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Wider-Bandwidth Operation of IEEE 802.11 for Extremely High Throughput: Challenges and Solutions for Flexible Puncturing

SANGHYUN KIM, (Member, IEEE), AND JI-HOON YUN, (Member, IEEE)
Department of Electrical and Information Engineering, Seoul National University of Science and Technology, Seoul 01811, South Korea

Corresponding author: Ji-Hoon Yun (jhyun@seoultech.ac.kr)

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ABSTRACT This paper aims to explain the wideband operation of IEEE 802.11, illustrate the challenges for wider-bandwidth support, and propose solutions. First, we describe the wideband operation of conventional IEEE 802.11 systems and the low-efficiency problem related to their contiguous channel-bonding limitations. Next, we describe how the puncturing of IEEE 802.11ax supports noncontiguous channel bonding. After that, we discuss the challenges of the limited bandwidth patterns of puncturing as a tradeoff problem between signaling overhead and transmission bandwidth. Using wider bandwidth facilitates a larger amount, thus a longer airtime, of resource-unit allocation information. To reduce this signaling overhead, splitting and delivering the information over multiple channels can be considered, but with the increased difficulty to find all of these channels available at the same time. We investigate this tradeoff problem based on a simple mathematical analysis and numerical data. We propose adaptation of the signaling structure for resource-unit allocation in either a statistical or opportunistic manner such that signaling of full resource-unit allocation information is made with minimal overhead. Comparative evaluation results are provided and analyzed for dense deployment and traffic load scenarios, demonstrating that the proposed adaptation always outperforms the conventional and static methods in terms of both bandwidth utilization and throughput.

INDEX TERMS IEEE 802.11, 802.11be, Wi-Fi, extremely high throughput, channel bonding, wider-bandwidth, puncturing.

I. INTRODUCTION

The ever-growing demands of mobile traffic have led to the continuous evolution of wireless communication systems. In particular, Wi-Fi networks are expected to account for over 50% of all IP traffic by 2022 [1] thanks to wide market penetration and successful evolution over generations. To meet even more stringent requirements for network throughput and latency, the IEEE 802.11 working group recently formed a new task group (named 802.11be) to discuss the next-generation physical-layer (PHY) and medium access control (MAC) standard of Wi-Fi, which is also called *extremely high throughput* (EHT) [2]–[4]. As the prior generations of IEEE 802.11 expanded the maximum operation bandwidth (Table 1) [5], increasing the peak data rate by *channel bonding*, EHT is expected to support an even wider bandwidth of up to 320 MHz [3], which is double that of the latest generation (802.11ax) [6].

TABLE 1. Operation bandwidth of IEEE 802.11 standards.

Version	Operation bandwidth
802.11a/b/g	20 MHz
802.11n	20, 40 MHz
802.11ac Wave1	20, 40, 80 MHz
802.11ac Wave2	20, 40, 80, 80+80, 160 MHz
802.11ax	20, 40, 80, 80+80, 160 MHz
802.11be	20, 40, 80, 80+80, 160, 240, 320 MHz (subject to change)

Contiguous channel bonding has been the rule of the conventional IEEE 802.11 for the use of a wide bandwidth beyond a single 20 MHz channel, which was the design choice for the simplicity of the transmitter and receiver hardware as well as the signaling protocol [7], [8] however became a major obstacle to exploiting wide bandwidths. According to the rule, a station is allowed to transmit in only a contiguous bandwidth of 20, 40, 80 or

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160 MHz [6].[1] In an extreme case, only a specific 20 MHz bandwidth is sensed busy, while the rest of the spectrum is all idle, however a station is not allowed to transmit beyond a 20 MHz bandwidth. Considering that the availability of bandwidths is sparse over the spectrum, changes with time and is unpredictable, the contiguous channel-bonding rule significantly restricts the utilization of the given spectrum [9].

Puncturing was first introduced in IEEE 802.11ax [6] to relive the restriction of contiguous channel bonding and is also expected to play a key role in wider-bandwidth operations in future generations, including EHT. Due to the use of orthogonal frequency-division multiple access (OFDMA) [10] in 802.11ax, a data frame is now composed of multiple resource units (RUs) in the frequency domain, each of which is a group of contiguous subcarriers and destined to a specific user. Within the OFDMA framework, puncturing enables the use of a set of sparsely available bandwidths in diverse patterns—which we call *bandwidth patterns* in the paper—by letting a transmitting station null the RUs of the channels sensed busy and selectively transmit in idle channels; thus, there is less interference in the bandwidth regions that are already occupied by other signals.

However, even with puncturing enabled, not all bandwidth patterns are supported for wideband transmission because signaling of RU allocation requires a specific set of channels to be available. To inform receiving stations of allocated RUs, the preamble of an OFDMA frame delivers the RU allocation information. However, the amount of this information increases and longer airtime is consumed as the frame conveys data for more users. IEEE 802.11ax reduces the signaling airtime by splitting the information into two parts and transmitting them in individual 20 MHz channels. This dual-channel approach, however, requires a specific contiguous 40 MHz bandwidth to be available at the time of transmission; otherwise, the signaling of complete information cannot be achieved, and thus, wideband transmission is not enabled.

To maximize the utilization of even wider bandwidth for future generations of IEEE 802.11, (1) supporting more diverse bandwidth patterns while (2) maintaining low signaling overhead is important. However, these two factors experience a *tradeoff*, described as follows:

- *Diverse bandwidth patterns*: A specific bandwidth pattern can be supported if a set of channels for signaling RU allocation information is available in the pattern. As multiple systems and devices may coexist in the unlicensed spectrum, it becomes less likely for a larger set of channels to be available at a certain time point. Therefore, using fewer channels for signaling RU allocation information diversifies the bandwidth patterns to be supported.
- *Low signaling overhead*: Supporting wider bandwidth facilitates the ability to serve more users in a single transmission for which a larger amount, thus a longer airtime, of RU allocation information is required. Splitting the RU allocation information into more fragments and delivering them over more bandwidth channels reduces the signaling overhead (airtime).

Therefore, understanding and balancing the tradeoff is the key to full exploitation of wider bandwidth.

There have been many research works on multichannel/wideband operation in wireless local area networks (WLANs). Wang *et al.* [11] proposed to allow stations with good signal strengths to use channel bonding by adjusting a clear channel assessment (CCA) threshold. The inefficiency of channel bonding for a single receiving station with a small frame size and the benefit of the parallel transmission for multiple stations were studied in [12], [13]. Lee *et al.* [14] proposed a genetic algorithm-based bandwidth determination scheme to optimize throughput against interference and collision. In [15], Chen *et al.* analyzed the relationships between the transmission, carrier sense, and interference ranges for channel bonding, and proposed a dynamic bandwidth selection protocol. Channel selection for channel bonding was considered for higher bandwidth utilization in [16]–[19]. Huang and Yang [20] proposed a protocol that gradually increases the bandwidth during transmission whenever new channels become available. Byeon *et al.* [21] developed an algorithm which adaptively enables/disables channel bonding considering the hidden interference. Fang *et al.* [22] proposed the approach for both an AP and relays to use available nonprimary channels for higher spectrum utilization. Deek *et al.* [23] implemented a network detector that identifies interference conditions affecting channel bonding decisions. The authors also proposed a link adaptation scheme that jointly adapts rate and bandwidth [24]. There were recent attempts to exploit deep reinforcement learning for bandwidth determination [25], [26]. WiZizz [27] handled the channel bandwidth in an on-demand manner to minimize energy consumption. The interactions between a group of neighboring WLANs that use channel bonding were analyzed using a continuous-time Markov network model in [28]–[30]. There have been many other performance analysis studies of channel bonding [31]–[36]. There have also been studies of multichannel aggregation for cellular systems in unlicensed spectrum, proposing adaptive deferral of an aggregated transmission to tackle the power leakage problem between channels [37] and new channel access mechanisms [38], [39].

However, most previous works focused on contiguous channel bonding, and the aforementioned tradeoff problem of noncontiguous bonding has not yet been explored in the literature.

This paper aims to provide an understanding of the wideband operation of IEEE 802.11, illustrating challenges for wider-bandwidth operation, and proposing solutions. First, we describe the wideband operation of conventional IEEE 802.11 systems and their contiguous channel-bonding limitations. Next, we describe how the puncturing of IEEE

[1] One exception is the use of two 80 MHz bandwidth parts in distinct bands at once in IEEE 802.11ac/ax (80+80 MHz operation). The 80+80 MHz operation is identical to the 160 MHz operation.

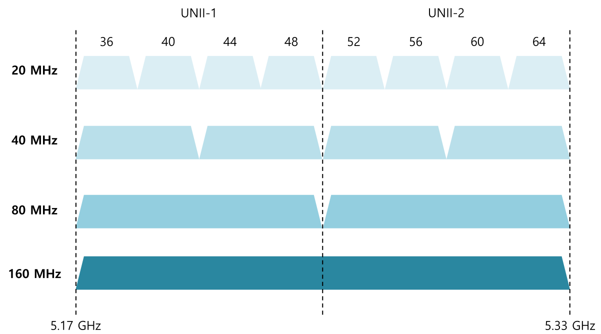


FIGURE 1. Channelization of IEEE 802.11 for various bandwidths in the 5 GHz band.

