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An Effective Wide-Bandwidth Channel Access in Next-Generation WLAN-Based V2X Communications

Hanseul Hong ¹, Young Yong Kim ¹, Ronny Yongho Kim ² and Woojin Ahn ^{3,*}

¹ School of Electrical & Electronic Engineering, Yonsei University, 50 Yonsei-ro, Seodaemun-gu, Seoul 03722, Korea; hhs0811@yonsei.ac.kr (H.H.); y2k@yonsei.ac.kr (Y.Y.K.)

² Department of Railroad Electrical & Electronic Engineering, Korea National University of Transportation, 157 Cheoldobakmulgwan-ro, Uiwang-si, Gyeonggi-do 16106, Korea; ronnykim@ut.ac.kr

³ Korea Railroad Research Institute, 176, Cheoldobakmulgwan-ro, Uiwang-si, Gyeonggi-do 16106, Korea

* Correspondence: woojin.ahn@krri.re.kr; Tel.: +82-31-460-5784

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Featured Application: Authors are encouraged to provide a concise description of the specific application or a potential application of the work. This section is not mandatory.

Abstract: As Intelligent Transport System (ITS) applications are diversified and amount of ITS data increases, high throughput and reliability are required in next-generation V2X communications. In order to meet such increased throughput and reliability requirements, IEEE 802.11bd, the next-generation V2X communication standard, has commenced standard development. One of the main features of IEEE 802.11bd is a 20-MHz bandwidth transmission. In this paper, a novel wide-bandwidth channel access scheme in next-generation Wireless Local Area Network (WLAN)-based vehicular communications is proposed. The proposed scheme is designed to provide fairness with other ITS devices and channel efficiency considering adjacent channel interference. By using the proposed scheme, through extensive simulations, it is verified that, while satisfying the fairness requirement with other ITS devices, the channel access delay of wide-bandwidth packet transmission can be optimized.

Keywords: WLAN; next generation V2X; channel access; wide-bandwidth transmission

1. Introduction

Intelligent Transport Systems (ITSs) have been developed and widely deployed with Vehicle-to-Everything (V2X) communication. Vehicles equipped with various sensors (e.g., radar, Lidar, and cameras) combined with Vehicle-to-Vehicle (V2V) communication to exchange sensed data enable automatic driving and platooning. Vehicle-to-Pedestrian (V2P) communication prevents traffic accidents by providing warning signals. In addition, various V2X applications enable driving convenience, road safety, traffic efficiency, road management, and infotainment. As various applications using V2X communication are developed, the required throughput and reliability are diversified. Moreover, as more onboard sensors are equipped in each vehicle, the communication requirements of throughput and reliability have increased.

At the time of this writing, the most widely deployed V2X communication system is Dedicated Short Range Communication (DSRC) using a set of Wireless Access in Vehicular Environments (WAVE) standards (Institute of Electrical and Electronics Engineers (IEEE) 1609 [1–3] and IEEE 802.11p [4]). Worldwide research projects and tests have proven that DSRC is a stable and efficient V2X communication system. Whereas DSRC is sufficient to provide basic and some advanced ITS services, more advanced future ITS services such as automated driving require more enhanced wireless

communication performance. Two important requirements in next-generation V2X communication systems are throughput and delay reduction.

In order to meet the requirements of next-generation V2X communication systems, the IEEE 802.11bd Task Group (TG) commenced V2X communication standardization in January 2019. IEEE 802.11bd's objective is to improve the throughput, transmission range, and positioning performance, preserving backward compatibility and fairness with conventional Outside Context of a Basic Service Set (OCB) devices [5–7]. One of the proposed features to improve throughput is wideband transmission using a 20-MHz channel for large data transmission. A 20-MHz channel can double the throughput performance compared to legacy DSRC systems using 10-MHz channels.

When the channel extension approach of IEEE 802.11n/ac is applied to 20-MHz transmission in V2X communication, the adjacent channel interference problem should be carefully considered. However, even though the channel access procedure is able to avoid adjacent channel interference problem in 20-MHz transmission, the channel extension approach of IEEE 802.11n/ac still cannot be applied in the V2X OCB environment owing to fairness concerns with conventional OCB devices and 10-MHz transmissions conducted by IEEE 802.11bd devices. When the channel load levels of two 10-MHz channels are not equal, the conventional channel extension scheme has higher channel access priority in the extended channel than the conventional OCB devices' 10MHz channel access because the conventional channel extension scheme has no back-off procedure on the extended channel. One of the most important requirements that IEEE 802.11bd must meet is fairness with legacy devices deployed with IEEE 802.11p devices. Since the IEEE 802.11p OCB configuration does not require association with Access Points (APs), there are no primary or secondary channels as in the Basic Service Set (BSS) of other IEEE 802.11 networks such as IEEE 802.11n/ac. In addition, each channel is used independently for its own purpose with equal importance. Therefore, the fairness issue in V2X environments is more severe than in other IEEE 802.11 networks.

There are prior researches to provide enhanced channel access mechanisms considering throughput and fairness under various IEEE 802.11 environments. Authors in reference [8] addresses unfairness caused by the wide-bandwidth transmission of IEEE 802.11ac in case of overlapping channels between neighboring APs. It provides channel allocation and scheduling methods to minimize the interference and enhance the fairness and network throughput considering different channel bonding levels. On the other hand, wireless mesh network of IEEE 802.11s is assumed in reference [9], where the authors propose an implementation method to provide proportional fairness without non-linear and non-concave optimization. However, these works assume static environments where APs or stations rarely move. Since there is no concept of AP in WLAN V2X scenario and all vehicles may change their positions dynamically, channel access methods considering static graphs are not suitable. The fair channel access scheme in WLAN V2X environment is considered in reference [10]. It compromises throughput and fairness considering multi-rate and multi-channel operation defined in IEEE 802.11p and IEEE 1609.4, respectively. It includes the grouping method of service channels (SCHs) regarding the data rate and the distance of transmission. However, in a real V2X environment, since WLAN V2X channels are pre-allocated and cannot be dynamically changed over time, throughput and fairness should be controlled with channel access schemes. Furthermore, 20-MHz transmission operation in the next generation V2X is not considered. In contrast to the related works, in this paper, the proposed channel access scheme jointly optimizes fairness and throughput performance for 20-MHz transmission under realistic WLAN V2X environment.

In this paper, a novel and effective wide-bandwidth channel access scheme in next-generation V2X communication systems is proposed. The proposed scheme is carefully designed to provide both enhanced fairness with other stations and reduced channel access delays. The proposed scheme is designed to alleviate interchannel interference problems that exist in OCB environments. The proposed architecture is able to effectively prevent a hidden node problem in the extended channel with the detection capability of exact channel usage time. The performance of the proposed scheme is analyzed in order to show the enhanced fairness. In addition to the proposed scheme, alternative channel-access

methods are given in the case of hardware limitations. In order to design the best scheme, the proposed scheme and other variant wideband channel access schemes are compared by computer simulations. Through extensive simulations, the best performing scheme is selected.

The rest of the paper is composed as follows. Section 2 presents background on conventional WLAN V2X communications and channel access schemes, Section 3 describes the proposed channel access scheme and alternative channel access schemes for the wide bandwidth of 20-MHz transmission in next-generation V2X communication systems, Section 4 provides extensive analysis of the fairness and delay performance of the proposed scheme, Section 5 evaluates the performance of the proposed scheme, Section 6 discusses the simulation results, and Section 7 concludes the paper.

