AP Coordination and Full-duplex enabled Multi-band Operation for the Next Generation WLAN: IEEE 802.11be (EHT)

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***Abstract*—Proliferating networking demands require the wireless local area networks (WLANs) to keep evolving. In May 2019, the IEEE 802 standards committee formally established the working group of the next generation WLAN: IEEE 802.11be. To satisfy the ultra-high definition video traffic and achieve the objective of extremely high throughput (EHT), multi-band operation (MB-Opr) is considered as one important technology. However, after deep analysis, simply adapting MB-Opr is not enough for the extremely high throughput requirements of IEEE 802.11be. This paper analyzes the possible schemes of AP coordination and full-duplex enabled MB-Opr, where AP coordination is also one key technology introduced by IEEE 802.11be. After that, we propose a MAC framework for AP coordination and full-duplex enabled MB-Opr that fits for all types of device capabilities. This framework is general enough that it has high scalability and good backward and forward compatibility. The simulation results confirm the performance advantages of proposed MAC framework and show that multi-band aggregation (MBA) and multi-band channel bonding (MBCB) outperform IEEE 802.11ax in throughput by 200% and 80.7%, respectively.**

I. Introduction

Wireless local area network (WLAN), together with cellular network, has become the dominant kind of wireless networks [1]. It is probable that the upcoming generation WLAN: IEEE 802.11ax will be released in early 2020 [2], [3], [4]. The key objective of IEEE 802.11ax is to significantly improve the network efficiency, so IEEE 802.11ax is also called high efficiency WLAN (HEW). Proliferating data demand requires wireless network to achieve increasingly high throughput. Ultra-high definition video and its related applications, such as 8K video and virtual reality, require extremely high throughput of next generation wireless networks [5], [6]. Therefore, in the past year, both academia and industry have begun to focus on the key technology of the next generation WLAN of IEEE 802.11ax, i.e. beyond IEEE 802.11ax. Consequently, the IEEE 802 standards committee formally established the working group of IEEE 802.11be in May 2019 [7]. The key objective of IEEE 802.11be is to extremely improve the maximum throughput of WLAN, so IEEE 802.11be is also called extremely high throughput (EHT) WLAN.

To achieve extremely high throughput, one of the most important technology introduced by IEEE 802.11be is multi-band operation (MB-Opr), which enables the access points (APs) and stations (STAs) to work in multiple frequency bands including 2.4GHz, 5GHz and newly introduced 6 GHz, simultaneously [8], [9]. The technical details of MB-Opr need to be fully studied and further designed. For example, multi-band channel bonding (MBCB), multi-band aggregation (MBA), and multi-band coordination (MBC).

However, just simply adapting MB-Opr is not enough for the extremely high throughput requirements of IEEE 802.11be. On the one hand, high-dense deployment is the target scenario of the next generation WLAN. It means a large number of APs and STAs are deployed in a limited geographical area, resulting in serious interference and collisions if without coordinations among APs. More seriously, MB-Opr such as MBCB exacerbates these problem since interferences and collisions become more serious and more likely to occur when APs and STAs work in very large bandwidth. On the other hand, full-duplex communications theoretically doubles the communication capacity and is becoming increasingly mature. Thus, introducing full-duplex communication is an important enabler for the next generation wireless networks [10].

Facing to the goal of extremely high throughput, this paper proposes AP coordination and full-duplex enabled multi-band operation for the next generation WLAN: IEEE 802.11be. It is worth noting that AP coordination is also an important key technology introduced by IEEE 802.11be [11]. Specifically, this paper firstly investigates the technical objective and the key technology of IEEE 802.11be. After that, This paper analyzes the possible schemes of AP coordination and full-duplex enabled MB-Opr. After that, we propose a MAC framework for AP coordination and full-duplex enabled MB-Opr that fits for all types of device capabilities such as MB-Opr only, AP coordination enabled MB-Opr, full-duplex enabled MB-Opr, and both AP coordination and full-duplex enabled MB-Opr. This framework is general enough that it has high scalability and good backward and forward compatibility. The simulation results confirm the performance advantages of proposed MAC framework and show that MBA and MBCB outperform single-band scheme in throughput by 200% and 80.7%, respectively.