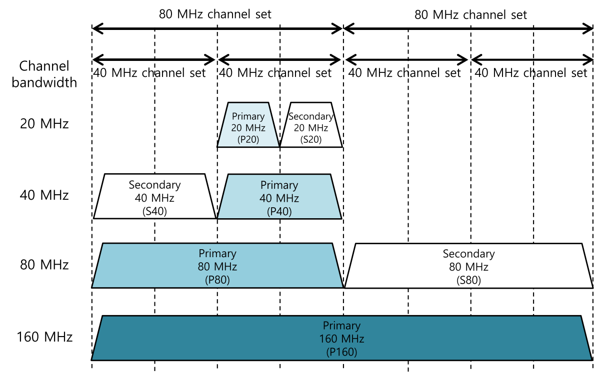


FIGURE 2. Contiguous channel bonding rule when the primary 20 MHz channel is the third (from the left) of the 20 MHz channels.

802.11ax is designed to relax the limitation and support noncontiguous channel bonding. After that, we discuss the challenges of puncturing due to limited bandwidth patterns in connection with the signaling structure of RU allocation information and investigate the tradeoff problem between signaling overhead and transmission bandwidth based on a simple mathematical analysis and numerical data. We introduce an adaptive construction framework for the RU allocation signaling structure that is applicable in either a statistical or opportunistic manner such that the signaling of full RU allocation information is guaranteed with minimal overhead. Comparative evaluation results are provided and analyzed in various dense deployment and traffic load scenarios, demonstrating that the proposed adaptation always outperforms conventional and static methods in terms of both bandwidth utilization and data throughput.

The rest of the paper is organized as follows. In Section II, we review the conventional wideband operation of IEEE 802.11. We describe the puncturing mechanism of IEEE 802.11ax in Section III. Section IV discusses the challenges of puncturing for wider-band operation, demonstrating the tradeoff based on numerical data, and Section V describes the proposed solutions. Section VI shows the performance comparison results, and Section VII concludes the paper.

II. WIDEBAND OPERATION OF CONVENTIONAL IEEE 802.11 FOR CONTIGUOUS BANDWIDTH

IEEE 802.11 defines frequency channels for bandwidths of 20, 40, 80 and 160 MHz, as illustrated in Fig. 1. A basic service set (BSS) of IEEE 802.11 selects a *primary 20 MHz channel* where all the comprising stations (an access point station (AP) and its associated non-AP stations) of the BSS exchange basic control frames including beacon frames and perform a backoff procedure for channel access. The frequency channels of IEEE 802.11 are further classified into two categories:

- *Primary channel*: A channel that includes the primary 20 MHz channel. According to the channel bandwidth, primary 20, 40, 80, and 160 MHz channels are available.
- *Secondary channel*: A neighboring channel of a primary channel that bonds with the primary channel to form another primary channel of the next wider bandwidth. According to the bandwidth, secondary 20, 40, and 80 MHz channels are available.

We denote a primary (secondary) X MHz channel as PX (SX) for short (e.g., P20, S40).

In conventional IEEE 802.11 networks, once a BSS determines its P20, a set of secondary channels to be bonded with a primary channel for a wider bandwidth is immediately determined such that only a contiguous bandwidth (corresponding to one of the primary channels) including the BSS P20 is used at a time, which is called *contiguous channel bonding*. Fig. 2 illustrates usable channels under contiguous channel bonding when the P20 of the BSS is the third of the 20 MHz channels from the left.

The wideband operation of IEEE 802.11 under the contiguous channel bonding rule is described as follows. First, as a station of a BSS completes a backoff procedure (its backoff count is about to reach zero) after the point coordination function interframe space (PIFS, 25μs in 5 GHz), the station performs CCA for S20 to check the availability of a 40 MHz bandwidth (P40). In Fig. 2, S20 is to the right of P20. If it is sensed idle, the availability of the 40 MHz bandwidth (P40) is confirmed. The procedure is repeated for the next wider secondary channel until the secondary channel is sensed busy[2] or the maximum operation bandwidth is reached.

The preamble of a transmitted frame conveys the information of its transmission bandwidth so that after decoding this part, every receiving station immediately knows how to tune its band filter according to the hard-coded channel-bonding rule. Accordingly, the conventional wideband operation greatly simplifies the operation logic of transmit and receive over a wide bandwidth, requiring signaling of the transmission bandwidth information only.

However, conventional wideband operation with contiguous channel bonding inefficiently exploits wide bandwidths due to the sparse, time-changing and unpredictable availability of individual channels. We illustrate the inefficiency problem in Fig. 3, where only one 20 MHz channel is busy (depicted as a red trapezoid), while all others are idle in the operation bandwidth of 160 MHz. In the illustration,

[2]If one of the 20 MHz channels comprising a target bandwidth is sensed busy, the bandwidth is assumed busy.

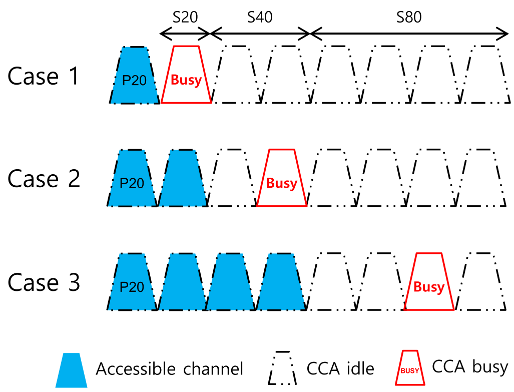


FIGURE 3. Inefficiency illustration of wideband operation with contiguous channel bonding (when the leftmost is a primary 20 MHz channel).

TABLE 2. Resource unit size and the number of resource units for different operation bandwidth cases in IEEE 802.11ax.

RU size (subcarriers)	Operation bandwidth			
	20 MHz	40 MHz	80 MHz	160 MHz
26	9	18	37	74
52	4	8	16	32
106	2	4	8	16
242	1	2	4	8
484	-	1	2	4
992	-	-	1	2
1984	-	-	-	1

the P20 of a transmitting station is the leftmost channel. In Case 1, S20 is busy, and the station is allowed to use a 20 MHz bandwidth (P20) only (depicted as a sky blue trapezoid) despite the availability of the right six 20 MHz channels (each depicted as a dotted-lined trapezoid). In Case 2, S40 is sensed busy, and the station can use a 40 MHz bandwidth (P40) only, leaving the right 80 MHz nonutilized. Likewise, in Case 3, the station uses the left 80 MHz bandwidth (P80) only. As illustrated in the figure, the conventional wideband operation with contiguous channel bonding fails to exploit the available spectrum well, and its efficiency significantly depends on the load statuses of individual channels.

III. PUNCTURING IN IEEE 802.11ax

Puncturing, which is applied for noncontiguous channel bonding, was first introduced in IEEE 802.11ax with the adoption of OFDMA. In the following, we describe wideband operation with puncturing and signaling for OFDMA.

A. WIDEBAND OPERATION WITH PUNCTURING

IEEE 802.11ax supports puncturing for downlink multiuser transmission of 80/160 MHz bandwidth. Within the framework of OFDMA, a bandwidth is divided into RUs, each of which is a group of contiguous subcarriers and allocated to a station such that multiple users can be served simultaneously.[3] The size of an RU and the number of RUs for different operation bandwidths are given in Table 2. With puncturing enabled, an AP prepares a multiuser OFDMA frame suited to the operation bandwidth and performs CCA

[3]IEEE 802.11be allows a multi-RU frame for a single user as well.

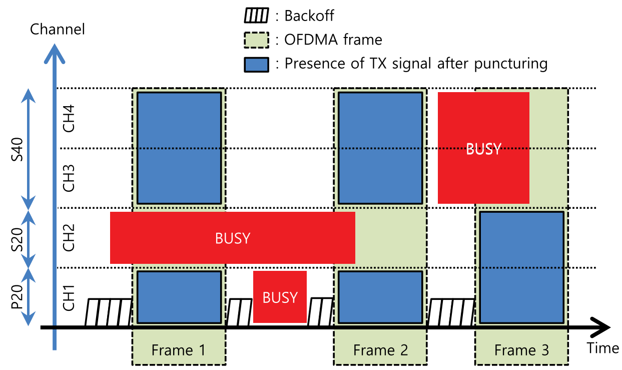


FIGURE 4. Illustration of wideband operation with puncturing for 80 MHz operation bandwidth.

for each 20 MHz channel within the bandwidth and PIFS before completing backoff in its P20. According to the CCA result, the AP nulls (punctures) the RUs within busy-sensed 20 MHz channel(s) and transmits the manipulated frame so that zero power is emitted in the already-occupied bandwidth part(s). Therefore, puncturing enables the use of noncontiguous bandwidth patterns. Fig. 4 shows an operation example of puncturing for 80 MHz operation bandwidth; P20 is the bottom channel (CH1). As shown in the figure, once a backoff process is completed, the RUs of a frame within busy channels are punctured and the punctured frame is transmitted. In Frames 1 and 2, the contiguous bonding cannot utilize the upper two channels (CH3 and CH4).

B. SIGNALING OF RESOURCE UNIT ALLOCATION

A station in a standby state hears only the P20 of its associated BSS. Therefore, the preamble of each OFDMA frame has to give the receiving stations the information of which RUs are allocated to each station, which we denote by *RU-info*, so that the stations tune their receive chain in time and decode the allocated RUs.

In IEEE 802.11ax, RU-info is placed in the HE-SIG-B field of the preamble. As depicted in Fig. 5(a), it is composed of one common field and multiple user block fields. Each user block field is in turn composed of one or two user fields, each containing a station ID to which an RU is allocated and the additional information needed for decoding (number of spatial streams, indication of transmit beamforming, modulation and coding scheme, dual carrier modulation, and coding). Therefore, the RU-info of a frame has a variable length depending on the number of users served by the frame. When a transmitting station (AP) uses a large number of RUs to serve a large number of users (up to 136 users for 160 MHz bandwidth), the length of HE-SIG-B becomes excessively long.