2. Background

2.1. Conventional V2X Communication Scheme in 5.9 GHz Band

The most widely deployed V2X communication scheme is DSRC, which employs a set of WAVE standards including the IEEE 1609 series and IEEE 802.11p, as described in [11]. The most widely used V2X frequency band used for V2X communication is the 5.9 GHz band, which is a licensed band. As described in reference [12], the Federal Communications Commission (FCC) in the U.S. initially allocated seven channels in the 5.9 GHz band in 1999 and defined each channel's usage and rules in 2003 and 2006, as in Figure 1.

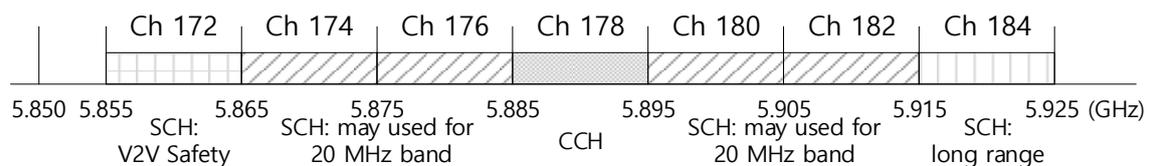


Figure 1. The 5.9 GHz channel allocation in the US.

As shown in the figure, Channel 178 (5.885 GHz–5.895 GHz band) is called the Control Channel (CCH), which is used only for safety messages and control messages. Channel 172 (5.855 GHz–5.865 GHz band) is dedicated to safety messages between vehicles, and Channel 184 (5.915 GHz–5.925 GHz band) is used to transmit frames to vehicles in a long communication range. The remaining channels can be used to send data frames regardless of message or data type. Two sets of 20-MHz channels (Channel 174 and Channel 176, and Channel 180 and Channel 182) can be used for 20-MHz frame transmissions.

IEEE 802.11p defines the Medium Access Control (MAC) and Physical (PHY) layers of V2X communication schemes in the 5.9 GHz band. The channel access schemes in IEEE 802.11p employ the Enhanced Distributed Channel Access (EDCA) mechanism of IEEE 802.11e with modified parameter values. EDCA is a contention-based channel access scheme with four different Access Categories (ACs) depending on traffic type: Video, Voice, Best Effort, and Background. Except for EDCA parameters for differentiated channel access per traffic type, EDCA is basically a Distributed Coordination Function (DCF) scheme. In a DCF scheme, when a station has data to transmit, it first senses for a DCF Interframe Space (DIFS) period to check if the medium is idle before it transmits the data frame.

There are two kinds of channel sensing methods—Preamble Detection (PD) and Energy Detection (ED). PD senses the channel status by decoding the signal duration included in the IEEE 802.11 preamble and the frame duration value indicated in the Duration field of frame. ED senses the channel status by detecting if there is any received signal power over a threshold value that is regarded as decoding a failure or an error. When the channel has a busy status, there are different procedures depending on the used channel sensing methods (PD or ED). If the channel is sensed as busy by PD during a DIFS period, then a back-off procedure is triggered after the DIFS period from the end of the sensed busy period. The back-off procedure waits for the back-off duration, which is determined by a randomly selected back-off counter.

On the other hand, if the channel is sensed as busy by ED during a DIFS period, then the stations must wait for an Extended Interframe Space (EIFS) period, which is a longer time period than DIFS after the end of the channel's busy status sensed by ED. An EIFS period is sufficiently long to protect the ongoing frame transaction where the transmitter of the frame that caused the channel to be busy needs to receive an acknowledge (ACK) frame to successfully complete the ongoing frame transaction. Therefore, an EIFS period includes the time for ACK frame transmission, i.e., $EIFS = \text{Transmission time of Ack frame at lowest PHY mandatory rate} + SIFS + DIFS$. By providing enough time in the EIFS period for a transmitter to receive an ACK frame, the hidden node problem caused by the ACK frame transmitter can be avoided.

In EDCA, in order to provide differentiated channel-access priorities depending on the traffic type, as shown in Figure 2, an Arbitration Interframe Space (AIFS) is used instead of the DIFS of the previously described normal DCF operation. AIFS values are different for the AC. The EIFS value is also adjusted with the AIFS period, i.e., $EIFS = \text{Transmission time of Ack frame at lowest PHY mandatory rate} + SIFS + AIFS$.

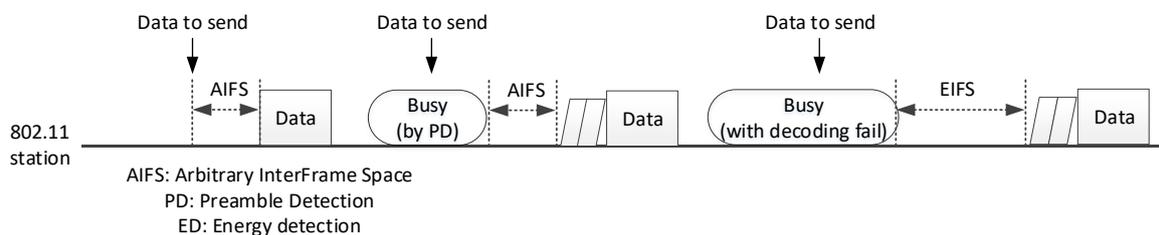


Figure 2. Channel access scheme in IEEE 802.11p.

In IEEE 802.11p, the default transmission bandwidth for frame transmission is 10 MHz. Doubled timing parameters are adopted compared to other IEEE 802.11 systems [13] because of a larger delay spread in the vehicular communication environment.

2.2. Conventional Channel Extension Scheme (Conventional AIFS)

When a 20-MHz channel is composed by two contiguous 10-MHz channels, the most simple 20-MHz channel access scheme reuses the existing wide-bandwidth channel access scheme defined in IEEE 802.11n and IEEE 802.11ac [14], which is used to access wider channels of 40 MHz, 80 MHz, and 160 MHz channels. In IEEE 802.11n and IEEE 802.11ac, a primary channel is defined as a common access channel used by all stations including AP in a BSS, and secondary channels are defined as the remaining channels of 40 MHz, 80 MHz, and 160 MHz with the primary channel.

The wide channel access in IEEE 802.11n and IEEE 802.11ac follows the EDCA channel access procedure on the primary channel and ED sensing on the secondary channel for a certain period before the end of the channel access procedure in the primary channel. The ED sensing period of the secondary channel depends on the operating band: PIFS in the 5 GHz band and DIFS in the 2.4 GHz band. When a busy channel is indicated in the secondary channels by ED sensing, the station may transmit a frame using only the primary channel, or a back-off procedure is restarted with a new back-off counter, preserving the contention window value and retransmission counter.

The previously described channel-access rule for 40-MHz channel access can be applied to 20-MHz channel access in IEEE 802.11bd. In reference [14], the primary channel was defined as the 10-MHz channel where an EDCA channel access procedure is performed, and the secondary channel was defined as the extended 10-MHz channel composing the 20 MHz channel. In order to provide enhanced fairness with stations using the secondary channel, using AIFS instead of PIFS is currently under discussion [14], as depicted in Figure 3. However, despite using AIFS, which has a longer waiting period than PIFS, there still exists a fairness problem with stations on the secondary channel because there is no back-off of the secondary channel. The fairness problem becomes worse when the channel load in the secondary channel is higher than the channel load of the primary channel because stations

on the secondary channel perform the back-off procedure as a result of EDCA procedure. The fairness problem should be carefully considered because fairness is one of the crucial requirements of IEEE 802.11bd [5,6].