The contributions of this paper are summarized as follows:

- To the best of our knowledge, this is the first work to thoroughly analyze the key technology and carefully design the MAC scheme for the multi-band operation of IEEE 802.11be since IEEE 802.11be task group was just established in May 2019.
- To the best of our knowledge, this paper is the first work to propose a MAC framework by introducing AP coordination and full-duplex to efficiently complement MB-Opr. The proposed framework is general and flexible that supports several kinds of detailed schemes. It is worth noting that both MB-Opr and AP cooperation are two key technologies introduced by IEEE 802.11be, and this paper proposes a framework to combine both of them.
- This paper evaluates the performance of AP coordination and full-duplex enabled MB-Opr by simulations and verifies the performance advantages.

The rest of this article is organized as follows. In Section II, the target scenario, technical objective and the key technology of IEEE 802.11be are analyzed and discussed. Several possible schemes of AP coordination and full-duplex enabled MB-Opr are discussed in Section III. In Section IV, we propose the MAC framework of AP coordination and full-duplex enabled MB-Opr for the next generation WLAN: IEEE 802.11be. Performance evaluation is presented in Section V. This paper is summarized in Section VI.

II. Introduction of IEEE 802.11be

A. Target Scenario of IEEE 802.11be

Video traffic has gradually become the dominant traffic of the Internet. According to Ericsson's report, video business will account for 60% of the total Internet business in 2018, and the volume of video business will increase by 34% annually, up to 74% in 2024 [12]. Therefore, the target traffic of IEEE 802.11be is ultra-high definition video traffic and its related applications such as 4K/8K online video transmission, virtual reality, and augmented reality. Moreover, in recent years, mobile Internet promotes the emergence of stringent real-time delay requirements, such as online game, real-time wireless medical, and wireless officing [13]. Thus, IEEE 802.11be also needs to support the stringent real-time delay traffic.

B. Technical Objective of IEEE 802.11be

To efficiently support the ultra-high definition video traffic scenario and stringent real-time delay traffic scenario, IEEE 802.11be is required to provide the maximum MAC layer throughput of at least 30 Gbps. It also needs to guarantee the reliability, latency and jitter of the stringent real-time delay traffic. Moreover, IEEE 802.11be is operated in the 2.4GHz, 5GHz, and 6GHz frequency bands. Consequently, IEEE 802.11be needs to guarantee the backward compatibility and coexistence with the legacy IEEE 802.11 versions, e.g., IEEE 802.11a/b/g/n/ac/ax.

C. Standardization Roadmap of IEEE 802.11be

The standardization roadmap of IEEE 802.11be [14] is shown in Fig. 1. In July 2018, IEEE 802.11 standard committee established a study group named extremely high throughput study group (EHT SG) aiming to beforehand study the application scenarios, technical objectives and key technology of EHT. After full study, the Project Authorization Request (PAR) document was released in May 2019 [7], which represents the establishment of the IEEE 802.11be Task group (TGbe). After the completion of specification framework document (SFD) in 2021, the Draft version 0.1, 1.0, 3.0 and 5.0 of IEEE 802.11be will be released in November 2020, May 2021, November 2022 and November 2023 respectively. The final revision of IEEE 802.11be standard amendment is expected to be released in May 2024.