To halve the airtime of the HE-SIG-B transmission, the user block fields are split equitably and assigned to two content channels, denoted HE-SIG-B1 and HE-SIG-B2. They are transmitted in parallel over two distinct 20 MHz bandwidths of P40 and repeated as a backup in S40, as shown in Fig. 5(a). That is, the entire P80 is used for

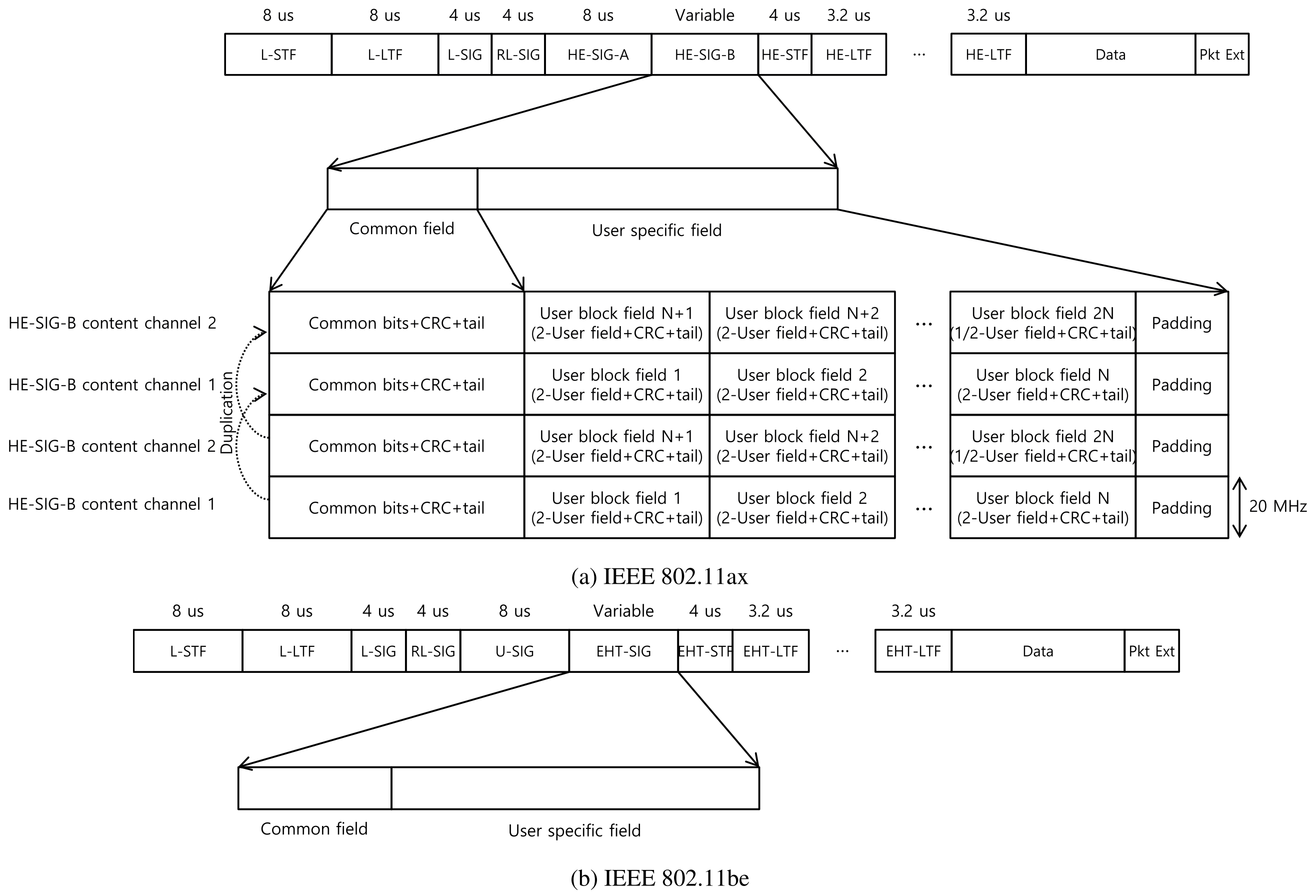


FIGURE 5. **Data frame format.**

RU-info signaling. To determine the location of an allocated RU, each station must decode both content channels in either P40 or S40. However, decoding one content channel in P40 and another in S40 is not allowed. There could be cases in which some part of P80 is sensed busy and thus needs to be punctured for transmission. If a transmitting station sees the availability of neither P40 nor S40, it deactivates the wideband transmission and transmits a 20 MHz frame in P20 since full RU-info cannot be given to receiving stations.

To let receiving stations know in advance whether to decode P40 and S40 to get RU-info at low complexity,[4] the puncturing mode (pattern) information is given in HE-SIG-A of the preamble using the bandwidth field, as illustrated in Fig. 6. Modes 1 through 3 correspond to no puncturing. Mode 4 indicates the puncturing of S20 in an 80 MHz frame, thus letting receiving stations decode the two HE-SIG-B channels in S40. Mode 6 indicates a 160 MHz frame with the same puncturing pattern as Mode 4. In contrast, for Modes 5 and 7, stations have to decode P40 to obtain HE-SIG-B1 and HE-SIG-B2. It is noted that the puncturing-mode indication does not give the information of the puncturing pattern in S80 since no RU-info channels are transmitted in S80 and thus any puncturing pattern is allowed there.

[4]Without this information, each receiving station should decode the RU-info in both P40 and S40.

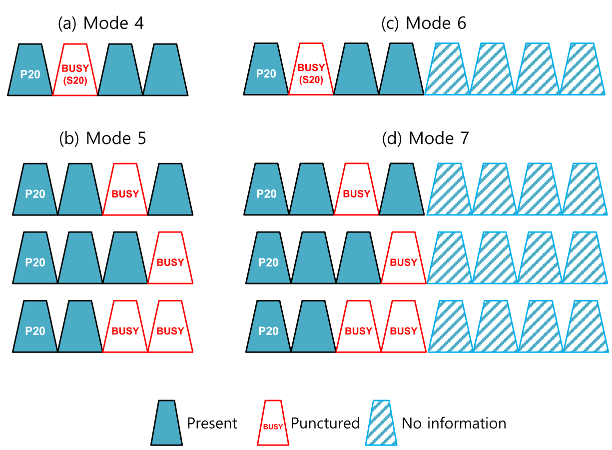


FIGURE 6. **Puncturing modes in IEEE 802.11ax.**

IEEE 802.11be uses a similar design for the frame format, as shown in Fig. 5(b), where the EHT-SIG field conveys RU-info.

IV. CHALLENGES OF WIDER-BANDWIDTH OPERATION

In this section, we discuss the challenges of wider-bandwidth operation, in particular on RU-info signaling.

Fig. 8 shows the cases in which wideband transmission is disabled in IEEE 802.11ax due to the failure of RU-info signaling, i.e., neither P40 nor S40 is available. In other

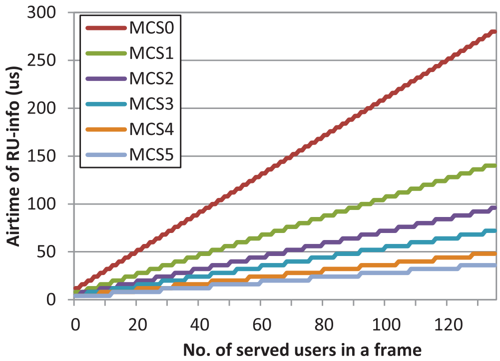


FIGURE 7. Airtime of RU allocation information in IEEE 802.11ax (HE-SIG-B) for various MCSs (obtained in Eq. (3)).

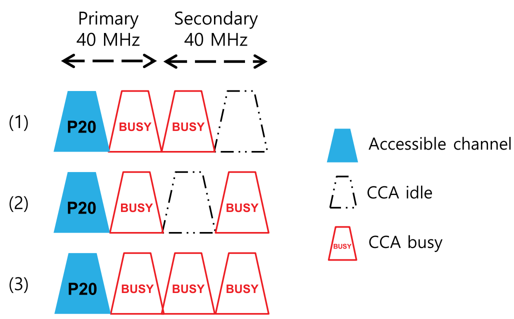


FIGURE 8. Failure cases of wideband transmission in IEEE 802.11ax.

words, for the three cases of Fig. 8, puncturing all the busy channels leads to the failure of RU-info signaling and thus is not allowed. As such, the bandwidth patterns supported by puncturing are limited due to the current RU-info signaling structure. The problem becomes more severe for wider bandwidth, e.g., 320 MHz in EHT, which allows more users to be served in a frame, thus increasing the amount of information bits for RU-info. As IEEE 802.11ax uses two content channels to reduce signaling overhead, EHT or the following generations can use more content channels. However, increasing the number of RU-info channels lowers the availability of bandwidth patterns in which all of the content channels can be transmitted at the same time. That is, there exists a tradeoff between signaling overhead and wideband transmission success.

In what follows, we investigate the two factors of the tradeoff based on the numerical data obtained via a simple mathematical analysis.