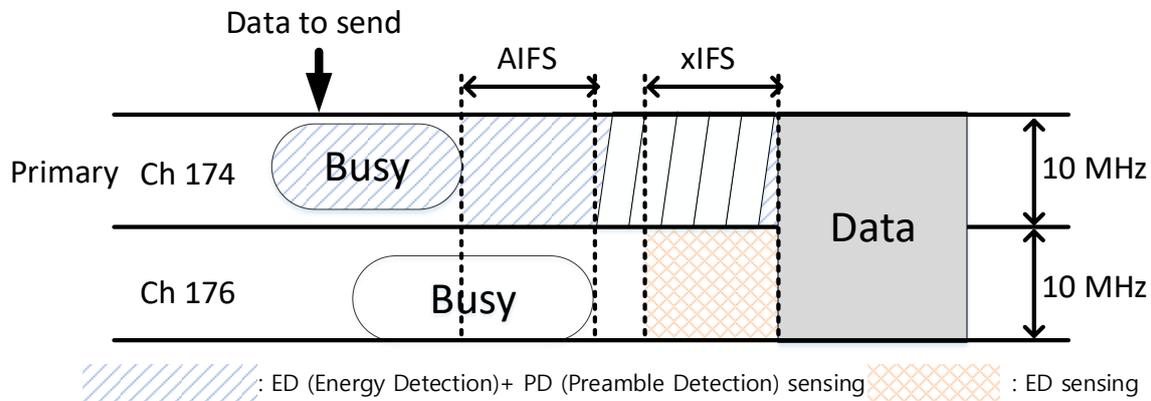


Figure 3. Application of conventional channel-extension scheme to 20-MHz channel access.

2.3. Adjacent Channel Interference Problem in V2X Communications

For the vehicular environment, there have been a number of prior studies [15,16] on adjacent-channel interference problems. Adjacent channel interference is caused by a power leakage of signals transmitted in neighboring channels, which is nonnegligible. Because of the adjacent-channel interference problem, transmission in nearby channels causes a degradation of the signal quality and an increased channel access delay. Therefore, to reduce negative impacts on the signal quality of the frame transmission on adjacent 10-MHz channels, authors in reference [17] suggested schemes to alleviate such channel interference caused by transmission in adjacent channels.

The previously described adjacent-channel interference problem should be taken into account for the channel access rule of wide-bandwidth transmission. In the wide-bandwidth channel access procedure in IEEE 802.11n or IEEE 802.11ac, when a busy channel is detected in the secondary channel by ED sensing, the station may transmit frames using only the primary channel. This is called a fallback operation. However, in V2X communication, a fallback operation causes an adjacent-channel interference problem because it transmits frames using adjacent channels even though a station senses transmission on the neighboring channel. The fallback operation causes more severe adjacent-channel interference by ignoring the transmissions in nearby channels. Therefore, in the proposed channel-access method for 20-MHz transmission, it is suggested not to allow the transmission of a 10-MHz fallback operation in case of a busy channel indicated in a secondary channel, as in reference [18].

3. Proposed Scheme and Its Variants

3.1. Proposed Channel Access Scheme for 20-MHz Transmission

A channel access scheme for 20-MHz frame transmission should ensure fairness with stations using an extended 10-MHz secondary channel, with the definitions of the primary channel and secondary channel as in [14]. In a BSS environment, the primary channel is a main channel used by all stations, and the secondary channels can be other BSSs' primary channels, which may be geographically separated where adjacent channel interference and channel extension fairness problems are not very serious.

However, in the OCB environment, each channel is equally important, with its own purpose. Stations using other channels cannot be geographically separated owing to the moving nature of vehicles. Therefore, adjacent channel interference and channel extension fairness problems are taken into account more seriously and carefully in an OCB environment (e.g., IEEE 802.11p and IEEE 802.11bd) than a BSS environment (e.g., IEEE 802.11n, IEEE 802.11ac, and IEEE 802.11ax). In the design

of the 20-MHz channel access scheme, fairness and adjacent interference avoidance are considered, and a minimized channel-access delay must be provided. In the proposed scheme, while fairness with stations operating in an extended 10-MHz channel is ensured, minimized channel-access delay is provided by preventing overprotection caused by dynamic sensing methods.

3.1.1. Device Architecture

In order to provide maximum performance, the device architecture of the proposed 20-MHz channel access scheme is designed to include two preamble detectors to perform PD sensing in both 10-MHz channels. The proposed station architecture to support the proposed scheme is shown in Figure 4. The proposed station architecture has an additional simplified receiver module with PHY layer receiver and simple MAC layer. In the proposed station structure, one preamble detector is a normal part of IEEE 802.11 MAC and PHY architecture [19], and the other preamble detector is part of the additional simplified receiver module. The additional simplified receiver module has a simplified MAC layer and PHY layer receiver for a secondary channel to perform PD sensing on that secondary channel. The added PHY receiver only includes the receiver part of a normal PHY layer [19]. The added simplified PHY and MAC layers for a secondary 10-MHz channel only includes the functionality of PD sensing: the decoding of the LENGTH field in the preamble’s L-SIG and Duration field in the MAC header of the received frames. The simplified receiver module detects the channel state of the secondary channel according to the decoded LENGTH field and Duration field. Since the simple MAC layer is only for the detection of channel usage time in the secondary channel, the decoded frames are not transferred to the upper layer.

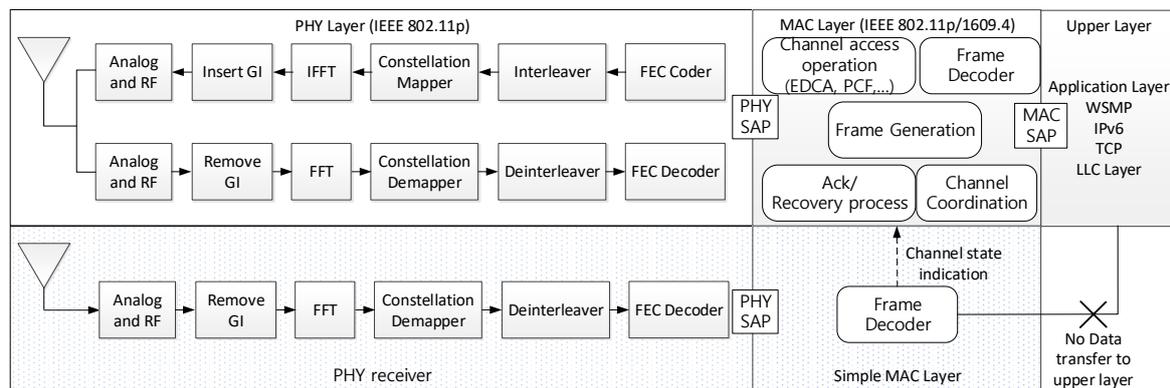


Figure 4. Proposed station architecture for 20-MHz channel access.

3.1.2. Proposed Channel Access Scheme (All Back-Off AIFS)

Based on the proposed device architecture as in Figure 4, each 10-MHz channel is able to perform carrier sensing (e.g., PD and ED) independently. Such independent carrier sensing capability enables the back-off of the entire 20-MHz channel, as depicted in Figure 5, which guarantees fair contention with other 10-MHz frame transmissions in each 10-MHz channel. In the proposed 20-MHz frame transmission scheme, the 20-MHz channel is determined to be idle when both 10-MHz channels are sensed as idle because of PD and ED sensing in each 10-MHz band. Channel sensing of the primary channel is performed by an IEEE 802.11 transceiver, and channel sensing of the secondary channel is performed by the previously described newly added receiver with simplified MAC layer and PHY layer. When the back-off duration expires, the station is able to transmit a 20-MHz frame without secondary-channel idle status checking for the AIFS duration as in the conventional AIFS scheme.

