Cognitive Radio Enabled Multi-channel Access for Vehicular Communications

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***Abstract*—The IEEE 1609.4 standard has been proposed to provide multi-channel operations in wireless access for vehicular environments (WAVE), where all the channels are periodically synchronized into control and service intervals. The communication device in each vehicle will stay at the control channel for negotiation and contention during the control interval, and thereafter switch to one of the service channels for data transmission in the service interval. The inefficiency of WAVE system comes from the fact that half of the time intervals of the service channels remain idle since all the stations are performing message contention within the control channel. In this paper, the cognitive radio-enabled multi-channel access (CREM) protocol is proposed to increase the channel utilization of IEEE 1609.4 standard. Based on the concept of cognitive radio, the vehicular stations are categorized into primary stations with safety-related messages and secondary stations with non-safety information to be delivered. Prioritized channel access is designed in the proposed CREM scheme in order to increase the transmission opportunity of primary stations. Moreover, extended time intervals are granted for primary stations to ensure reliability for data transmission. The enhanced CREM (CREM-E) protocol is proposed to further opportunistically increase the channel utilization of secondary stations. Simulation results show that the proposed CREM-E scheme outperforms the existing IEEE 1609.4 protocol with enhanced channel utilization and smaller waiting time intervals.**

I. Introduction

The IEEE 1609 family of standards for wireless access in vehicular environments (WAVE) [1] is defined to support applications for intelligent transportation systems (ITSs), including safety and emergency services, automated toll collections, traffic management, and commercial transactions between vehicles. It specifies the architecture and management functions to enable secure vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) wireless communications. In order to facilitate the ITS applications, a local area network is formed by a WAVE basic service set (WBSS) consisting two types of major architectural components, i.e. the onboard units (OBUs) in vehicles and the roadside units (RSUs) installed in road infrastructure, which are denoted as stations in this paper.

Specifically, the IEEE 1609.4 standard [2] is proposed to enhance the IEEE 802.11p medium access control (MAC) protocol [3] for multi-channel operations as illustrated in Fig. 1. The WAVE system is designed to operate on the 75 MHz spectrum in the licensed ITS 5.9 GHz band. The operating spectrum is divided into seven channels, including one con-

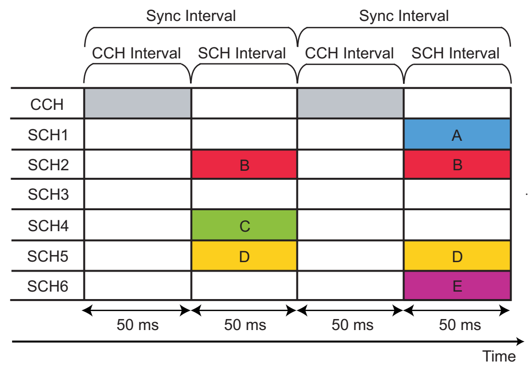


Fig. 1. Schematic diagram of multi-channel operation in IEEE 1609.4 standard.

trol channel (CCH) and six service channels (SCHs), each with 10 MHz bandwidth. On the other hand, from the time domain perspective, all the seven channels are periodically synchronized via the *Sync Interval* with default length of 100 ms, which is equally divided into the 50 ms CCH interval and the 50 ms SCH interval. As shown in Fig. 1, all the stations utilize the common CCH within the CCH intervals to transmit control or management messages; while the SCH intervals of six SCHs are employed by the stations within the WBSS to deliver data frames for information exchange. It is intuitive to observe that half of the time (i.e. during the CCH intervals) within the SCHs can not be utilized for data transmission since all the stations are either transmitting or listening to the control messages in the CCH during the CCH intervals. Furthermore, the reliability for transmitting emergency or safety messages cannot be guaranteed according to the existing WAVE standard.