A. SIGNALING OVERHEAD OF RU-INFO

Consider the airtime of RU-info for a data frame. The airtime of RU-info is variable depending on the operation bandwidth, number of users and modulation and coding scheme (MCS), while the other parts of the preamble have a fixed duration. For the calculation of the airtime, we assume that the basic structure of RU-info follows that of IEEE 802.11ax. As depicted in Fig. 5, RU-info of 802.11ax consists of the common field and user-specific field. The number of bits of the common field, which we denote $L^{\mathrm{cm}}_{\text{RU-info}}$, is given as

$$L^{\mathrm{cm}}_{\text{RU-info}} = \overbrace{\text{8-bit}}^{\text{RU allocation subfield}} \times i + \overbrace{\text{1-bit}}^{\text{Center 26-tone RU}} + \overbrace{\text{4-bit}}^{\text{CRC}} + \overbrace{\text{6-bit}}^{\text{Tail}} \quad (1)$$

where $i = 1, 2, 4$ for 20/40, 80, and 160 MHz, respectively. The following user-specific field consists of multiple user block fields, each of which is defined as a set of one or two user fields (21 bits per field), a cyclic redundancy check (CRC, 4 bits) and a tail field (6 bits). Basically, a user block field has two consecutive user fields to specify the information of two users. If there remains one user in the final user block field (due to an odd number of users), a single user field is included. Suppose that a frame is for M receiving users and RU-info is evenly distributed over N_{ch} content channels ($N_{ch} = 2$ for 802.11ax). The final length of the user-specific field is aligned with the longest content channel (shorter content channels are padded with dummy bits). The number of user fields assigned to the longest content channel is $\lceil M/N_{ch} \rceil$, and they are paired to form a user block field with CRC and a tail attached. If they are odd, the final field forms a user block field alone. Therefore, the number of user block fields of the longest content channel is expressed by $\lceil \lceil M/N_{ch} \rceil /2 \rceil$, and the number of bits of the longest content channel is obtained as

$$L^{\mathrm{usr}}_{\text{RU-info}} = \left\lceil \frac{M}{N_{ch}} \right\rceil \times \overbrace{\text{21-bit}}^{\text{User field}} + \left\lceil \frac{\lceil M/N_{ch} \rceil}{2} \right\rceil \times (\overbrace{\text{4-bit}}^{\text{CRC}} + \overbrace{\text{6-bit}}^{\text{Tail}}). \quad (2)$$

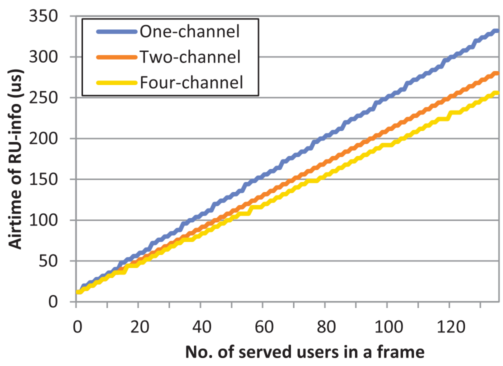
The number of bits per symbol (4 μs), denoted B_{sym}, is [26, 52, 78, 104, 156, 208] bits at MCS0 to MCS5. Finally, the airtime of RU-info, denoted $T_{\text{RU-info}}$, is obtained as

$$T_{\text{RU-info}} = \frac{L^{\mathrm{cm}}_{\text{RU-info}} + L^{\mathrm{usr}}_{\text{RU-info}}}{B_{sym}} \times 4\mu s = \frac{\overbrace{8i + 11}^{\text{Common field}} + \overbrace{21 \cdot \lceil M/N_{ch} \rceil + 10 \cdot \lceil \lceil M/N_{ch} \rceil /2 \rceil}^{\text{User specific field}}}{B_{sym}} \times 4\mu s. \quad (3)$$

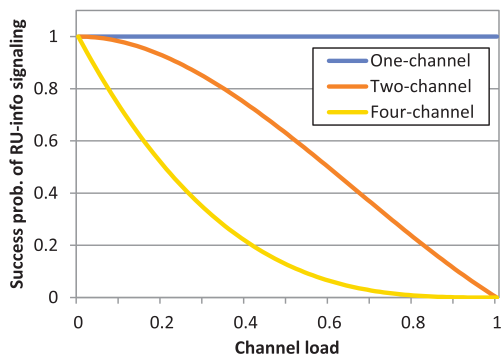
Fig. 7 shows the $T_{\text{RU-info}}$ of a 160 MHz frame at various MCSs in 802.11ax. As shown in the figure, $T_{\text{RU-info}}$ increases linearly as the number of served users of a frame increases and becomes as long as 280 μs for 136 users at MCS0. The lines however show step-wise increases because Eq. (3) includes ceilings.

B. WIDER-BAND TRANSMISSION (Signaling Success) PROBABILITY

Assume that the channel load ρ for each 20 MHz channel is an independent and identically distributed random variable interpreted as the probability that the channel is sensed busy.



(a) Airtime



(b) Signaling success probability

FIGURE 9. Airtime (MCS0) and signaling success probability of RU-info for a varying number of content channels (obtained in Eqs. (3) **and** (4)**, respectively).**

Given that a backoff process is completed, to make a wideband transmission, all the content channels of RU-info should be transmitted, and thus, the corresponding bandwidth should be idle. That is, the success probability of RU-info signaling, which we denote by p, is obtained as the probability that a transmitting station sees N_{ch} channels to be idle among all RU-info content channels. If $N_{ch} = 1$, RU-info signaling is guaranteed in the primary channel with probability one due to the backoff completion. For $N_{ch} = 2$, RU-info signaling succeeds if the channel next to the primary channel is idle, otherwise another pair of channels are idle; the probabilities of the cases are obtained as $1-\rho$ and $\rho(1-\rho)^2$, respectively. If $N_{ch} = 4$, all channels of P80 have to be idle for a success of RU-info signaling, thus leading to the success probability of $(1-\rho)^3$. Therefore, p is obtained as

$$p = \begin{cases} 1 & N_{ch} = 1 \\ (1-\rho) + \rho(1-\rho)^2 & N_{ch} = 2 \\ (1-\rho)^3 & N_{ch} = 4; \end{cases} \tag{4}$$

Both factors (signaling overhead and success probability) for a varying number of RU-info content channels are shown in Fig. 9. As expected, the airtime of RU-info decreases as RU-info is transmitted over more content channels; using four content channels results in 24% less airtime than using one channel. However, the success probability of RU-info signaling dramatically decreases with increasing content channels, especially for higher channel load. Since both factors highly affect the effective throughput, this observation implies that the RU-info signaling structure is the key to the success of wider-bandwidth transmission.

V. DESIGN OF ADAPTIVE RU-INFO CONSTRUCTION

We now design adaptive RU-info construction schemes to solve the problem formulated in the previous section.

The optimal balance of the tradeoff mainly depends on two conditions: the number of served users in a frame and the channel loads. Therefore, a potential solution is to adaptively construct RU-info content channels for these conditions. That is, a transmitting station monitors the conditions and accordingly determines the RU-info structure rather than using a fixed structure so that bandwidth exploitation is maximized while signaling overhead is minimized.

The determination of the candidate signaling structures still needs to meet the design constraints that the prior generation considered for affordable complexity, as we list below:

- *Maximum number of parallel content channels*: As the number of content channels for RU-info signaling increases, the signaling overhead decreases, however the receiving stations should be capable of decoding more content channels at the same time. An extreme case for minimum signaling overhead with 320 MHz bandwidth is to run a set of 16 content channels, requiring a station to be capable of concurrently decoding all of these channels, which is costly due to the increased complexity. We consider up to four content channels that correspond to 80 MHz bandwidth.
- *Bandwidth range of RU-info signaling*: A set of RU-info content channels can be repeated as a backup in another bandwidth to maximize the possibility that at least one set of content channels are transmitted successfully. Which set of content channels to decode is informed by the preamble as a puncturing mode, and each of the receiving stations should be able to readily tune to the corresponding bandwidth part. Therefore, more repetitions require a station to be capable of immediate tuning to farther bandwidth. We limit the repetitions of RU-info channels within P80 like 802.11ax. This restricts a station from tuning its receive chain beyond its P80 during the preamble reception.
- *Placement of RU-info channels*: In IEEE 802.11ax, a set of RU-info content channels are placed in a contiguous bandwidth so that a station needs to tune to the minimum bandwidth part at a certain time. We consider the same constraint in our design, i.e., contiguous placement of RU-info channels.

Under the abovementioned constraints, the following modes of the RU-info structure are available:[5]

- *One channel*: Full RU-info is delivered via a single 20 MHz channel. Despite having the largest signaling

[5]The three-channel mode can also be considered however cannot repeat a set of content channels by integer-multiple times within P80; thus, it is omitted.