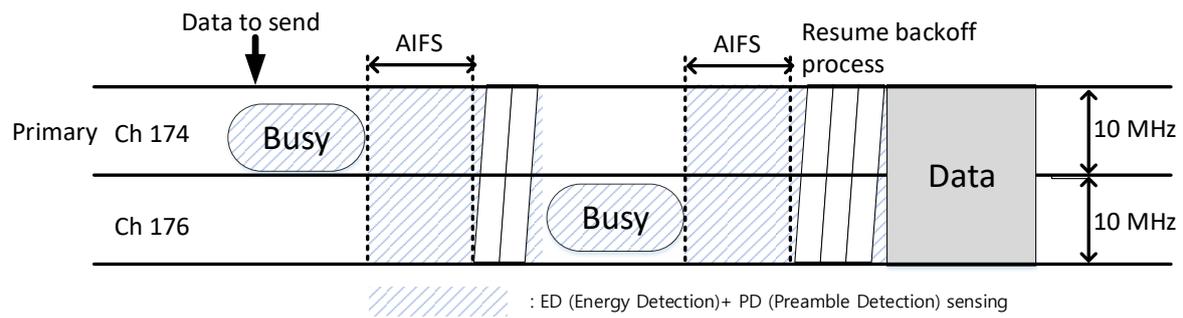


Figure 5. Proposed channel access scheme for 20-MHz transmission.

3.2. Alternative Channel Access Schemes for 20-MHz Transmission

Since there might be hardware restrictions in adding the proposed simplified receiver, several variant 20-MHz frame transmission schemes with a single transceiver are also proposed. Without the proposed simplified receiver, both detection and decoding, i.e., ED and PD, of received 10-MHz frames in the secondary channel are difficult to implement. Therefore, with a single transceiver, only ED sensing is performed in the secondary channel. To the best of our knowledge, today’s common WLAN implementation already employs such ED sensing in secondary channels for wide-bandwidth channel operation. Since fairness must be considered more seriously in OCB communication environments than BSS communication environments, new back-off procedures with ED sensing in secondary channels need to be designed. Since fairness and medium access delays have a trade-off relationship, in the design of the proposed variant schemes, the joint optimization of both aspects must be considered.

3.2.1. Modified Conventional Wideband Channel Access Scheme with AIFS Period (Start AIFS + End AIFS)

Since the conventional AIFS-based wideband channel access scheme does not perform back-off operations in secondary channels, in order to consider fairness carefully in secondary channels under an OCB environment, the conventional AIFS-based wideband channel access scheme must be modified. The modification of the conventional AIFS method includes the sensing of both 10-MHz channels before performing the back-off procedure, as illustrated in Figure 6.

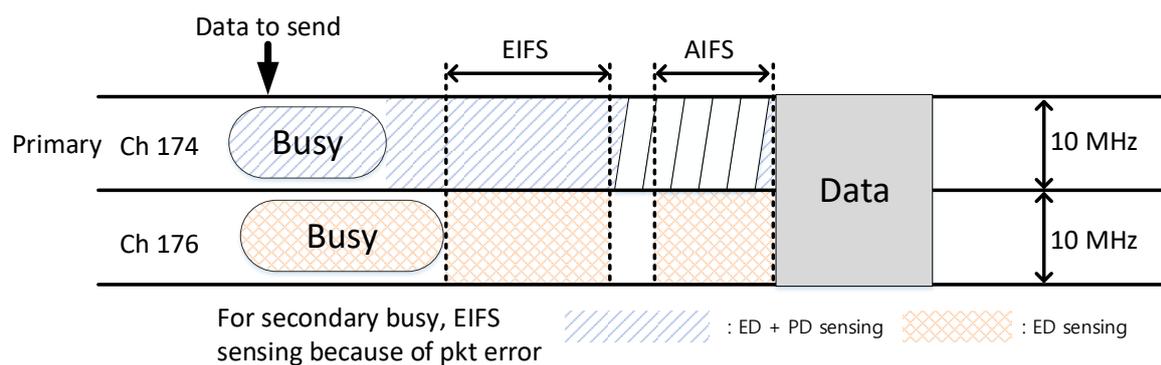


Figure 6. Access variant scheme for 20-MHz channel with modification of conventional wideband channel access scheme.

As in the conventional AIFS method, channel sensing in the primary channel can be performed with PD and ED sensing. In the proposed modification, since the modified conventional wideband channel access scheme only requires one transceiver, ED-based channel sensing can only be used in the secondary channel because PD sensing in the secondary channel is not general. When a busy channel is detected with ED sensing in the secondary channel, the busy-channel duration cannot be known. Therefore, in order to minimize the impact of 20-MHz frame transmission using the secondary

channel and protect the ongoing frame transaction (i.e., data frame + ACK) of the secondary channel, a relatively long waiting period of the EIFS duration must be applied. The rest of the channel access procedure after the back-off operation is conducted as in the conventional AIFS-based wideband channel access method.

3.2.2. Sensing of 20-MHz Channel for all Durations of Back-Off Procedure (All Back-Off EIFS)

Another 20-MHz channel access variant scheme is the modification of the proposed channel access method described in Section 3.1.2 to allow for one-transceiver design. In order to guarantee fairness, 20-MHz channel sensing for the duration of the back-off procedure is performed, as in the proposed method. Since this scheme also requires one transceiver, ED sensing can only be performed on the secondary channel during the back-off procedure. In this scheme, the 20-MHz channel is determined to be idle when each 10-MHz channel is sensed to be idle as a result of PD and ED sensing in the primary channel and ED sensing in the secondary channel. When a station has data to transmit using a 20-MHz channel, AIFS sensing and a back-off procedure are performed in the 20-MHz band, which can ensure a channel idle state for each decrement of the back-off counter. Since only ED sensing can be applied to the secondary channel, any detected busy state invokes EIFS duration waiting, as shown in Figure 7.

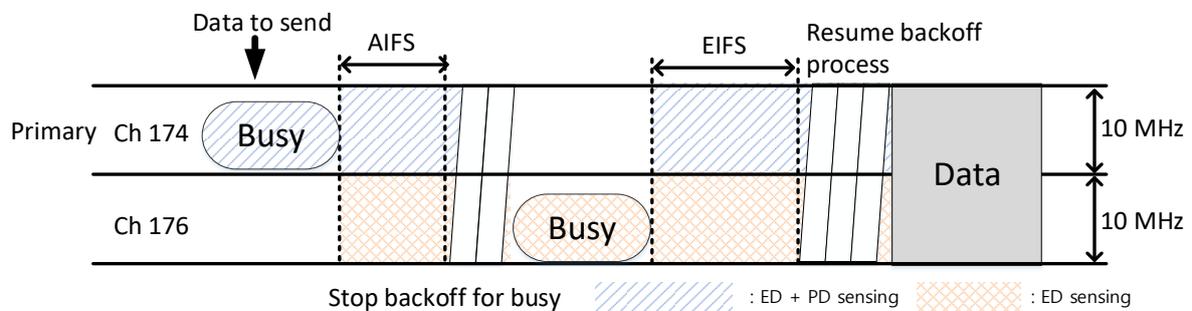


Figure 7. Alternative 20-MHz channel access scheme with all back-off approach for 20-MHz transmission.

4. Delay Analysis of All Back-Off AIFS Channel Access Scheme

The performance of 20-MHz transmission can be measured with two metrics: 1. fairness with other devices transmitting a 10-MHz frame in a secondary channel, and 2. the throughput of frames transmitted using a 20-MHz channel. The fairness metric can be measured by the mean access delay of frames carried in a 10-MHz frame in the secondary 10-MHz band. The throughput metric can be measured by the mean access delay and frame transmission latency carried in the 20-MHz channel.

For simplicity, in the performance analysis, there are several assumptions: full buffer traffic and one AC with the same AIFS number (AIFSN) and contention window value. The mathematical modeling of this paper is based on the Markov chain modeling in [20]. In addition, the transmitted frame size in each 10-MHz band is assumed to be the same in every transmission.