D. Overview of Key Technology of IEEE 802.11be

To efficiently support the target scenarios and achieve the technical objectives, IEEE 802.11be introduces several key technologies, or named technical features. We classify these features into four directions:

1) The physical layer (PHY) capability enhancements

PHY capability is a direct and fundamental factor affecting the maximum throughput. To enhance the maximum throughput, bandwidth in frequency domain and stream number in spatial domain are two important aspects of PHY capability. Therefore, two features are introduced in IEEE 802.11be PAR:

- Frequency domain. IEEE 802.11be tries to introduce 320MHz channel bonding (CB) and further improves the non-contiguous CB. Noting that IEEE 802.11ac and IEEE 802.11ax can only use 160MHz for transmission at most. Furthermore, 6GHz is a new band for IEEE 802.11be (and IEEE 802.11ax), so to efficiently use 6GHz band is quite important for the EHT requirements.
- Spatial domain. IEEE 802.11be tries to introduce 16 spatial streams to further improve the communication capacity comparing with 8 spatial streams in IEEE 802.11ax. Moreover, MIMO technology needs to be improved to adapt to large spatial stream number.

Furthermore, although not mentioned in the PAR document, we believe some new modulation technologies such as 4096-QAM are suggested to be considered in IEEE 802.11be.

2) Multi-band operation (MB-Opr)

Multiple frequency bands including 2.4GHz, 5GHz, and 6GHz are available for IEEE 802.11be. This means that IEEE 802.11be devices can use multiple bands to enjoy WiFi services at the same time. But, how to fully use multi-band and how to design the technical details of multi-band operation are quite important.

3) Multi-AP coordination

IEEE 802.11ax introduced spatial reuse to improve the area throughput of multiple basic service sets (BSSs). However, without efficient interference management and control, SR can not obtain its advantages, but will bring serious inter-BSS interference, thus deteriorating the performance of the

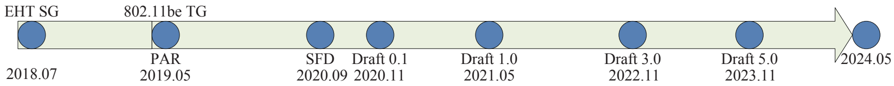


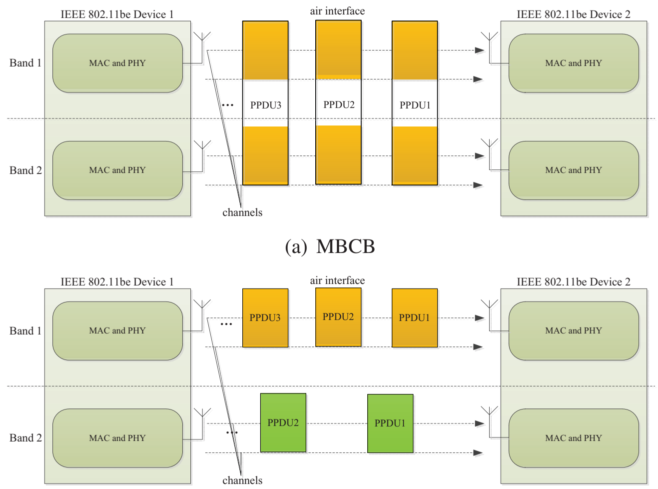
Fig. 1. Standardization roadmap of IEEE 802.11be.

whole network. Therefore, IEEE 802.11be tries to introduce multi-AP coordination to exactly manage the interferences and guarantee the area throughput.

4) Transmission reliability enhancements

Aiming to guarantee the quality of services (QoS) and quality of experiences (QoE) of stringent real-time delay traffic scenario, transmission reliability enhancement is one basic technical point. IEEE 802.11be tries to introduce new retransmission technology such as hybrid automatic repeat quest (HARQ). It is worth noting that it may be the first time to use HARQ for IEEE 802.11.

The MAC layer technologies are quite important and complicated which need to be studied carefully. Therefore, to achieve extremely high throughput, the primary technical objective, we in this paper focus on MB-Opr and try to combine multi-AP coordination as well as full-duplex with MB-Opr to efficiently improve the throughput of IEEE 802.11be. We believe full-duplex is also an promising technology for IEEE 802.11be.



(a) MBCB

(b) MBA

Fig. 2. Principle of MB-Opr.