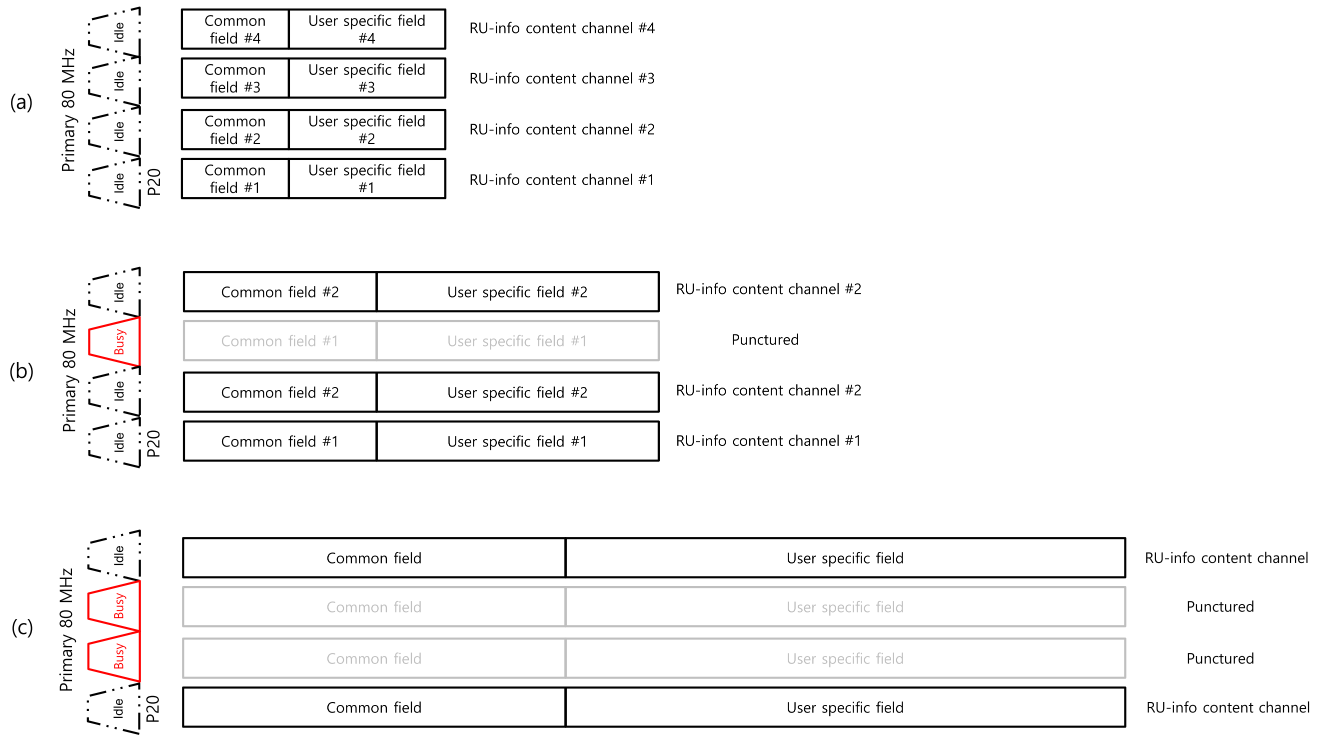


FIGURE 10. **Example operation cases of different RU-info signaling structure modes.**

overhead, RU-info signaling is always successful via P20, thus maximizing bandwidth utilization.

- *Two channels*: Same as 802.11ax, RU-info is delivered via two 20 MHz channels. This is a balanced choice between the other two modes in terms of both signaling overhead and success probability.
- *Four channels*: This mode minimizes the signaling overhead, however maximizes the signaling failure probability since the entire P80 should be idle for signaling and thus can be used under low channel loads.

When we make the signaling structure adapt to the channel loads (or bandwidth patterns), two different levels of adaptation can be considered:

- *Statistical adaptation*: According to the statistics of the channel loads, a transmitting station determines the signaling structure such that the success of signaling is maximized, without real-time construction or switching between different modes. However, it is possible that a preconstructed signaling structure does not fit the bandwidth pattern at the time of transmission, and thus wideband transmission is not enabled.
- *Opportunistic adaptation*: According to the CCA result immediately before transmission, a transmitting station identifies the bandwidth pattern and selects the signaling structure mode with minimal overhead and guaranteed signaling success. This outperforms statistical adaptation in terms of both wideband transmission successes and signaling overhead since the selected signaling structure is always that fitting the bandwidth pattern. This can be implemented in two ways: (1) real-time construction of a specific structure mode and (2) preconstruction of all or selected structure modes and real-time switching among them.

Fig. 10 illustrates the opportunistic adaptation of the RU-info signaling structure for three bandwidth patterns in P80. In Case (a), the entire P80 is idle; thus, RU-info is organized into four content channels to minimize the signaling overhead. In Case (b), P40 is idle while S40 is busy, so RU-info is organized into two content channels, which is the case of 802.11ax. The third 20 MHz channel is punctured, and receiving stations have to decode the RU-info channels of P40. In Case (c), none of the above conditions are met, and the whole RU-info is transmitted in P20 at the expense of long airtime. Puncturing the second and third 20 MHz channels is needed, however signaling of full RU-info is still performed. The fixed RU-info structure of 802.11ax consumes more airtime in Case (a) and results in a failure of wideband transmission in Case (c). As a result, the adaptation approach balances signaling overhead and wider-bandwidth exploitation.

The detailed procedure of the proposed adaptive RU-info construction scheme for a general set of RU-info structure modes denoted by $\mathcal{M}$ is given as a pseudocode in Algorithm 1 and described in the following. If the statistical adaptation is enabled and RU-info for a forthcoming transmission opportunity is preconstructed based on the statistics of channel loads (load-aware RU-info preconstruction scheme), a set of RU-info structure modes that are likely to succeed in signaling (eligible) is picked out of $\mathcal{M}$ and preconstructed as $\mathcal{M}_{el}$. The implementation details of this operation considered in our simulation is as follows; (1) the channel loads are obtained as per-channel busy probabilities (measured from

Algorithm 1 Adaptive RU-Info and Frame Construction

$\mathcal{C}$: Set of channels in the operation bandwidth
$N_{ch}(k)$: Number of content channels for RU-info mode k
$\mathcal{M}$: Set of available RU-info signaling structure modes
$\mathcal{M}_{el}$: Set of RU-info structure modes eligible for a given bandwidth pattern
$\mathcal{M}_{el} \leftarrow \mathcal{M}$
if load-aware preconstruction is enabled **then**
  for $l \in \mathcal{C}$ **do**
    if channel l is expected to be busy **then**
      for $k \in \mathcal{M}_{el}$ **do**
        if signaling of mode k fails for busy channel l **then**
          $\mathcal{M}_{el} \leftarrow \mathcal{M}_{el} - \{k\}$
        end if
      end for
      if load-aware bonding is enabled **then**
        Puncture channel l in a preconstructed frame
      end if
    end if
  end for
  Construct RU-info structures in $\mathcal{M}_{el}$
end if
if backoff is completed **then**
  Obtain the current bandwidth pattern via CCA
  for $k \in \mathcal{M}_{el}$ **do**
    if signaling of mode k fails for the bandwidth pattern **then**
      $\mathcal{M}_{el} \leftarrow \mathcal{M}_{el} - \{k\}$
    end if
  end for
  $k^* = \arg\max_{k \in \mathcal{M}_{el}} N_{ch}(k)$
  if a preconstructed frame is present **then**
    if the frame fits the bandwidth pattern **then**
      Apply RU-info mode k^* to the frame
    else
      Construct a frame using the primary channel only
    end if
  else
    Construct a data frame using RU-info mode k^* and puncture it according to the bandwidth pattern
  end if
  Transmit the constructed frame
end if

previous CCA results), (2) a bandwidth pattern is randomly generated based on the probabilities, (3) all RU-info structure modes that fit the bandwidth pattern are selected and preconstructed (more implementation details are given in Section VI.A). Likewise, if preconstruction of the entire data frame is additionally enabled (load-aware bonding scheme), a frame punctured for the randomly generated bandwidth pattern is constructed. If the opportunistic adaptation is used, the above preconstruction procedure is not needed. Upon completion of a backoff procedure, the station obtains the current bandwidth pattern via per-channel CCA, excludes noneligible modes, and selects the mode using the highest number of content channels among the remaining ones. If RU-info preconstruction is used, the exclusion of noneligible modes is from $\mathcal{M}_{el}$. Finally, the data frame to transmit is constructed using the selected mode and punctured according to the current bandwidth pattern. If a preconstructed RU-info/frame is present and does not fit the bandwidth pattern, only the primary channel is used for transmission.

TABLE 3. Simulation parameters.

Parameter	Value
Transmission bandwidth	20, 40, 80, 160, 320 MHz
Subcarriers of a RU	52
Number of RUs per 20 MHz	4
OFDM symbols for 20 MHz signaling	4 (16 us)
Number of stations per 20 MHz	4
MCS index for payload	1∼11
Spatial streams (per station)	4
Packet size	1000 bytes
Maximum aggregation size (per station)	64
Short interframe space (SIFS)	16 us
DCF interframe space (DIFS)	34 us
Slot time	9 us
Min. contention window size (CWmin)	15
Max. contention window size (CWmax)	1023

VI. PERFORMANCE EVALUATION

We evaluate and compare the performance of RU-info signaling modes and adaptation in the operation bandwidth of 320 MHz in various overlapping BSSs (OBSSs) deployment and traffic load conditions.[6] Two configuration scenarios are considered:

- *Homogeneous configuration scenario*: The same MCSs and traffic generation rates are configured for all stations.
- *Heterogeneous configuration scenario*: Randomly chosen MCSs and traffic generation rates are configured for individual stations.