Since the total latency is the sum of the access delay, frame transmission delay, and additional delay for retransmission, the average value of the latency can be expressed as

$$L_w = d_w + T_w + (\text{mean retransmission delay}), \tag{1}$$

where L_w is the mean latency, d_w is the mean access delay, and T_w is the mean transmission delay of the 20-MHz frame transmission. When the transmitted frame is a broadcast frame, the retransmission delay can be omitted.

Similarly, the mean latency of frame transmission in the primary 10-MHz channel is the sum of the access delay and mean transmission delay, T_p , and the mean latency of the frame transmission in the secondary 10-MHz channel is the sum of the access delay and transmission delay in the secondary channel, T_s . Since the same transmission delay value is used, $T_p = T_s$ in the analysis.

To obtain the access delay of frames carried in 20-MHz channels in the all back-off AIFS scheme, the transmission probability of each station should be calculated. Since the channel access scheme of all back-off AIFS includes an EDCA back-off operation with the modification of the channel state decision, the Markov-chain state transition diagram is the same as the Markov-chain diagram depicted in [20], with the assumption of the same AC. Based on the approach in [20], the transmission probability can be calculated as the sum of state probabilities with back-off counter 0, which is expressed as

$$\tau_w = \sum_{i=0}^m b_{i,0}, \tag{2}$$

where $b_{i,0}$ is the state probability of the i th back-off procedure with back-off counter 0 of the Markov chain as defined in reference [20].

From the transmission probability τ_w , the probability of frame transmission in a 20-MHz channel by k stations in each slot, $P_w(k)$, can be defined as

$$P_w(k) = \binom{N_w}{k} \tau_w^k \cdot (1 - \tau_w)^{N_w - k}, \tag{3}$$

where N_w is the number of stations with buffered data to transmit using 20-MHz frames.

Since a collision occurs when two or more stations transmit frames in one slot, the collision probability of 20-MHz frame transmission in one slot P_w^{col} can be derived as

$$P_w^{col} = 1 - P_w(0) - P_w(1). \tag{4}$$

Similarly, the transmission probabilities transmitted in primary and secondary 10-MHz bands τ_p and τ_s can be calculated using the same scheme of Equation (2) from the model in reference [20]. The transmission probabilities of 10-MHz frames by k stations in each 10-MHz band in one slot $P_p(k)$ and $P_s(k)$ can be derived as

$$P_p(k) = \binom{N_p}{k} \tau_p^k \cdot (1 - \tau_p)^{N_p - k}, \tag{5}$$

$$P_s(k) = \binom{N_s}{k} \tau_s^k \cdot (1 - \tau_s)^{N_s - k}, \tag{6}$$

where N_p and N_w denote the number of stations having buffered frames to transmit using 10-MHz frames in the primary and secondary channels, respectively. As in Equation (4), the collision probabilities of 10-MHz frame transmission in the primary channel and secondary channel can be obtained as $P_p^{col} = 1 - P_p(0) - P_p(1)$ and $P_s^{col} = 1 - P_s(0) - P_s(1)$, respectively.

The mean access delay of frames transmitted in the 20-MHz channel, d_w , can be converted to

$$d_w = AIFS + E [\text{length of a slot time for a 20 MHz frame}] / \tau_w, \tag{7}$$

where $AIFS = SIFS + AIFSN \cdot aSlotTime$.

Assuming that $T_p = T_s$, E [length of a slot time for a 20 MHz frame] is calculated as

$$\begin{aligned}
 E[\text{length of a slot time for a 20MHz frame}] = & P_p(0) \cdot P_s(0) \cdot P_w(0) \cdot aSlotTime \\
 & + P_p(0) \cdot P_s(0) \cdot P_w(1) \cdot (T_w + AIFS + aSlotTime) \\
 & + P_p(1) \cdot P_s(0) \cdot P_w(0) \cdot m_s(T_p + AIFS + aSlotTime) \\
 & + P_p(0) \cdot P_s(1) \cdot P_w(0) \cdot m_p(T_s + AIFS + aSlotTime) \\
 & + P_p(1) \cdot P_s(1) \cdot P_w(0) \cdot (T_p + AIFS + aSlotTime) \\
 & + P_p^{col} \cdot P_s(0) \cdot P_w(0) \cdot m_s(T_p + EIFS + aSlotTime) \\
 & + P_p(0) \cdot P_s^{col} \cdot P_w(0) \cdot m_p(T_p + EIFS + aSlotTime) \\
 & + P_p^{col} \cdot P_s^{col} \cdot P_w(0) \cdot (T_p + EIFS + aSlotTime) \\
 & + P_p(1) \cdot P_s^{col} \cdot P_w(0) \cdot (T_p + AIFS + aSlotTime + m_p(EIFS - AIFS)) \\
 & + P_p^{col} \cdot P_s(1) \cdot P_w(0) \cdot (T_p + AIFS + aSlotTime + m_s(EIFS - AIFS)) \\
 & + P_p(0) \cdot P_s(0) \cdot P_w^{col} \cdot (T_w + EIFS + aSlotTime) \\
 & + (1 - P_p(0) \cdot P_s(0)) \cdot (P_w(1) + P_w^{col}) \cdot (\max(T_w, T_p) + EIFS + aSlotTime)
 \end{aligned} \tag{8}$$

where $m_s(x)$ is the mean holding time for the secondary channel for duration x , and $m_p(x)$ is the mean holding time for the primary channel for duration x .

Since busy-channel states may occur in the primary channel and the secondary channel in a cascaded manner, the mean holding time for the secondary channel, $m_s(x)$, can be obtained by a recursive function:

$$\begin{aligned}
 m_s(x) = & x + \sum_{i=1}^{\lceil x/aSlotTime \rceil} (P_s(0))^{i-1} P_s(1) m_p(T_{sch_AIFS} - x + i \times aSlotTime) \\
 & + \sum_{i=1}^{\lceil x/aSlotTime \rceil} (P_s(0))^{i-1} P_s^{col} m_p(T_{sch_EIFS} - x + i \times aSlotTime)
 \end{aligned} \tag{9}$$

for $x \leq T_{sch_AIFS}$, and

$$\begin{aligned}
 m_s(x) = & x + \sum_{j=1}^{n_s(x)} (P_s(0))^{j-1} P_s(1) (m_p(x - T_{sch_AIFS} - j \times aSlotTime) - x + T_{sch_AIFS} + j \times aSlotTime) \\
 & + \sum_{i=1}^{\lceil (x - n_s(x) \times aSlotTime) / aSlotTime \rceil} (P_s(0))^{n_s(x)} (P_s(0))^{i-1} P_s(1) m_p(T_{sch_AIFS} - (x - n_s(x) \times aSlotTime) + i \times aSlotTime) \\
 & + \sum_{i=1}^{\lceil x/aSlotTime \rceil} (P_s(0))^{i-1} P_s^{col} m_p(T_{sch_EIFS} - x + i \times aSlotTime), n_s(x) = \lfloor (x - T_{sch_AIFS}) / aSlotTime \rfloor
 \end{aligned} \tag{10}$$

where $T_{sch_AIFS} < x \leq T_{sch_EIFS}$ and $T_{sch_AIFS} = T_s + AIFS + aSlotTime$ and $T_{sch_EIFS} = T_s + EIFS + aSlotTime$.

The mean holding time for the primary channel, $m_p(x)$, can be calculated in the same way as (9) and (10), with the substitution of $P_s(k)$, P_s^{col} , $m_p(x)$, T_{sch_AIFS} , and T_{sch_EIFS} for $P_p(k)$, P_p^{col} , $m_p(x)$, T_{pch_AIFS} , and T_{pch_EIFS} when $T_{pch_AIFS} = T_p + AIFS + aSlotTime$ and $T_{pch_EIFS} = T_p + EIFS + aSlotTime$.