III. AP COORDINATION AND FULL-DUPLEX ENABLED MB-OPR

A. IEEE 802.11be Device Capability Description

IEEE 802.11be introduces MB-Opr and AP coordination, while full-duplex is also an important capability that significantly increases the maximum throughput. Considering cost and complexity, different devices have different capabilities, and thus different MAC processes are required. We divide the device capability into five types: no MB-Opr, MB-Opr only, MB-Opr with AP coordination, MB-Opr with full-duplex, and AP coordination and full-duplex enabled MB-Opr. This paper does not focus on the no MB-Opr type because this type is the same as legacy devices such as IEEE 802.11ax. In the following subsections, we analyze the features of different device capabilities. In the next section, we propose a unified MAC framework for all the device capabilities.

B. MB-Opr without AP Coordination and Full-duplex enabled MB-Opr

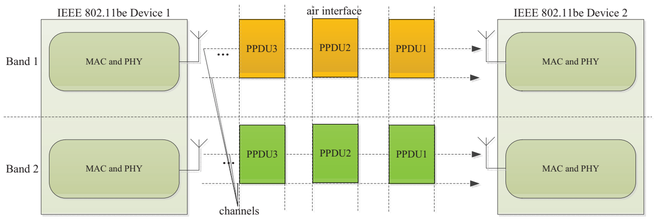
If the IEEE 802.11be only has MB-Opr capability, there are two possible schemes.

1) MBCB: MBCB scheme directly extends channel bonding of traditional IEEE 802.11. In legacy IEEE 802.11, several $20MHz$ channels can be combined into a larger bandwidth, $40MHz$, $80MHz$, and $160MHz$, to transmit one PHY protocol data unit (PPDU). Noting that all the bonded channels are located in one frequency band such as $5GHz$. In IEEE 802.11be devices, to achieve extremely high throughput, it is allowed to bond channels from different bands such as $5GHz$ and $6GHz$, thus further larger bandwidth can be used for transmission such as $80MHz + 80MHz$, and $160MHz + 160MHz$. The principle can be depicted by Fig. 2(a).

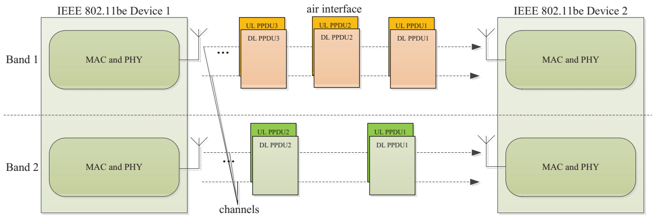
2) MBA: MBA scheme enables IEEE 802.11be devices to transmit and receive PPDUs in multiple bands independently. In this case, the devices send PPDUs in each band rather than constructing one unified PPDU by bonding multi-band. Compared with MBCB, MBA scheme has more flexibility. In fact, a series of technical details need to be studied for MBA. For example, is it allowed multiple bands to support same or different traffic streams? How to address entities in multiple bands? How to design the BSS Management solutions? *and etc.* The principle can be depicted by Fig. 2(b).

C. MB-Opr with Full-duplex

We extend the terminology "full-duplex" into two types: out-of-band full-duplex and in-band full-duplex, where in-band full-duplex is also known as full duplex. Out-of-band full-duplex is easier to implement than in-band full-duplex. If the IEEE 802.11be devices have the out-of-band full-duplex capability, Two adjacent frequency bands can perform MBA independently as shown in Fig. 2(b). Otherwise, either MBA cannot be used, or it is necessary to ensure that multiple bands are sent or received simultaneously, as shown in Fig. 3(a). If the IEEE 802.11be devices have the in-band full-duplex capability, APs and STAs can transmit and receive simultaneously in each band, which significantly improves the maximum throughput, as shown in Fig. 3(b). Obviously,



(a) MB-Opr without out/in-band full-duplex.



(b) MBA with in-band full-duplex

Fig. 3. Principle of full-duplex enabled MB-Opr.

whether out-of-band full-duplex or in-band full-duplex, the MBCB is always applicable.