Different research work has been proposed based on the IEEE 802.11p/1609 standards [4–8]. Performance evaluation of IEEE 802.11p protocol was conducted in [4] in view of throughput, collision probability, and delay under different numbers of nodes. In order to improve the inefficiency resulting from fixed backoff window size, both the centralized and distributed approaches with optimal window size are proposed in [5] for the V2I communications. A solicitation-based MAC protocol is proposed in [6] for the IEEE 802.11p network to alleviate the problems caused by high mobility vehicles. For alleviating potential unbounded delay caused by the contention scheme in the IEEE 802.11p standard, a self-organizing time division multiple access (STDMA) scheme was proposed in [7] to ensure successful transmission of time-critical traffic between the vehicles. However, without the consideration of multi-channel operation as defined in the IEEE 1609.4 standard, all the schemes mentioned above only assume a single SCH for data transmission in the IEEE 802.11p network. The work presented in [8] adopts multi-channel operation defined in IEEE 1609.4 specification. Extended SCH interval, i.e. odd multiple of the original SCH interval, is exploited to improve the channel access with enhanced throughput performance. However, elongated non-safety data delivery can severely degrade safety or emergency messages that require immediate and time-bounded transmission.

Therefore, the cognitive radio-enabled multi-channel access (CREM) protocol is proposed in this paper to address two major concerns in the WAVE standard as follows: (a) to improve the unutilized CCH intervals in the SCHs; and (b) to increase the transmission reliability of safety-related messages. The concepts of primary user (PU) and secondary user (SU) defined in cognitive radio network (CRN) [9; 10] are correspond to the stations that are delivering the safety messages and non-safety information, respectively. In order to provide privilege for safety information, the PUs are designed to possess smaller contention window (CW) size comparing with that of the SUs. More opportunities for channel access will be available to the PUs in order to successfully deliver their safety-related messages. Moreover, the PU is allowed to occupy an SCH to continuously transmit its entire message for multiple sync intervals until the completion of data delivery. In order to further promote the channel utilization of the WAVE system, an enhanced CREM (CREM-E) protocol is proposed which allows the SUs to transmit their data for an additional sync interval if there does not exist a PU that failed in transmission in the current CCH interval. It is shown in the simulation results that the proposed CREM and CREM-E schemes can effectively increase the channel utilization comparing with the original IEEE 1609.4 standard. Meanwhile, the transmission opportunities for safety-related messages can also be preserved.

II. Multi-channel Operation in IEEE 1609.4 standard

The coordinated universal time (UTC) is adopted for all the stations as the synchronization scheme for the sync intervals. The stations will switch to the CCH in every CCH interval to either listen or transmit advertisement messages, and potentially switch into one of the SCH during the SCH interval for data transmission. According to the IEEE 1609.4 standard, the interaction between the stations is provided based on the formation of WBSS. From the service point of view, a WBSS is defined by a set of cooperating WAVE stations which consists of a single provider as the WBSS initiator and one or multiple WBSS users. During the CCH interval, a provider P_i that intends to deliver information to some of the users u_i will broadcast the WAVE services advertisement (WSA) frame on the CCH. The WSA frame mainly includes the following three fields: (a) the identification (ID) number of WBSS, (b) the SCH that the provider plans to switch into, and (c) the intended MAC addresses of users for data transmission. If one or multiple users agree to receive data from the provider, a WSA response (WSAR) frame will be issued by the user to acknowledge the reception of WSA frame. After receiving the WSAR frame from one of the targeting users, both the provider and user will switch to the corresponding SCH that is recorded in the WSA frame in the following SCH interval.

There can be multiple providers that intend to compete for the utilization of the six SCHs. The random backoff scheme is utilized to alleviate potential collision between the WSA frames on the CCH during the CCH interval. Furthermore, after listening to the successful WSA/WSAR handshake from one provider within the same CCH interval, the other providers that still intend to deliver WSA frames will adjust their targeting SCH to avoid conflict on using the same SCH. They will select a different SCH in the upcoming SCH interval if their corresponding WSA/WSAR handshake is successfully conducted. There can be the possibility that a provider failed in broadcasting its WSA frame or did not receive the WSAR frame from any of the user due to the occurrence of frame collision. The provider will have to wait until the next sync interval for another WSA announcement with enlarged contention window size. After the contention and negotiation processes, the stations will switch to their corresponding SCHs in the SCH interval to conduct data transmission.

