE Sync Interval with one ACCHI. It is understood that multiple ACCHIs can inserted in the SCHI.

CONCLUSION

Traffic accidents, congestions and delays in transportation systems have caused significant loss of life and wasted energy. To improve safety and efficiency of the transportation systems and to enable new services and applications, IEEE WAVE and ISO CALM have been developed as international standards for ITS applications. However, WAVE and CALM may experience long latency caused by multi-channel operation and nondeterministic nature of the CSMA/CA channel access mechanism. WAVE and CALM may also drop life saving safety messages due to channel congestion. In this paper, we propose technologies to reduce latency and increase channel coverage in multi-channel vehicular environments. To address congestion control and improve safety message dissemination reliability, we also propose techniques to deal with congested channels and guarantee vehicle with safety message gains channel access first. The proposed technologies can significantly reduce latency and improve reliability of the safety message transmission in vehicular communication networks.

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