D. MB-Opr with AP Coordination

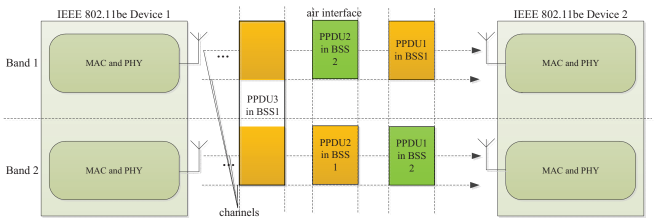


Fig. 4. Principle of AP coordination enabled MB-Opr.

IEEE 802.11be introduces the coordinations between APs. This significantly avoids interferences among BSSs. As shown in Fig. 4, during each transmission opportunity, multiple APs could coordinate with each other to optimize scheduling and multi-band resource allocation in order to obtain the better area throughput.

E. MB-Opr with AP Coordination and Full-duplex

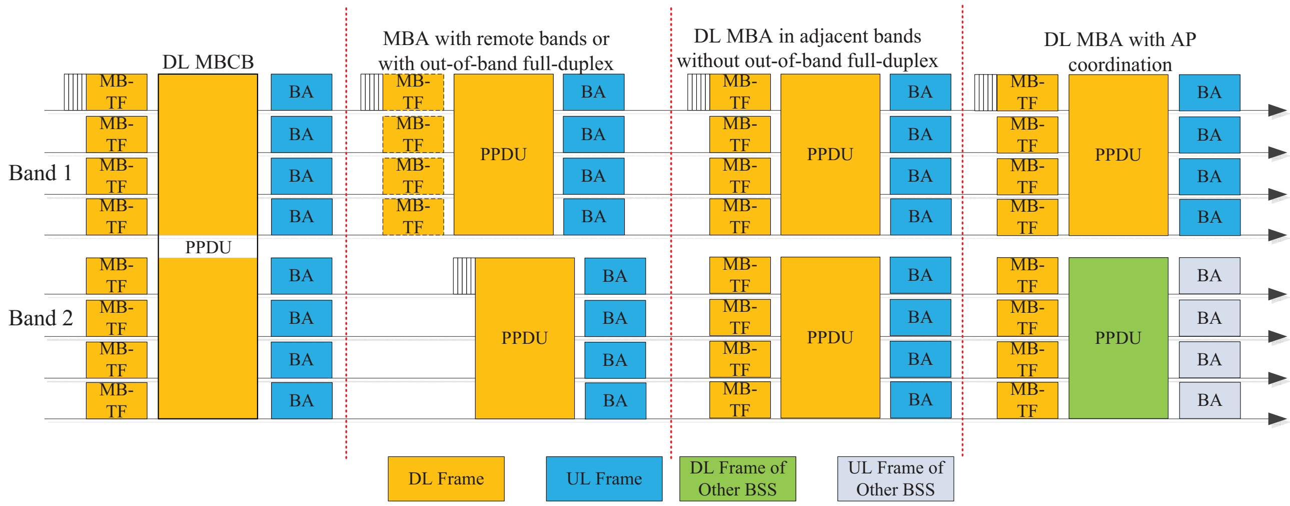
The AP coordination and full-duplex enabled MB-Opr can obtain both advantages of full-duplex and AP coordination, and also further brings greater flexibility. On the other hand, this type requires the highest cost and implementation complexity. There are two research methods. The first one named "one-fit-one" is to study the MAC protocol and frame format of each capability type separately such as MBCB, MB-Opr in adjacent bands without out-of-band full-duplex, MB-Opr with AP coordination, *and ect*. Its advantages lie in its simplicity and directness, but its disadvantage lies in its great challenge to scalability and backward/forward compatibility of IEEE 802.11. The second one named "one-fit-all" is to study a MAC framework that supporting all types of capability. Its advantages lie in great scalability and backward/forward compatibility of IEEE 802.11, while its disadvantage lie in the design difficulties. In this paper, based on our rich experiences on the MAC protocol and algorithm design in IEEE 802.11, we propose a general MAC framework for MB-Opr with different capabilities of IEEE 802.11be.