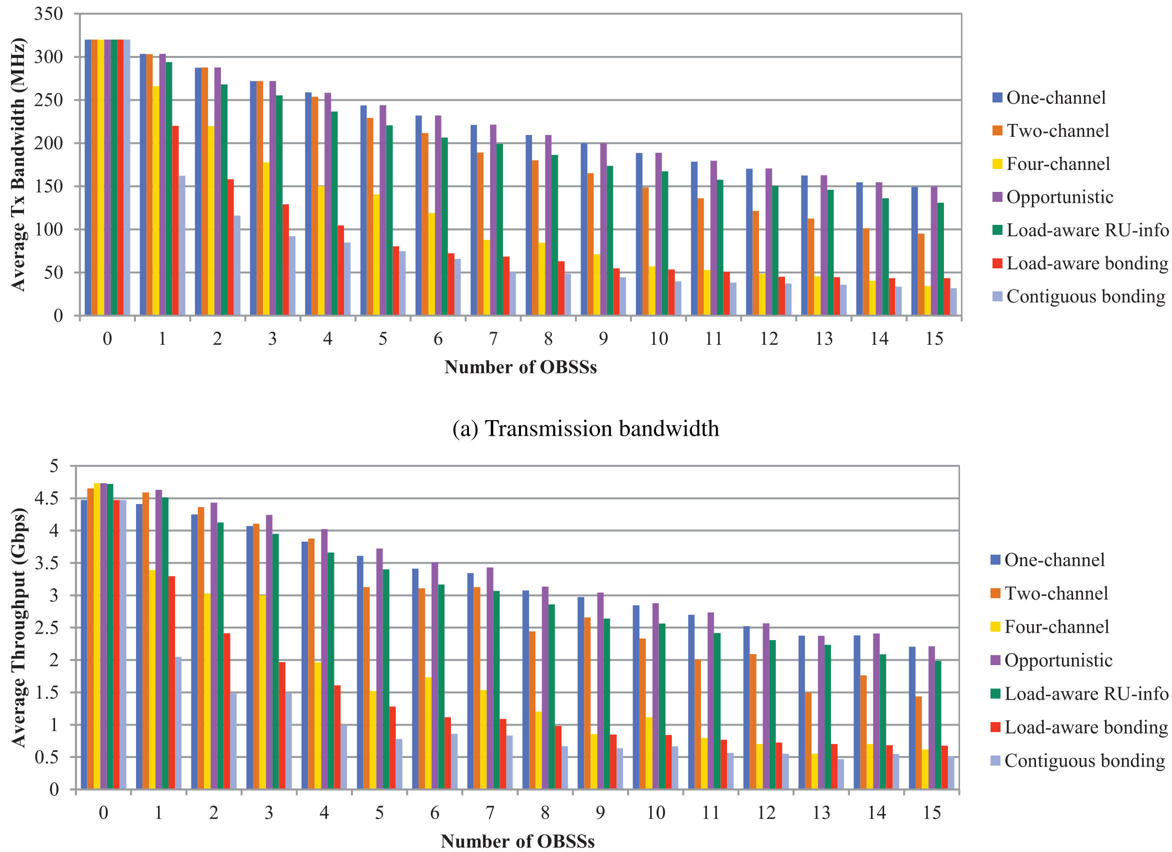
The simulation parameters are listed in Table 3. To focus on the impact of the RU-info structure, we assume that transmission failures are only caused by collision and all BSSs reside in each other's carrier sense range. We consider downlink transmission. Especially for the four-channel mode, we implement it to seek a contiguous bonding opportunity when signaling fails for alleviated performance degradation.

A. HOMOGENEOUS CONFIGURATION SCENARIO

First, we investigate how the throughput of a wider-bandwidth BSS is affected by a varying number of legacy single-channel (20 MHz) OBSSs. The wider-bandwidth AP is in a full-buffer state while each OBSS has a traffic rate of 50 Mbps. Legacy OBSSs are distributed randomly among 20 MHz channels. Each result point is an average of ten simulation runs.

Fig. 11 shows the average of the transmission bandwidth and system throughput at MCS7. As the number of OBSSs

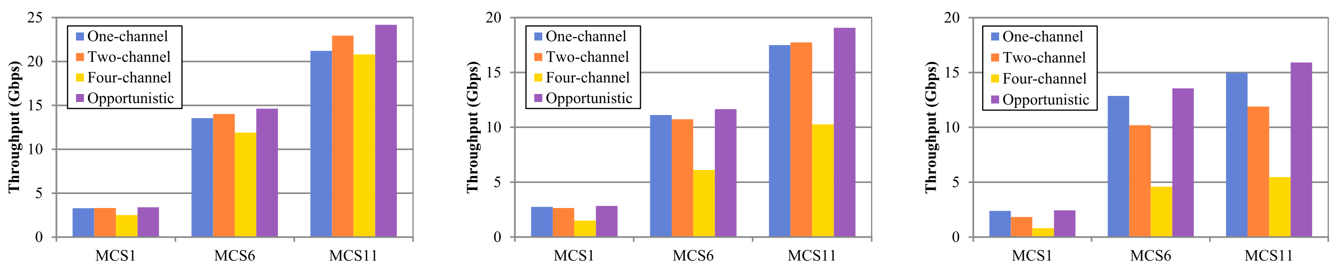
[6] We used a Matlab-based in-house simulator.



(a) Transmission bandwidth

(b) Throughput

FIGURE 11. Comparison of RU-info signaling variants for a varying number of OBSSs.



(a) OBSS load: 1 Mbps

(b) OBSS load: 10 Mbps

(c) OBSS load: 50 Mbps

FIGURE 12. Throughput comparison for varying traffic loads of OBSSs.

increases, the transmission bandwidth gets more probable that a part of the RU-info channels are occupied by OBSSs. Thus, among the RU-info structure modes, the four-channel mode has the fastest decreasing rate while the one-channel mode always achieves the highest transmission bandwidth. The two-channel mode is between them. The bandwidth utilization of the one-channel mode is the highest, however, its throughput is not always the best due to the signaling overhead and is even as low as the contiguous channel bonding for the number of OBSSs of zero as shown in Fig. 11(b) (the throughput of this mode is lower than that of the two-channel mode when the number of OBSSs is less than five). As a result, the trend of the throughput is similar to that of the transmission bandwidth but not exactly the same. The signaling overhead offsets the gain obtained from the extra utilization of frequency resources. If the MCS of the payload increases (it is expected to increase further in future generations including EHT), the impact of the RU-info overhead increases (as shown in Figs. 12 and 13). As such, the best RU-info structure mode depends on the population of OBSSs in the operation bandwidth. In the meantime, the opportunistic adaptation adapts to the environmental conditions

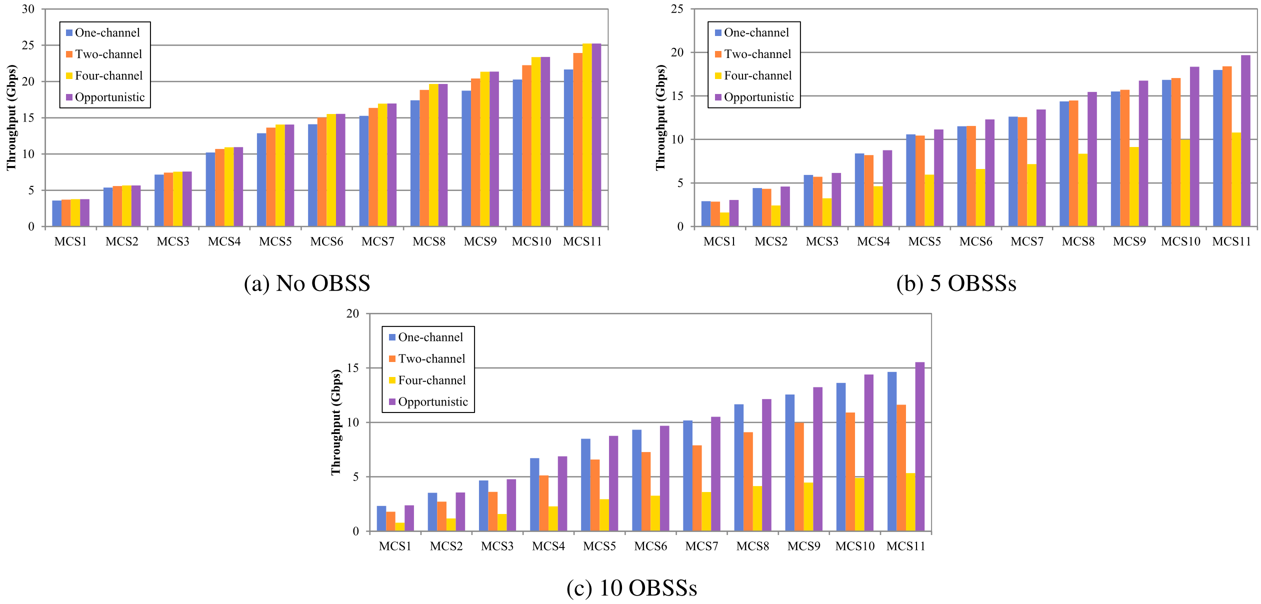


FIGURE 13. Throughput for different MCS.

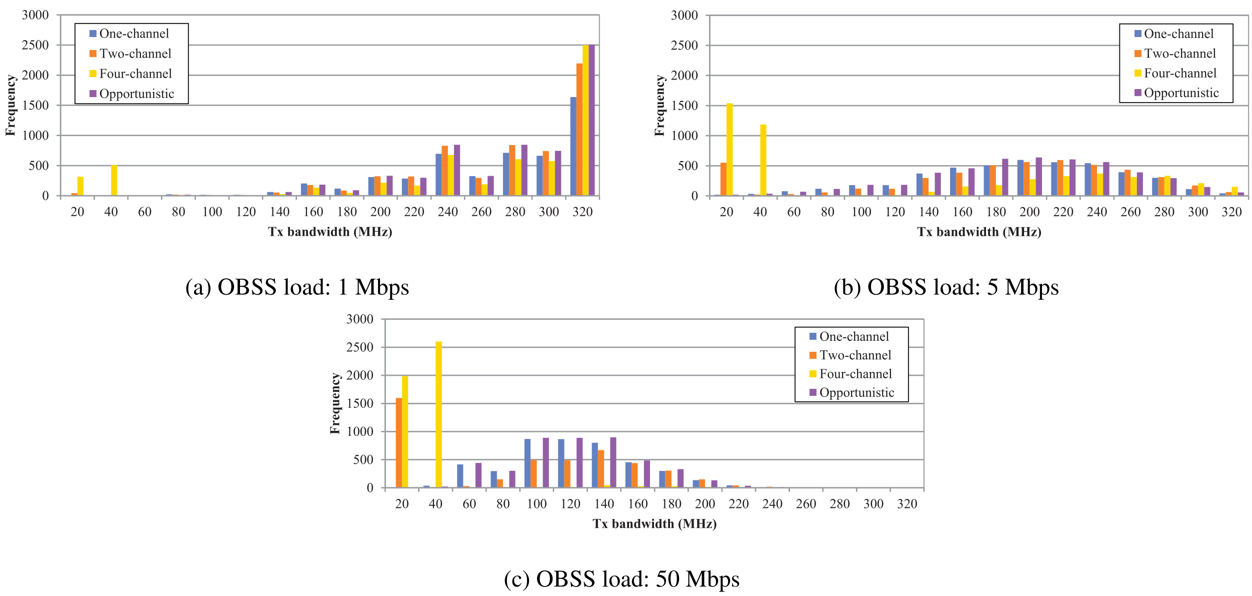


FIGURE 14. Tx bandwidth for random MCS, traffic generation rates.

and switches between modes, thus always achieving the best bandwidth and throughput at the same time (e.g., as the number of OBSSs increases, the opportunistic adaptation tends to more frequently use fewer content channels). The opportunistic adaptation achieves even higher throughput than the best-fixed mode since its selected mode is always optimal for every transmission while a fixed mode is not.