The mean access delay of frames carried in the secondary 10-MHz channel, d_p , can be converted to

$$d_p = AIFS + E [\text{length of a slot time in primary 10 MHz}] / \tau_p, \tag{11}$$

where E [length of a slot time in primary 10 MHz] is calculated as

$$\begin{aligned}
 E[\text{length of a slot time in primary 10 MHz}] = & P_p(0) \cdot I_{wp}(0) \cdot aSlotTime \\
 & + P_p(1) \cdot I_{wp}(0) \cdot (T_p + AIFS + aSlotTime) \\
 & + P_p(0) \cdot I_{wp}(1) \cdot (T_w + AIFS + aSlotTime) \\
 & + P_p^{col} \cdot I_{wp}(0) \cdot (T_p + EIFS + aSlotTime) \\
 & + P_p(0) \cdot I_{wp}^{col} \cdot (T_w + EIFS + aSlotTime) \\
 & + \{(1 - P_p(0)) \cdot (1 - I_{wp}(0))\} \cdot (\max(T_p, T_w) + EIFS + aSlotTime)
 \end{aligned} \tag{12}$$

where $I_{wp}(k)$ is the interference probability to the primary channel by the 20-MHz frame sent by k stations.

When i_{wp} denotes the interference probability to primary channel by a certain station transmitting a 20-MHz frame, $I_{wp}(k)$ can be derived as

$$I_{wp}(k) = \binom{N_w}{k} i_{wp}^k \cdot (1 - i_{wp})^{N_w - k} \tag{13}$$

and $I_{wp}^{col} = 1 - I_{wp}(0) - I_{wp}(1)$.

Since a backoff counter decreases only when both channels are in the idle state in the *all backoff AIFS* scheme, the interference probability by a certain station transmitting a 20-MHz frame, i_{wp} , can be written as

$$i_{wp} = p_{sidle}(AIFS + aSlotTime) \cdot \tau_w, \tag{14}$$

where $p_{sidle}(AIFS + aSlotTime)$ is the channel idle probability of the secondary channel for *AIFS + aSlotTime*, and is approximated as

$$p_{sidle}(AIFS + aSlotTime) \approx \left(\frac{d_s - aSlotTime}{d_s} \right)^{\lceil \frac{AIFS + aSlotTime}{aSlotTime} \rceil \cdot N_s}. \tag{15}$$

Similarly to Equation (11), the mean access delay of frames carried in the primary 10-MHz channel, d_s , can be converted to

$$d_s = AIFS + E [\text{length of a slot time in secondary 10 MHz}] / \tau_s, \tag{16}$$

where E [length of a slot time in secondary 10 MHz] is calculated as

$$\begin{aligned} E[\text{length of a slot time in secondary 10 MHz}] &= P_s(0) \cdot I_{ws}(0) \cdot aSlotTime \\ &+ P_s(1) \cdot I_{ws}(0) \cdot (T_s + AIFS + aSlotTime) \\ &+ P_s(0) \cdot I_{ws}(1) \cdot (T_w + AIFS + aSlotTime) \\ &+ P_s^{col} \cdot I_{ws}(0) \cdot (T_s + EIFS + aSlotTime) \\ &+ P_s(0) \cdot I_{ws}^{col} \cdot (T_w + EIFS + aSlotTime) \\ &+ \{(1 - P_s(0)) \cdot (1 - I_{ws}(0))\} \cdot (\max(T_s, T_w) + EIFS + aSlotTime) \end{aligned} \tag{17}$$

where $I_{ws}(k)$ is the interference probability to the secondary channel by the 20-MHz frame sent by k stations. From the interference probability to secondary channel by 20-MHz frame transmission, i_{ws} , $I_{ws}(k)$ can be derived as

$$I_{ws}(k) = \binom{N_w}{k} i_{ws}^k \cdot (1 - i_{ws})^{N_w - k} \tag{18}$$

and $I_{ws}^{col} = 1 - I_{ws}(0) - I_{ws}(1)$, where i_{ws} is derived as

$$i_{ws} = p_{pidle}(AIFS + aSlotTime) \cdot \tau_w, \tag{19}$$

where $p_{pidle}(AIFS + aSlotTime)$ is the channel idle probability of the primary channel for *AIFS + aSlotTime*, and is approximated as

$$p_{pidle}(AIFS + aSlotTime) \approx \left(\frac{d_p - aSlotTime}{d_p} \right)^{\lceil \frac{AIFS + aSlotTime}{aSlotTime} \rceil \cdot N_p}. \tag{20}$$

In order to show that the analysis is accurate, a brief simulation is performed under full-buffered traffic and simulation result is compared with analysis values. As a main consideration point of the proposed method is the fairness with 10-MHz transmissions on the secondary channel, the analysis result of the mean access delay of 10-MHz transmissions in the secondary channel is compared with the

simulation result. As shown in Figure 8, the analysis can be verified as accurate by comparing it with the simulation result in terms of the mean access delay of 10-MHz transmissions in the secondary channel.

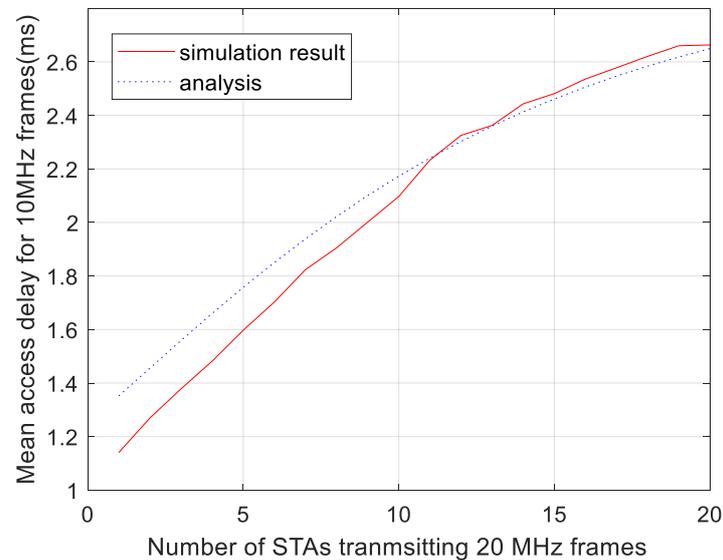


Figure 8. Comparison between analysis and simulation, in terms of the mean access delay of 10 MHz transmissions in the secondary channel.

However, the main assumption in the analysis is full-buffered environment, where each STA always has data to transmit. Since the full buffer assumption causes too heavy load in each channel, the simulation is performed with reduced number of STAs.

5. Results

In order to investigate the performance of the proposed channel-access schemes in terms of the fairness and efficiency (latency) of the 20-MHz frame defined in IEEE 802.11bd, rigorous simulations are performed. The time driven simulator implemented using MATLAB is utilized in the performance evaluation. In the simulation, 20-MHz channel is composed of two contiguous 10 MHz-channels and each 10-MHz channel has two states: channel busy state and channel idle state. Multiple STAs independently perform channel access when frames are generated with their interarrival times following an exponential distribution. Two kinds of STAs are implemented: STAs performing 10-MHz channel access and STAs performing 20-MHz channel access following the schemes in this paper. The transmission of each STA changes the state of the corresponding channel(s) to channel busy state. In case of 20-MHz channel access, upon successful channel access, both primary and secondary channels become channel busy state. If 20-MHz frame transmissions are unfair, i.e., greedy with the 10-MHz frame transmissions of the secondary channel, then the 10-MHz frame transmitted in the secondary channel has a longer medium access delay than 10-MHz frames with only channel contention. In order to clearly measure the fairness performance, the traffic of the secondary 10-MHz channel is set to be congested. To implement the different levels of channel load, different number of STAs generating background 10 MHz frames is employed.