IV. MAC Framework of AP Coordination and Full-duplex Enabled MB-Opr

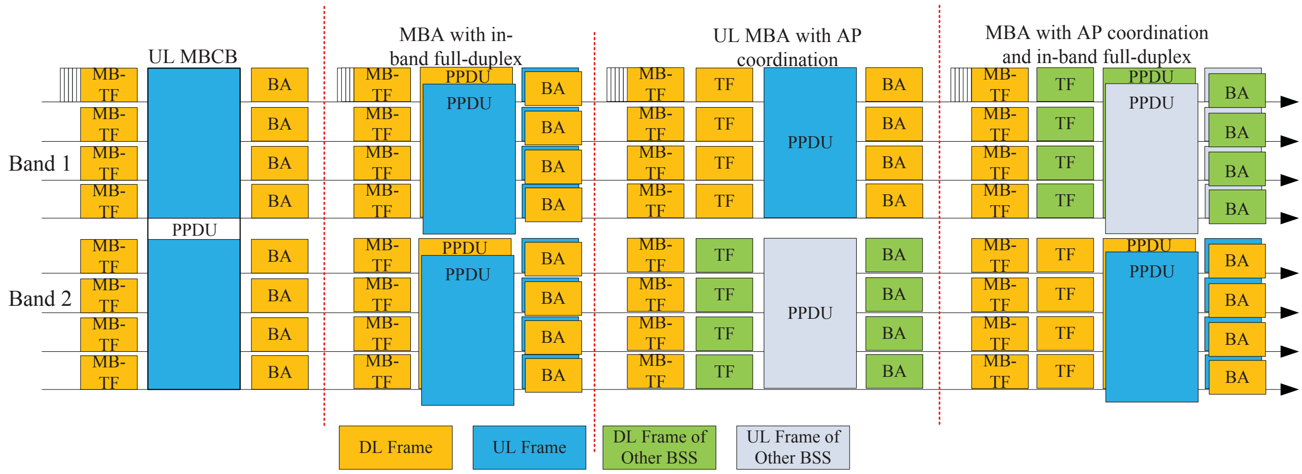
Since the introduction of MB-Opr in IEEE 802.11be involves the cooperation of MAC and PHY between multiple bands, it brings significant complexity to MAC protocol. The introduction of full-duplex and AP coordination technology makes this problem more serious. MAC protocol is quite important for IEEE 802.11be. This section proposes a unified MAC framework for AP coordination and full-duplex enabled MB-Opr.

As shown in Fig. 5, the channel access and transmission are unified in one MAC framework for all types of device capabilities in IEEE 802.11be. The proposed MAC framework starts with trigger frame (TF), which is specified in IEEE 802.11ax. Fig. 5(a) depicts the downlink (DL) process. It is worth noting that channel protection and bandwidth negotiation are out of the scope of this paper.

- DL MBCB. In the channel access phase, AP performs the backoff procedure in the primary channel in one band according to legacy IEEE 802.11, and PIFS carrier sensing is adopted for the other channels in the same band or different bands. After AP finishes backoff, it sends multi-band TF (MB-TF) to STAs. Then, AP sends MBCB PPDU to STAs. Finally, STAs reply with block acknowledgement (BA) to AP in every transmitted channel by using duplicated method.
- MBA with remote bands or with out-of-band full-duplex. In this case, both AP and STA can work in different band independently. Naturally, both AP and STAs perform channel access and transmission in different bands independently, even one band for UL transmission and other band for DL transmission simultaneously. The legacy IEEE 802.11 based transmission procedure as shown in band 2 of Fig. 5(a) and the MB-TF based transmission procedure as shown in band 1 of Fig. 5(a) are both applicable.
- DL MBA in adjacent bands without out-of-band full-duplex. In this case, sending in one band will seriously suppress the receiving in other bands. Thus, the sending and receiving status of multi-bands should be synchronized. After AP completes backoff, it sends MB-TF to STAs, and then sends one PPDU in every band at the same time. Finally, STAs reply with BA in every channel. More importantly, uplink (UL) transmission in this case is similar, which is no need to further provide a figure because of the space limitation.
- DL MBA with AP coordination. In this case, the primary AP sends MB-TF to secondary AP and allocate the band resource to multiple APs. After that, each AP send PPDU



(a) DL framework.