For evaluation of the statistical adaptation approach, the two versions of load-aware adaptation schemes—load-aware RU-info and load-aware bonding—are also considered for comparison in Fig. 11. In the simulation, these schemes estimate online the busy probability of each channel as the ratio of the CCA-busy occurrences of the channel among previous ten transmissions. The load-aware RU-info

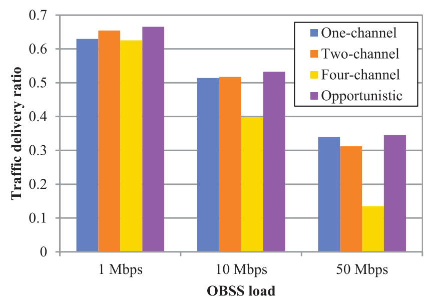
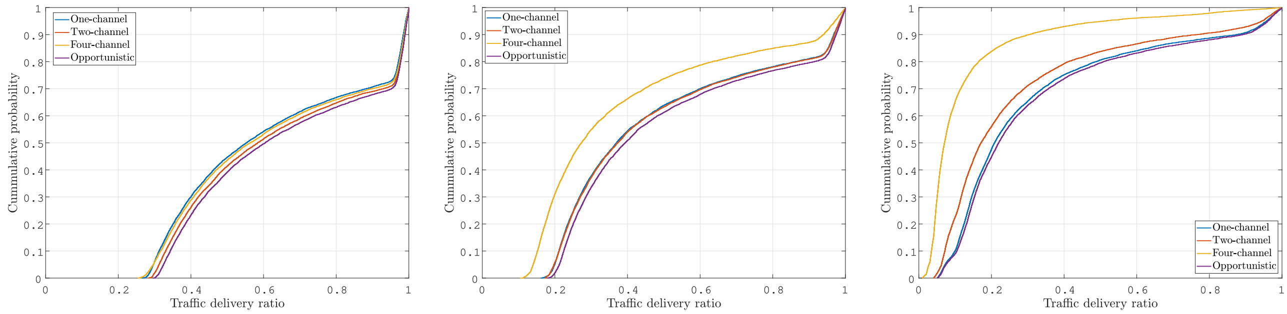


FIGURE 15. Mean traffic delivery ratio for different per-OBSS traffic generation rates in the heterogeneous configuration scenario.

scheme shows degradation in both transmission bandwidth and throughput compared to the opportunistic adaptation,



(a) OBSS load: 1 Mbps (b) OBSS load: 5 Mbps (c) OBSS load: 50 Mbps

FIGURE 16. CDFs of the per-station traffic delivery ratio in the heterogeneous configuration scenario; the per-OBSS traffic generation rate is specified.

but the degree of degradation is somewhat limited. This implies that, if realtime RU-info construction is not affordable, the load-aware preconstruction can also be considered as a solution. The load-aware bonding, however, does not work well, in particular in high-load conditions, approaching the contiguous bonding in the end. As expected, the contiguous channel bonding is shown to always achieve the lowest transmission bandwidth and throughput compared to all non-contiguous channel bonding methods. It is noted that the noncontiguous bonding uses the same channel access mechanism as the contiguous bonding. Therefore, the performance gain of the noncontiguous bonding over the contiguous bonding comes from better bandwidth utilization, not from aggressive behavior.

Next, we consider a varying traffic rate of OBSSs when there are 12 OBSSs within the operation bandwidth of the wider-bandwidth BSS, for a varying MCS of the wider-bandwidth AP. There are three type of OBSSs (four for each type) supporting 80, 40, and 20 MHz operation bandwidths. Within each 80 MHz bandwidth, three OBSSs, one for each type, are deployed, with each P20 being randomly selected. The wider-bandwidth AP is in a full-buffer state while the traffic rate of OBSSs varies in [1, 10, 50] Mbps. The observed trend of the throughput performance with increasing traffic rate of OBSSs shown in Fig. 12 is similar to that with increasing number of OBSSs shown in Fig. 11. When the traffic rate is as small as 1 Mbps, the two-channel mode achieves higher throughput than the one-channel mode because of lower signaling overhead. As the traffic load increases, however, a mode with fewer channels is better for RU-info signaling success and ultimately, for the traffic rate of 50 Mbps, the one-channel mode is the best among the fixed channel modes while the four-channel mode demonstrates as poor of a performance as contiguous channel-bonding (no puncturing). The two-channel mode balances the success probability and overhead of RU-info signaling on well on average however not at every moment, and thus, the opportunistic adaptation always achieves the highest throughput. The figure also shows that as the MCS of the wider-bandwidth AP increases the throughput gap between the opportunistic adaptation and the one-channel mode increases. This is because a higher MCS results in the shorter airtime of the payload and the higher percentage of the RU-info airtime within a frame; the one-channel mode has the longest airtime of RU-info among all modes, thus having the highest percentage of the RU-info airtime. The throughput trends for all MCSs of IEEE 802.11ax with a varying number of OBSSs are shown in Fig. 13, also showing that as MCS gets higher the throughput gap increases.

B. HETEROGENEOUS CONFIGURATION SCENARIO

In this scenario, traffic generation rates for individual stations are randomly chosen from one to 50 Mbps, and MCSs are also randomly chosen from MCS7 to MCS11. The number of legacy OBSSs is 12 with the traffic generation rates of 1, 5, and 50 Mbps. Since the traffic generation rates for stations are now heterogeneous, we evaluate the performance in terms of the traffic delivery ratio, which is obtained as the ratio of the achieved throughput to the generated traffic rate.

The frequency of transmissions using different transmission bandwidths is shown in Fig. 14. When the OBSS's traffic generation rate is 1 Mbps, all schemes under comparison tend to use larger bandwidths overall. However, the one-channel mode has a significantly lower frequency of the usage of 320 MHz. This results from its low transmission efficiency due to the longest airtime of RU-info, which makes both the wider-bandwidth BSS and OBSSs deliver less traffic and thus experience higher contention, leading to less opportunities of available wide bandwidths. The four-channel mode shows the high usages of 20 and 40 MHz because it requires the entire P80 to simultaneously be idle, which is less likely with OBSSs. Interestingly, when the OBSS's traffic generation rate is 5 Mbps, the four-channel mode uses 320, 300, and 280 MHz more frequently than the opportunistic adaptation. This is the opposite case of the one-channel mode for the OBSS's traffic generation rate of 1 Mbps explained above; the low channel usage of the four-channel mode makes OBSSs flush generated traffic better and results in higher availability of wide bandwidths.

The throughput results are shown in Fig. 15 for varying OBSS loads. When the OBSS traffic generation rate is as low as 1 Mbps, the one and four-channel modes achieve the worst performance, implying that both the RU-info airtime and the signaling success probability are the affecting factors of the performance in this OBSS load condition. The two-channel mode balances the factors in this condition. When the OBSS traffic generation rate increases to 10 and 50 Mbps, the signaling success probability becomes a more dominant factor and the four-channel mode significantly deteriorates in performance.

The cumulative distribution functions (CDFs) of the per-station traffic delivery ratio are shown in Fig. 16 for the OBSS traffic generation rates of 1, 10, and 50 Mbps. The CDFs show that the opportunistic adaptation outperforms all of the fixed modes for all stations. This finding implies that the opportunistic adaptation achieves a performance gain by efficiently utilizing available bandwidth patterns.

VII. CONCLUSION

In this paper, we illustrated the wideband operation of conventional IEEE 802.11 with the contiguous channel bonding rule and described how the new puncturing mechanism of IEEE 802.11ax facilitates higher bandwidth utilization. We demonstrated the challenges to wider bandwidth as a result of the fixed two-channel signaling structure of RU-info under the design of IEEE 802.11ax. In this regard, we investigated the tradeoff between signaling overhead and transmission bandwidth. After that, we demonstrated the solutions and benefits to balancing the tradeoff in either an opportunistic or a statistical manner to solve these challenges. Through comprehensive simulations, we showed the performance gains of the proposed solutions over fixed RU-info signaling structures in various network environments.

REFERENCES

[1] *Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2017–2022*, Cisco Syst., San Jose, CA, USA, Feb. 2019.

[2] *802.11 EHT Proposed Project Authorization Request*, IEEE Standard P802.11be PAR Rev.6, Mar. 2019.

[3] *Specification Framework for TGbe*, IEEE Standard P802.11be SFD Rev.8, Feb. 2020.

[4] D. Lopez-Perez, A. Garcia-Rodriguez, L. Galati-Giordano, M. Kasslin, and K. Doppler, "IEEE 802.11be extremely high throughput: The next generation of Wi-Fi technology beyond 802.11ax," *IEEE Commun. Mag.*, vol. 57, no. 9, pp. 113–119, Sep. 2019.

[5] *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications*, IEEE Standard 802.11, 2016.

[6] *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment Enhancements for High Efficiency WLAN*, IEEE Standard P802.11ax Draft 7.0, Sep. 2020.