Moreover, if a provider possesses a larger size of data to transmit, several sync intervals will be required to complete the data delivery. That is, in order to transmit data in more than one SCH interval, the provider has to broadcast and contend its WSA frame in every CCH interval until the transmission is finished. Fig. 1 illustrates how the five WBSSs (i.e. from A to E), initiated by their corresponding providers, are established to conduct data delivery. It is observed that all the stations in the network will need to switch into the CCH in the CCH interval for channel contention and resource allocation. During the following SCH interval, the stations within each WBSS will switch to their corresponding SCH for data delivery. It is obvious that all the CCH intervals in the SCHs are not utilized by any of the stations. Moreover, in the case that continuous data is required to be delivered, e.g. for WBSS B, all stations within WBSS B will still need to terminate their transmission during the CCH interval to contend for the channel usage in the following SCH interval.

III. Proposed Cognitive Radio Enabled Multi-channel Access (CREM) Protocols

The main targets of propose CREM protocol are both to enhance the channel utilization and to promote the transmission reliability of safety-related data delivery. For achieving such goals, the concept of cognitive radio is adopted in the proposed CREM scheme, i.e. by mapping the providers with

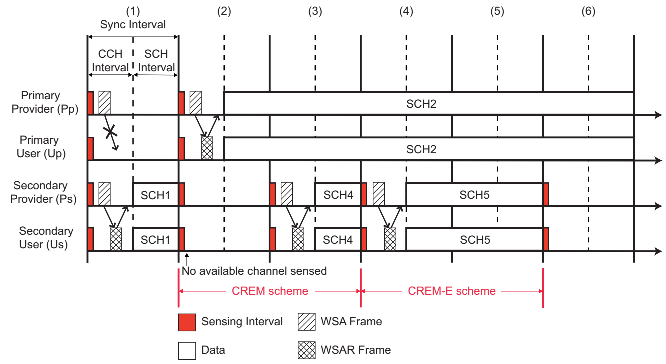


Fig. 2. The operations in proposed CREM/CREM-E protocols.

safety-related messages as PUs, e.g. emergency or police cars, and those with non-safety information as SUs, e.g. commercial and general automobiles. In other words, the primary provider P_p will have higher privilege in channel negotiation and is allowed to have persistent opportunity to deliver its data until finished. The secondary provider P_s, on the other hand, will only be able to transmit data if there exists spectrum holes within the network. Based on the proposed CREM protocol, it can be assured that the primary providers will possess higher opportunities to utilize the SCHs relatively to the secondary providers in the network. The detail mechanisms of proposed CREM scheme are described in the following subsection.

A. Detail Mechanisms of CREM Scheme

In order to perform the concept of cognitive radio, the capability of conducting wide-band spectrum sensing [11] is required for all the stations. As shown in Fig. 2, every station will update the spectrum condition of all the six SCHs by using its radio transceiver at the beginning of every sync interval. After monitoring and acquiring the channel information of the six SCHs, the station will establish its own channel status table (CST) which indicates if the channel is either in idle or busy state. The providers that intend to perform data transmission will start with transmitting WSA frames on the CCH during the CCH interval in order to contend for channel access. Based on its CST information, an unoccupied SCH will be selected by the provider as a targeting channel to switch into, which will be recorded in the WSA frame. A handshake is completed in the case that one of the WBSS member transmits the corresponding WSAR frame for acknowledgement.