(b) UL & UL+DL framework

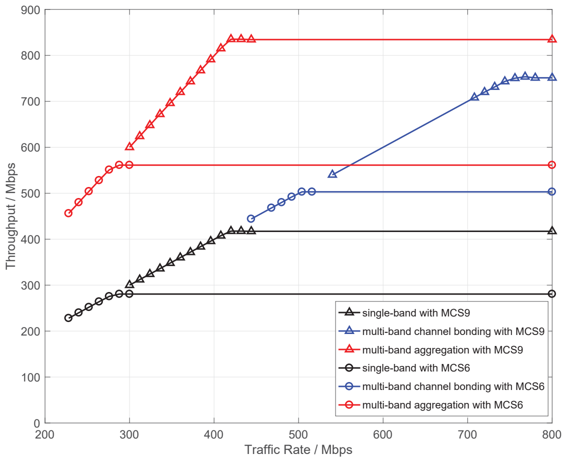
Fig. 5. MAC framework for AP coordination and full-duplex enabled MB-Opr.

in specific band according to the resource allocation. It is also allowed one AP to use channels from more than one band or partial of one band.

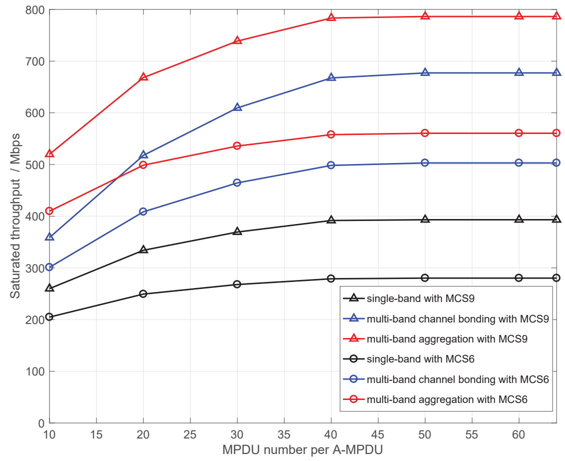
Fig. 5(b) depicts the UL and UL+DL process.

- UL MBCB. In this case, after AP sending MB-TF, STAs send UL MBCB PPDU and then AP replies with duplicated BA in every channels.
- MBA with in-band full-duplex. In this case, the MB-TF contains the resource allocation information of both UL and DL transmissions. Then, AP send DL PPDU in each band while STA also transmit UL PPDU in each band simultaneously. After that, both AP and STA send BA in each band. Self-interference canceling (SIC) needs to be used for both AP and STA to decode the signals.
- UL MBA with AP coordination. Comparing with DL process, this case needs another TF that is similar to the TF in IEEE 802.11ax to assign resources in own BSS. The primary AP sends MB-TF containing the resource allocation for multiple APs. After that, both primary AP and secondary AP need to send TF to allocate resource for own STAs in their allocated band. Then, STAs from multiple BSS send UL PPDU in allocated band. Finally, AP replies with BA.
- UL MBA with AP coordination and in-band full-duplex. This case is similar with the UL MBA with AP coordination case, the difference lies in that the resource allocation information include both UL and DL allocation results while full-duplex transmissions are supported.

We highlight that this paper proposes a MAC framework to all types of AP coordination and full-duplex enabled MB-Opr. This framework is general enough that it has high scalability and good backward/forward compatibility. Moreover, it is worth noting that this paper just proposed a MAC framework, a series of technical details need to design in the future.



(a) Throughput performance with traffic rate.



(b) Saturated throughput performance with aggregated MPDU number.

Fig. 6. Performance evaluation results.