Under such environments, the mean access delays of frames in the secondary channel for the proposed schemes are compared. Since fairness and efficiency need to be jointly designed, the latency performance of the proposed schemes is also investigated. The best scheme is that which provides the minimum impact on the secondary 10-MHz frame transmissions and short channel access delays of 20-MHz frame transmissions. In order to investigate the efficiency of the proposed schemes, the mean access delays of 20-MHz frames of the proposed schemes are compared.

The mean access delay is the main component that causes latency in a broadcast environment, which is the typical communication environment of V2X. In the simulation, stations generate a frame to

transmit with their interarrival times following an exponential distribution with an average interarrival time of 100 ms. For simplicity, an ideal channel is assumed, and all traffic is assumed for one AC. In addition, for simplicity, only broadcast frames, which do not require ACK, are transmitted in the simulation because the main type of V2X message is a broadcast message among many V2X applications [21]. As the effect of fairness can be clearly measured under a highly congested environment in the secondary channel, the simulation is performed under high traffic in the secondary channel and low traffic in the primary channel. Therefore, in the simulation, 200 stations transmit 10-MHz frames in the secondary channel, and 10 stations transmit 10-MHz frames in the primary channel. The other simulation parameters are listed in Table 1.

Table 1. Simulation Parameters.

Name	Value
Frame Length (10-MHz frame)	500 Bytes
Frame Length (20-MHz frame)	2000 Bytes
AC	AC_BE
MCS	2

Figure 9 shows mean and standard deviation of the medium access delay of 10-MHz frames transmitted in the secondary channel and mean and standard deviation of the medium access delay of 20-MHz frames as the number of stations transmitting 20-MHz frames increases from 10 to 200. As in Figure 9a,c, the proposed 20-MHz channel access scheme, the all back-off AIFS scheme, provides the minimum impact on the medium access delay of 10-MHz frames transmitted in the secondary channel in terms of mean and standard deviation. The standard deviation of all back-off AIFS scheme provides smaller standard deviation than the conventional method, providing the minimum impact on the number of 10-MHz transmissions with high contention delay caused by 20-MHz transmissions. Since all back-off AIFS has good performance in terms of the medium access delay of 10-MHz transmission, it will be beneficial when delay sensitive data are transmitted using 10-MHz bandwidth in V2X applications. Thus, the proposed scheme provides the maximum fairness with 10-MHz frame transmissions in the secondary channel.

In addition, the all back-off AIFS scheme shows good delay performance, in terms of mean and standard deviation of the medium access delay of 20-MHz frames. If there is a design limitation with one receiving antenna and the decoder, the proposed scheme cannot be used, and the alternative channel access schemes described in Section 3.2 should be used. When the station includes only one receiving antenna and decoder, trade-off occurs between the medium access delay of 10-MHz frames in the secondary channel and the medium access delay of 20-MHz frames depending on the channel access scheme with ED sensing of the secondary channel.

Specifically, when the conventional AIFS scheme is applied to the channel access of a 20-MHz frame, fair contention with 10-MHz frame transmissions including stations using IEEE 802.11p is not possible. On the other hand, the start AIFS + end AIFS scheme and all back-off EIFS scheme ensure fairness and low impact on 10-MHz frame transmissions in the secondary channel. However, the EIFS sensing procedure in such channel access schemes (start AIFS + end AIFS scheme and all back-off EIFS scheme) causes overprotection of 10-MHz frames transmitted in the secondary channel. This results in a large medium access delays in the transmission of 20-MHz frames.

In order to measure the performance of the proposed channel access method clearly, channel load in each 10-MHz channel needs to be considered. Medium access delay is highly affected by channel load in each 10-MHz channel. Because two 10-MHz channels are considered and high channel load clearly shows the impact on the performance, two cases for the channel load are considered: high channel load in the primary channel and high channel load in the secondary channel. The simulation results of Figure 9 show how high channel load in the secondary channel affects the performance of the channel access schemes. In order to show the impact on the channel access schemes in case of high

channel load in a primary channel, the mean access delay of 10-MHz frames in the secondary channel is measured as the number of stations transmitting 20-MHz frames increases from 10 to 200 under the high load condition of the primary channel. As shown in Figure 10, all channel access schemes show similar performance since 20-MHz channel access is not easily initiated due to a high channel load condition in the primary channel.

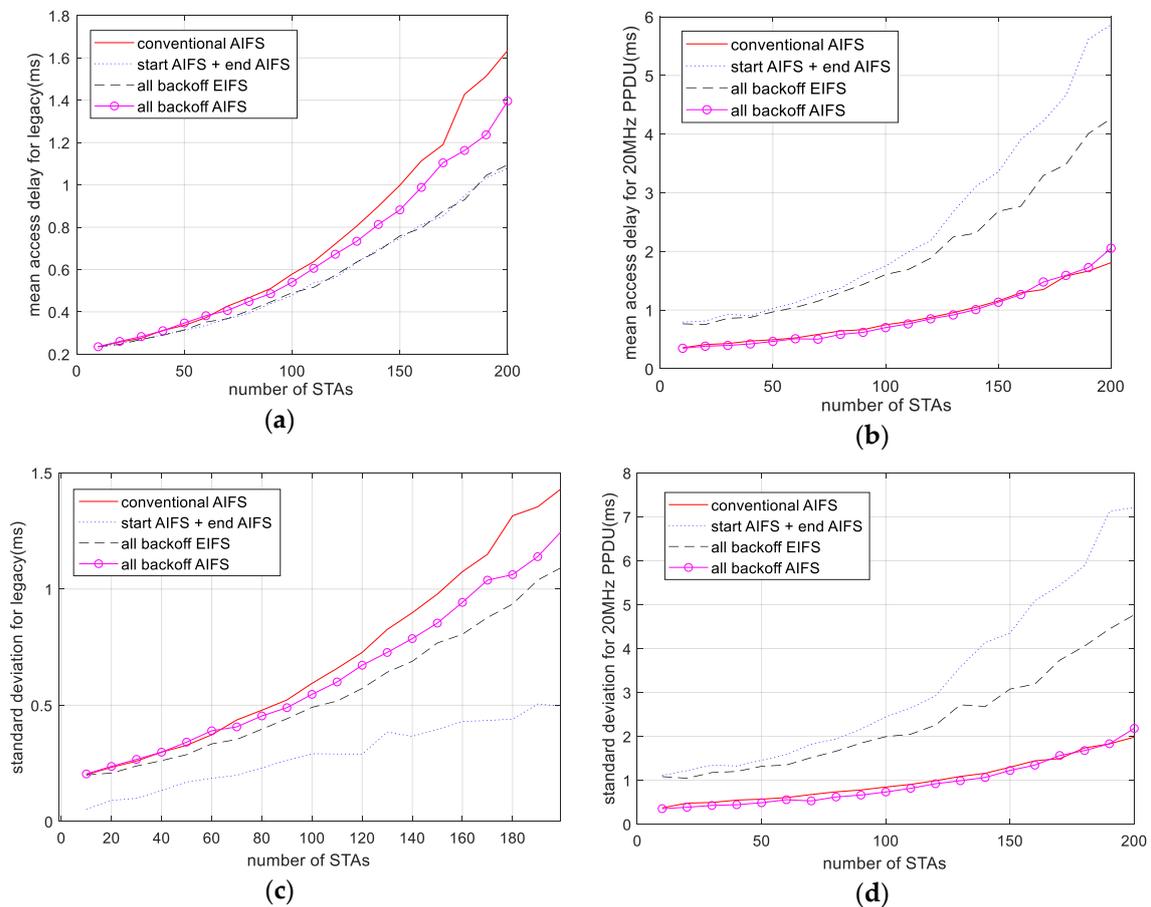


Figure 9. Comparison between channel access schemes in terms of effects on transmissions in secondary channel and mean access delay of 20-MHz frame: (a) mean access delay of 10-MHz frame sent in the secondary channel; (b) mean access delay of 20-MHz frame; (c) standard deviation of 10-MHz frame sent in the secondary channel; (d) standard deviation of 20-MHz frame.