For achieving prioritized channel access between P_p and P_s, the enhanced distributed channel access (EDCA) mechanism proposed in IEEE 802.11e standard [12] will be utilized. The EDCA scheme defines different access categories (ACs) in a station associated with their distinct arbitration inter-frame spaces (AIFSs) and CW sizes. In order to provide P_p with higher opportunity for channel access, P_p will be assigned with high-priority AC which is associated with smaller value of AIFSs and CW sizes. As a consequence, P_p should possess greater chance to win the channel contention comparing with P_s, which is designated with low-priority AC. After the reception of successful WSA/WSAR handshakes from the other providers, a provider will update its own CST in order to record the change of channel states. In other words, if a provider observes a successful handshake from another provider that contains the same selected SCH as targeting channel, it will choose another unoccupied SCH based on its CST. After the completion of contention process during the CCH interval, the stations that are granted with an SCH will be switched to that channel for data transmission. The behaviors for data delivery will be different for the two different types of providers, i.e. P_p and P_s, as stated in the following.

1) Primary Providers: Based on the CREM protocol, P_p is privileged to transmit data until completion as long as it acquires the possession of an SCH. The primary provider can transmit its data for more than one sync interval without having to return to the CCH in the CCH intervals. In other words, the primary provider does not need to conduct channel sensing and contention during its data transmission within the CCH intervals. After the data transmission has finished, P_p will return to the normal sync intervals and channel switching processes. The primary provider can start another new data transmission by conducting channel contention on the CCH in the CCH interval.

2) Secondary Providers: According to the prioritized EDCA scheme, the secondary providers possess lower priority to contend for channel access of SCHs. In the case that the data size from a P_s is larger than an SCH interval, more than one sync intervals will be necessary to complete the data transmission. P_s will have to conduct channel sensing, contention, and negotiation processes within multiple CCH intervals on the CCH in order to accomplish it data transmission.

Fig. 2 shows the examples to explain the operations of the proposed CREM protocol. It is noted that only one pair of primary provider and user (P_p, u_p) and one pair of secondary provider and user (P_s, u_s) are shown in the diagram for explaining purpose. There are still other providers and users that are competing for data transmission within the six SCHs. In the first sync interval, both P_p and P_s are conducting prioritized channel contention with other providers on CCH within the CCH interval. Assuming that the the secondary provider P_s wins the channel contention while the primary provider P_p fails in the contention due to packet collision, the pair (P_s, u_s) will both switch to the SCH 1 during the SCH interval to conduct data transmission. At the second sync interval, it is considered that the primary provider P_p finally successes in channel contention and start to conduct data delivery at SCH 2. Based on the design of proposed CREM protocol, P_p will continue its data transmission in the following third to sixth sync intervals due to its privilege usage of channel. On the other hand, the secondary provider P_s may observe that there does not exist available SCHs in its CST during the channel sensing period of the second sync interval, which prevents P_s from delivering its WSA frames. Until the third sync interval, P_s succeeds in channel contention and conduct frame transmission on SCH 4.

It is noted that the concept of primary provider adopted in the proposed CREM protocol is slightly different from the conventional CRNs. The PU defined in conventional CRNs is not required to possess the capability of sensing the channel state since every PU is designated with a pre-specified channel for data transmission. On the other hand, in our proposed CREM scheme, the primary provider is required to conduct channel sensing and contention at the beginning of its data delivery. The major reason for channel contention is owing to the available SCHs are not specified for any of the primary providers. All the primary and secondary providers are required to contented for channel access on the CCH within the CCH interval. On the other hand, the required channel sensing for the primary provider is due to the existence of multiple primary providers that are contending and utilizing the available six SCHs. Without channel sensing, the providers will not able to recognize if there exist other primary providers that are using any of the SCH continuing from previous sync intervals.

B. Proposed CREM-E Scheme

The main target of proposed CREM-E protocol is to opportunistically increase the channel utilization of secondary providers without sacrificing too much channel access opportunity of the primary providers. In the original CREM protocol, the secondary providers can only conduct data transmission in a single SCH interval after winning the channel access. The design concept of CREM-E scheme, on the other hand, is to allow the secondary providers to extend their data delivery for an additional sync interval if there does not exist failed handshake from primary provider in the CCH interval.