V. Performance Evaluation

In this section, we deploy some simulations to evaluate the performance of MB-Opr. The maximum throughput is the most important metric of IEEE 802.11be. Thus, to easily get the maximum throughput of WLAN system, we set one BSS with only one AP and one STA. The area is a square of $20m \times 20m$, where AP is located in the geographical center while STA is randomly distributed in the BSS. Burst traffic is adopted. The simulation parameters are shown in Tab. I, and all the parameter values are set according to IEEE 802.11ax. To evaluate the performance, we compare three schemes: MBA, MBCB, and singe-band scheme. We improved our previously designed IEEE 802.11ax integrated simulation platform [15], [16] to deploy the simulations.

TABLE I
Simulation Parameter Settings

Parameter	Value
Access categories	Best Effort (AC_BE)
Packet size of each MDPU	$1500 Bytes$
Short inter frame space (SIFS)	$16\mu s$
Distributed inter frame space (DIFS)	$34\mu s$
Arbitration inter-frame space (AIFS)	$43\mu s$
Minimum contention window (CW_{min})	15
Minimum contention window (CW_{max})	1023
Single-band bandwidth	$80MHz$
Multi-band bandwidth	$80MHz + 80MHz$
Modulation and coding scheme (MCS)	HE MCS9 and HE MCS6
Guard interval (GI)	$0.8\mu s$
Channel code rate	$5/6$
Channel Model	large-scale fading
Maximum MPDU number per A-MPDU	64
Number of spatial streams (NSS)	1

Fig. 6(a) depicts the throughput performance varying with traffic rate. It can be observed that the throughput of single-band scheme is the lowest among three schemes. The reason is natural that the single-band scheme has the most narrow bandwidth. With the increase of traffic rate, the throughput of all schemes increases first and then stabilizes, because each scheme has experienced the process from unsaturated to saturated. For the same MCS, for example MCS9, MBA and MBCB outperform single-band scheme in throughput by 200% and 80.7%, respectively. We explain this results from two aspects. On the one hand, MBA enables the MAC and PHY of each band to work independently, thus the throughput can be twice as high as that of single-band scheme. On the other hand, although MBCB also utilizes multi-band for transmission, it requires MAC and PHY to be correlated among multiple bands. For example, the carrier sensing and backoff process are correlated. More importantly, since the maximum aggregation MPDU number is fixed, MBA aggregates twice as many MDPUs as MBCB in one time transmission because MAC is independent for MBA. It can be expected that the throughput of MBCB will approach that of MBA as the number of aggregated MPDUs increases. Finally, for the same scheme, the throughput of MCS9 is higher than that of MCS6.

Fig. 6(b) depicts the saturated throughput performance varying with aggregated MPDU number. We also obtain that the saturated throughput of single-band scheme is the lowest among three schemes. With the increase of aggregated MPDU number, the throughput of all schemes increases first and then stabilizes because the MAC efficiency keeps increasing. When the aggregated MPDU number is 64, for MCS9, MBA and M-BCB outperform single-band scheme in saturated throughput by 200% and 70.9%, respectively.

VI. Conclusion

Ultra-high definition video traffic is the key feature of future wireless networks which requires extremely high throughput of the next generation WLAN. IEEE 802.11be that is considered as the next generation WLAN working group was formally established in May 2019. MB-Opr is one of the most important features of IEEE 802.11be to achieve the objective of extremely high throughput. However, simply adopting MB-Opr without other technologies assisted is not enough. This paper introduces AP coordination and full-duplex to MB-Opr, analyzes the possible schemes, and proposes a MAC framework of AP coordination and full-duplex enabled MB-Opr. The proposed MAC framework is general enough that fits all possible schemes. It has high scalability and backward and forward compatibility. The simulations confirm the performance advantages of proposed MAC frame. The simulation results show that the performance of proposed MAC frame work and confirm that MBA and MBCB outperform single-band scheme in throughput by 200% and 80.7%, respectively. The future work includes the technical detail designs of the MAC protocol, and the scheduling algorithm.

ACKNOWLEDGMENT

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