In order to clearly show how well the proposed scheme performs in terms of channel access delay, the mean access delay of 20-MHz frames is compared with the mean access delay of 10-MHz frames under the same channel load level. For 20-MHz frame transmission, the number of stations transmitting 20-MHz frames increases from 10 to 200 and for 10-MHz frame transmission, the number of stations transmitting 20-MHz frames increases from 10 to 200 to provide the same channel load level for both cases. The result in Figure 11 shows the outstanding delay performance of the proposed scheme in terms of fair contention with 10 MHz transmissions.

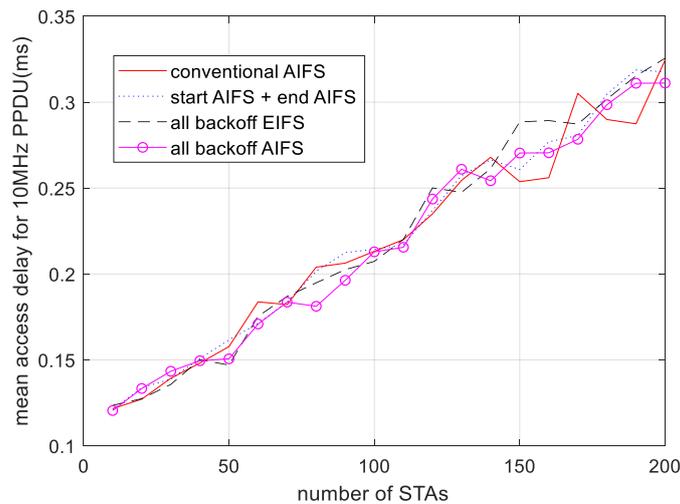


Figure 10. Comparison between channel access schemes under high load in a primary channel.

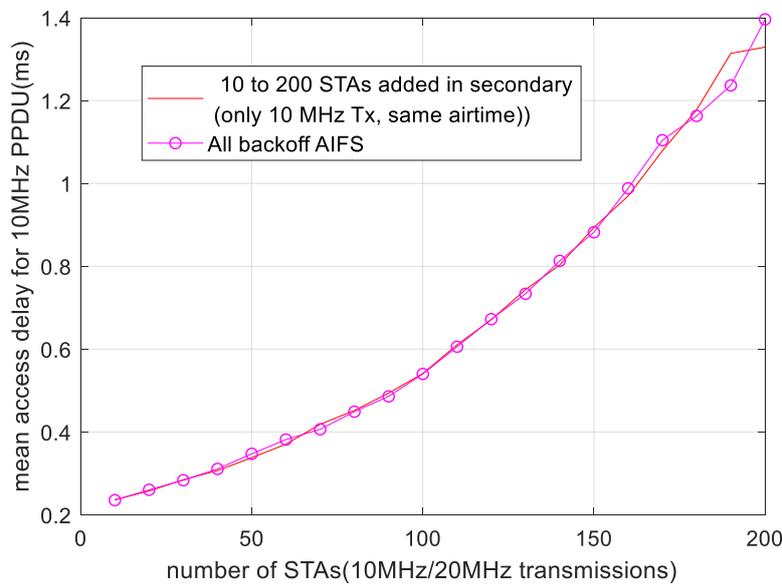


Figure 11. Performance comparison between 10 MHz transmission and 20 MHz transmission under the same channel load.

6. Discussion

As described in the previous section, the conventional AIFS scheme, which is a similar approach to the wideband channel access scheme adopted in IEEE 802.11n and IEEE 802.11ac, does not perform fair contention with 10-MHz transmissions in the secondary channel. This is because the channel access procedure of a 20-MHz frame in the conventional AIFS scheme performs a back-off procedure only in the primary channel, while channel access for 10-MHz frame transmissions in the secondary channel senses the channel for the entire back-off period.

The proposed 20-MHz channel access scheme, called the all back-off AIFS scheme, enables fair contention of both channels despite channel congestion on each channel because of the back-off procedure that considers the channel states of the primary and secondary channels. In addition, as all back-off AIFS includes two receivers to enable PD and ED sensing in both channels, overprotection leading to the performance degradation of 20-MHz frame transmission can be effectively prevented.

On the other hand, if there is one receiver in the station, only ED sensing can be applied to the secondary channel when PD sensing (decoder) is applied to the primary channel. In such an ED

sensing case, since the decoding of frames is usually infeasible, a back-off operation in the secondary channel should be performed based on the EIFS period to provide enough time for the transmitter of frames in the secondary channel to receive an ACK frame. This EIFS sensing operation is a basic procedure in the IEEE 802.11 specification whenever frame decoding to acquire the frame transmission duration fails.

Although the EIFS sensing ensures fairness and ACK frame protection, the EIFS period leads to the overprotection of 10-MHz frame transmissions in the secondary channel because the channel access scheme in a 10-MHz frame waits for the AIFS period before resuming the back-off procedure when it decodes frames and acquires the frame transmission duration. In other words, during the EIFS and AIFS time difference, the back-off counter is decreased and the transmission of the 10-MHz frame may be performed in case of expiration of the back-off procedure. Meanwhile, the channel access procedure for the 20-MHz frame is still waiting for the EIFS period. As a result, the medium access delay of the 10-MHz frame in the start AIFS + end AIFS scheme and all back-off EIFS period is further decreased, while the delay of the 20-MHz frame transmission is further increased.

7. Conclusions

In this paper, a fair and efficient channel access scheme for a 20-MHz frame in next-generation WLAN-based V2X communication was proposed. As applications of V2X communication have proliferated recently, more throughput is required for WLAN V2X communication than the throughput supported by IEEE 802.11p. As a result, IEEE 802.11bd, the so-called Next-Generation V2X (NGV), was established. Standardization is being developed to enhance throughput and communication range performance while maintaining fairness with existing deployed IEEE 802.11p-compliant vehicular devices. In IEEE 802.11bd, the 20-MHz frame format was proposed to increase channel utilization and to improve throughput performance.

The channel access scheme for a 20-MHz frame must ensure fair contention with the channel access procedure of 10-MHz frame transmissions in each 10-MHz channel while providing the acceptable transmission latency of a 20-MHz frame. The proposed channel access scheme was designed to jointly optimize fairness and throughput performance. The proposed scheme performs a back-off procedure for the entire 20-MHz bandwidth with PD and ED sensing of each 10-MHz channel using two receivers, leading to fair contention with 10-MHz frame transmission and preventing overprotection.

Simulation results showed that the proposed scheme met fairness requirements and provided the best 20-MHz transmission performance by avoiding overprotection in a secondary channel. In this paper, alternative 20-MHz channel access schemes were also proposed in order to overcome hardware limitations. However, if only one receiver can be implemented in the station, since ED sensing can only be applied to the secondary channel, then a trade-off occurs between the fairness and the delay of the 20-MHz frame. In alternative 20-MHz channel access schemes, a joint design between fairness and delay performance was applied in order to provide an acceptable trade-off.

In next-generation WLAN-based V2X communication, with the proposed scheme, the requirements of future V2X applications can be met by providing the maximum throughput performance and minimum impact on the extending channel.

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