The mechanism of proposed CREM-E scheme can also be shown by observing from the fourth sync interval in Fig. 2. It is noted that the frame transmission over consecutively sync intervals of primary provider P_p still valid in the CREM-E scheme. Since all the stations, except P_p, will listen to the CCH within the CCH interval, it is observable for all the providers to identify if there exist a failed WSA/WSAR handshake from a primary provider. Assuming that there does not exist any primary provider that fails in channel contention during the CCH interval of the fourth syn interval, all the secondary providers will extend their data transmission for an additional sync interval. As shown in Fig. 2, P_s will transmit the data during the fourth SCH interval and the entire fifth sync interval. On the other hand, if there exists a primary provider that fails in the handshake process, the secondary providers will only deliver their data within the upcoming SCH interval. Without having the channel occupied by the secondary providers, the primary providers will possess more opportunity to succeed in the channel contention in order to preserve their transmission reliability. Based on the proposed CREM-E scheme, the privilege of primary provider will be slightly sacrificed in order to increase the channel utilization of the secondary providers. It will be shown in the simulation results that the total channel utilization can be enhanced with the adoption of proposed CREM-E scheme comparing with the original CREM protocol.

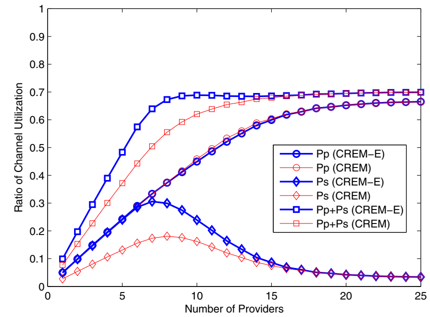


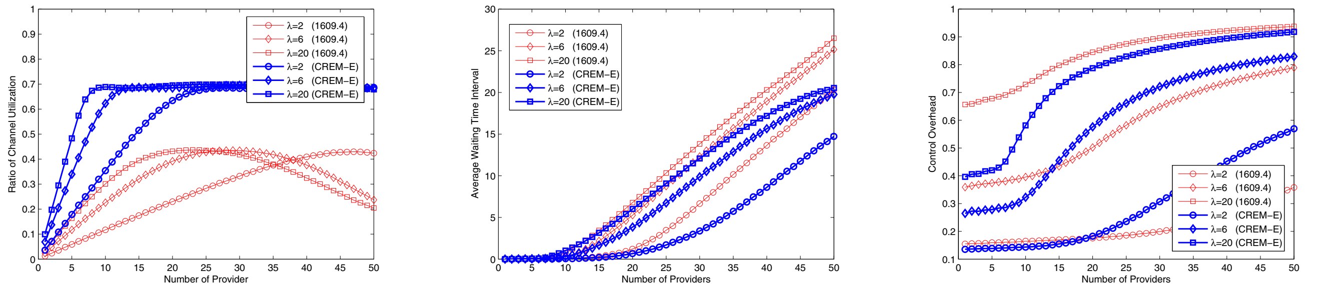
Fig. 3. Ratio of channel utilization vs. number of providers.

IV. Performance Evaluation

The performance of the proposed CREM and CREM-E schemes are evaluated and compared with the original IEEE 1609.4 protocol via simulations. The parameters defined in the IEEE 1609.4 standard [2] are adopted in the simulations, e.g. sync interval $=$ 100 ms, CCH interval $=$ 50 ms, SCH interval $=$ 50 ms, number of CCH $=$ 1, and number of SCH $=$ 6. The parameters defined in IEEE 802.11e standard [12] are utilized for prioritized channel access in both CREM and CREM-E protocols. Moreover, Poisson traffic with arrival rate λ is assumed for both primary and secondary providers. The data rate is 3 Mbps and the frame size is designed to be exponentially distributed with mean value $=$ 300 Kbits, which corresponds to the transmission time to be twice of an SCH interval. Noted that equal number of primary providers and secondary providers are assumed in the network. Each provider is designed to deliver its data frame to a corresponding user. Furthermore, 5 ms of channel sensing period is required at the beginning of each sync interval for the proposed CREM/CREM-E scheme, which is not required by the IEEE 1609.4 protocol.