[7] L. Deek, E. Garcia-Villegas, E. Belding, S.-J. Lee, and K. Almeroth, "The impact of channel bonding on 802.11 n network management," in *Proc. 7th Conf. Emerg. Netw. Exp. Technol. (CoNEXT)*, 2011, pp. 1–12.

[8] M. Park, "IEEE 802.11ac: Dynamic bandwidth channel access," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2011, pp. 1–5.

[9] O. Bejarano, E. Knightly, and M. Park, "IEEE 802.11ac: From channelization to multi-user MIMO," *IEEE Commun. Mag.*, vol. 51, no. 10, pp. 84–90, Oct. 2013.

[10] S. C. Yang, *OFDMA System Analysis and Design*. Norwood, MA, USA: Artech House, 2010.

[11] W. Wang, F. Zhang, and Q. Zhang, "Managing channel bonding with clear channel assessment in 802.11 networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2016, pp. 1–6.

[12] A. A. Alsufyani and K. H. Almotairi, "Design of an adaptive multi-channel algorithm in WLANs," in *Proc. 2nd Int. Conf. Comput. Appl. Inf. Secur. (ICCAIS)*, May 2019, pp. 1–6.

[13] J. Fang and I.-T. Lu, "Efficient channel access scheme for multiuser parallel transmission under channel bonding in IEEE 802.11ac," *IET Commun.*, vol. 9, no. 13, pp. 1591–1597, Sep. 2015.

[14] S.-S. Lee, T. Kim, S. Lee, K. Kim, Y. H. Kim, and N. Golmie, "Dynamic channel bonding algorithm for densely deployed 802.11ac networks," *IEEE Trans. Commun.*, vol. 67, no. 12, pp. 8517–8531, Dec. 2019.

[15] Y.-D. Chen, D.-R. Wu, T.-C. Sung, and K.-P. Shih, "DBS: A dynamic bandwidth selection MAC protocol for channel bonding in IEEE 802.11 ac WLANs," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2018, pp. 1–6.

[16] A. Zakrzewska and L. Ho, "Dynamic channel bandwidth use through efficient channel assignment in IEEE 802.11ac networks," in *Proc. IEEE 90th Veh. Technol. Conf. (VTC-Fall)*, Sep. 2019, pp. 1–6.

[17] S. Khairy, M. Han, L. X. Cai, Y. Cheng, and Z. Han, "Enabling efficient multi-channel bonding for IEEE 802.11ac WLANs," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2017, pp. 1–6.

[18] A. Zakrzewska and L. Ho, "Dynamic channel bandwidth use through efficient channel assignment in IEEE 802.11ac networks," in *Proc. IEEE 90th Veh. Technol. Conf. (VTC-Fall)*, Sep. 2019, pp. 1–6.

[19] S. Barrachina-Munoz, F. Wilhelmi, and B. Bellalta, "Online primary channel selection for dynamic channel bonding in high-density WLANs," *IEEE Wireless Commun. Lett.*, vol. 9, no. 2, pp. 258–262, Feb. 2020.

[20] P. Huang, X. Yang, and L. Xiao, "Dynamic channel bonding: Enabling flexible spectrum aggregation," *IEEE Trans. Mobile Comput.*, vol. 15, no. 12, pp. 3042–3056, Dec. 2016.

[21] S. Byeon, C. Yang, O. Lee, K. Yoon, and S. Choi, "Enhancement of wide bandwidth operation in IEEE 802.11ac networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2015, pp. 1547–1552.

[22] J. Fang and I.-T. Lu, "Efficient utilisation of extended bandwidth in 802.11ac with and without overlapping basic service sets," *Electron. Lett.*, vol. 50, no. 24, pp. 1884–1886, Nov. 2014.

[23] L. Deek, E. Garcia-Villegas, E. Belding, S.-J. Lee, and K. Almeroth, "Intelligent channel bonding in 802.11n WLANs," *IEEE Trans. Mobile Comput.*, vol. 13, no. 6, pp. 1242–1255, Jun. 2014.

[24] L. Deek, E. Garcia-Villegas, E. Belding, S.-J. Lee, and K. Almeroth, "Joint rate and channel width adaptation for 802.11 MIMO wireless networks," in *Proc. IEEE Int. Conf. Sens., Commun. Netw. (SECON)*, Jun. 2013, pp. 167–175.

[25] H. Qi, H. Huang, Z. Hu, X. Wen, and Z. Lu, "On-demand channel bonding in heterogeneous WLANs: A multi-agent deep reinforcement learning approach," *Sensors*, vol. 20, no. 10, p. 2789, May 2020.

[26] R. Karmakar, S. Chattopadhyay, and S. Chakraborty, "SmartBond: A deep probabilistic machinery for smart channel bonding in IEEE 802.11ac," in *Proc. IEEE Conf. Comput. Commun. (INFOCOM)*, Jul. 2020, pp. 2599–2608.

[27] O. Lee, J. Kim, and S. Choi, "WiZizz: Energy efficient bandwidth management in IEEE 802.11 ac wireless networks," in *Proc. 12th Annu. IEEE Int. Conf. Sens., Commun., Netw. (SECON)*, Jun. 2015, pp. 136–144.

[28] B. Bellalta, A. Checco, A. Zocca, and J. Barcelo, "On the interactions between multiple overlapping WLANs using channel bonding," *IEEE Trans. Veh. Technol.*, vol. 65, no. 2, pp. 796–812, Feb. 2016.

[29] S. Barrachina-Muñoz, F. Wilhelmi, and B. Bellalta, "To overlap or not to overlap: Enabling channel bonding in high-density WLANs," *Comput. Netw.*, vol. 152, pp. 40–53, Apr. 2019.

[30] S. Barrachina-Munoz, F. Wilhelmi, and B. Bellalta, "Dynamic channel bonding in spatially distributed high-density WLANs," *IEEE Trans. Mobile Comput.*, vol. 19, no. 4, pp. 821–835, Apr. 2020.

[31] M. Han, S. Khairy, L. X. Cai, Y. Cheng, and F. Hou, "Capacity analysis of opportunistic channel bonding over multi-channel WLANs under unsaturated traffic," *IEEE Trans. Commun.*, vol. 68, no. 3, pp. 1552–1566, Mar. 2020.

[32] S. Khairy, M. Han, L. X. Cai, Y. Cheng, and Z. Han, "A renewal theory based analytical model for multi-channel random access in IEEE 802.11ac/ax," *IEEE Trans. Mobile Comput.*, vol. 18, no. 5, pp. 1000–1013, May 2019.

[33] M. Peng, K. Zhang, and C. Kai, "Channel bonding based on game theory in dense WLANs," in *Proc. IEEE 11th Int. Conf. Commun. Softw. Netw. (ICCSN)*, Jun. 2019, pp. 263–267.

[34] A. Faridi, B. Bellalta, and A. Checco, "Analysis of dynamic channel bonding in dense networks of WLANs," *IEEE Trans. Mobile Comput.*, vol. 16, no. 8, pp. 2118–2131, Aug. 2017.

[35] M.-S. Kim, T. Ropitault, S. Lee, and N. Golmie, "A throughput study for channel bonding in IEEE 802.11ac networks," *IEEE Commun. Lett.*, vol. 21, no. 12, pp. 2682–2685, Dec. 2017.

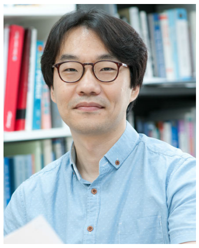
[36] M. Yazid and A. Ksentini, "Stochastic modeling of the static and dynamic multichannel access methods enabling 40/80/160 MHz channel bonding in the VHT WLANs," *IEEE Commun. Lett.*, vol. 23, no. 8, pp. 1437–1440, Aug. 2019.

[37] L. H. Vu and J.-H. Yun, "Adaptive self-deferral for carrier aggregation of LTE-LAA with RF power leakage in unlicensed spectrum," *IEEE Access*, vol. 7, pp. 89292–89305, Jul. 2019.

[38] L. H. Vu and J.-H. Yun, "Power leakage-aware multi-carrier LBT for LTE-LAA in unlicensed spectrum," in *Proc. IEEE Int. Symp. Dyn. Spectr. Access Netw. (DySPAN)*, Oct. 2018, pp. 1–10.

[39] L. H. Vu and J.-H. Yun, "Multi-carrier listen before talk with power leakage awareness for LTE-LAA in unlicensed spectrum," *IEEE Trans. Cognit. Commun. Netw.*, vol. 5, no. 3, pp. 678–689, Sep. 2019.

SANGHYUN KIM (Member, IEEE) is currently pursuing the Ph.D. degree with the Department of Electrical and Information Engineering, Seoul National University of Science and Technology (SeoulTech), Seoul, South Korea. His current research focuses on wireless networks in unlicensed spectrum.



JI-HOON YUN (Member, IEEE) received the B.S. degree in electrical engineering from Seoul National University (SNU), Seoul, South Korea, in 2000, and the M.S. and Ph.D. degrees in electrical engineering and computer science from SNU, in 2002 and 2007, respectively.

In 2012, he was with the Department of Computer Software Engineering, Kumoh National Institute of Technology, as an Assistant Professor. He was a Postdoctoral Researcher with the Real-Time Computing Laboratory, The University of Michigan, Ann Arbor, MI, USA, in 2010, and a Senior Engineer with the Telecommunication Systems Division, Samsung Electronics, Suwon, South Korea, from 2007 to 2009. He is currently an Associate Professor with the Department of Electrical and Information Engineering, Seoul National University of Science and Technology (SeoulTech), Seoul, South Korea. His current research focuses on mobile networking and computing.