Fig. 3 illustrates the ratio of channel utilization versus total number of providers in comparison with the proposed CREM and CREM-E schemes. Since the purpose of this comparison is to observe the effectiveness of CREM-E protocol, three different cases including primary providers (P_p), secondary providers (P_s), and total providers ($P_p + P_s$) are illustrated in the figure. The arrival rate is assumed as $\lambda = 20$ frames/sec for both primary and secondary providers. By adopting the CREM-E protocol, it can be observed that the ratio of channel utilization for total providers is comparably larger than that of the CREM scheme. The enhanced ratio of channel utilization from CREM-E scheme is primarily owing to the increased ratio from the secondary providers as shown in the curves with circles in Fig. 3.

Figs. 4(a) to 4(c) illustrate the performance comparison between the proposed CREM-E and IEEE 1609.4 protocols under different values of arrival rates, i.e. $\lambda = 2$, 6, and 20 frames/sec. It is observed from Fig. 4(a) that the channel utilization can be increased for both schemes as the arrival rate is augmented. The proposed CREM-E scheme can attain



(a) Ratio of channel utilization

(b) Waiting time slot

(c) Control overhead

Fig. 4. Performance comparison of three metrics vs. number of providers.

around 70% of channel utilization under three different cases; while the 1609.4 protocol can only reach around 40% of channel utilization. With larger number of providers, the CREM-E method can still preserve the ratio of channel utilization due to its effective usage of CCH intervals for data transmission. On the other hand, owing to the severe frame collision, the channel utilization from conventional 1609.4 protocol decreases as the number of providers increases. Fig. 4(b) shows the average waiting time interval of each arrival with respect to the number of providers. It is noted that a single waiting time interval is denoted as the length of an SCH interval, i.e. 50 ms. It can be seen from Fig. 4(b) that the proposed CREM-E scheme results in lower waiting time comparing with the 1609.4 protocol under different arrival rates and number of providers, e.g. around 5 intervals less under arrival rate $=2$ frames/sec and number of providers $=50$.

Fig. 4(c) shows the comparison of control overhead, which is calculated as the average number of handshaking from a provider within a sync interval. With lower arrival rate under $\lambda=2$ frames/sec, it is observed that the proposed CREM-E scheme will incur higher control overhead comparing with the 1609.4 protocol under larger number of providers. The major reason is that the higher channel utilization from CREM-E method results in less idle spectrum for the secondary providers. With large amount of providers co-existing and contending to transmit data, each provider needs to contend and retry for channel access, which increases the number of WSA/WSAR handshakes. However, with increased value of arrival rate, i.e. $\lambda = 20$ frames/sec, excessive amount of handshakes is required for both protocols to announce and conduct data transmission. Larger amount of collision will happen due to the overloaded traffic, which makes providers to frequently rebroadcast their handshake frames. Nevertheless, the proposed CREM-E protocol can still maintain lower control overhead since each WAS/WASR handshake will be good for elongated intervals of data transmission.

V. Conclusion

In this paper, the cognitive radio-enabled multi-channel access (CREM) protocol is proposed to enhance the channel utilization of IEEE 1609.4 standard for vehicular networks. Primary providers and secondary providers are respectively defined in the proposed CREM scheme that corresponds to safety-related and non-safety messages. For the primary providers, prioritized channel access scheme is utilized to increase the transmission opportunity; while elongated transmission time is adopted to increase the channel utilization. The enhanced CREM (CREM-E) protocol further increase the channel utilization of secondary provider by opportunistically increasing its transmission time interval. Numerical results show that both the CREM and CREM-E schemes can provide better performance in channel utilization, as compared to the conventional IEEE 1609.4 protocol.

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