Mobile Networks and Applications (2020) 25:1765–1780
https://doi.org/10.1007/s11036-020-01567-7

Survey and Perspective on Extremely High Throughput (EHT) WLAN — IEEE 802.11be

Mao Yang[1] · Bo Li[1]

Published online: 16 June 2020

Abstract

The IEEE 802.11ax for Wireless Local Area Network (WLAN), one of the most important wireless networks, will be released in 2020. In recent years, ultra-high definition video service and real-time applications attract increasing attention. Therefore, the next generation WLAN (beyond IEEE 802.11ax): IEEE 802.11be task group (TGbe) was formally established in 2019, which regards achieving extremely high throughput (EHT) as its core technical objective. This article investigates and analyzes the key technologies of IEEE 802.11be, and further provides our perspectives and insights on it. Specifically, this article gives a brief overview on IEEE 802.11be, including the target scenario and technical objective, key technologies overview, and the standardization process. After that, we further investigate, analyze and provide perspectives on the key technologies of IEEE 802.11be including multi-band operation, multi-AP coordination, enhanced link reliability, and latency & jitter guarantee. To the best of our knowledge, this is the first work to investigate, analyze and provide insights on IEEE 802.11be.

Keywords Wireless local area networks · IEEE 802.11be · WiFi · Extremely high throughput · Low Latency

1 Introduction

Wireless traffic demands have been continuously increasing. Ericsson's latest mobility report shows that from 2020 to 2024, the mobile traffic will grow by 30 percent compound annual growth rate (CAGR) [1]. Wireless local area network (WLAN) is one of the most important and popular wireless networks. Cisco's statistics shows that the traffic carried by WiFi was accounted for 43 percent of global IP traffic in 2017, and the ratio will rise to 51 percent by 2022 [2]. Thus, both industry and academia focus on the evolving technical features and standardization of WLAN. IEEE 802.11ax or named high-efficient WLAN (HEW), considered as WiFi 6, will be released in 2020 [3–6].

Improving maximum throughput is the most important evolving goal of wireless networks including cellular network and WLAN for a long time. Especially in recent years, the throughput requirements of wireless services are becoming increasingly stringent. For example, the emergence of 4K/8K video, virtual reality (VR), augmented reality (AR), mobile cloud computing, and other services in recent years poses great challenges to the throughput of WLAN. Therefore, before the formal release of IEEE 802.11ax, industry and academia immediately regard extremely high throughput as the core technical objective of the new generation WLAN. In May 2019, the IEEE 802.11be Task Group (TGbe) was established [7]. The IEEE 802.11be is named as extremely high throughput (EHT) WLAN, probably considered as WiFi 7.

To achieve the technical objective, IEEE 802.11be introduces a series of key technologies. We classify them as five classes: physical layer (PHY) enhancements, multi-band operation, multi-AP coordination, enhanced link reliability, and latency & jitter guarantee [8]. Physical layer enhancements include larger bandwidth such as $320MHz$ and $240MHz$, multiple input multiple output (MIMO) enhancement such as 16 spatial streams, new tone-plan, new preamble puncture method, and etc. Multi-band operation enables the access points (APs) and non-AP stations (STAs

✉ Mao Yang
yangmao@nwpu.edu.cn

Bo Li
libo.npu@nwpu.edu.cn

[1] School of Electronics and Information, Northwestern Polytechnical University, Xi'an, Shaanxi, People's Republic of China

for short in the sequel) to simultaneously work in multiple bands in order to fully use the frequency resources. Multi-AP coordination enables the cooperation among APs so that the "win-win" situation can be achieved. Enhanced link reliability tries to further improve the link adaptation and to introduce some new technologies such as the hybrid automatic repeat quest (HARQ). Latency & jitter guarantee means IEEE 802.11be aims to improve the worst case latency feature to satisfy the real-time applications such as online game and VR.

Since the TGbe has just been established, the research of these key technologies is still in the preliminary stage of exploration. Therefore, this article investigates and analyzes the key technologies of IEEE 802.11be, and further provides our perspectives and insights on it. Specifically, this article gives a brief overview on IEEE 802.11be, including the target scenario and technical objective, key technologies overview, and the standardization process. After that, we further investigate, analyze and provide perspectives on the key technologies of IEEE 802.11be including multi-band operation, multi-AP coordination, enhanced link reliability, and latency & jitter guarantee in detail. The investigation and analysis contain the progress of standardization, academia solutions, and our perspectives. To the best of our knowledge, this is the first work to fully investigate, analyze and provide insights on IEEE 802.11be.

The structure of this article is summarized as follows. Section 2 provides a brief overview of IEEE 802.11be. Sections 3–6 investigate and analyze multi-band operation, multi-AP coordination, enhanced link reliability, and latency & jitter guarantee, respectively. Finally, Section 7 concludes this article.

2 Brief overview of IEEE 802.11be

2.1 Target scenario and technical objective

Video traffic is the dominant traffic type of Internet and mobile Internet at present and in the near future. Video traffic accounted for 60 percent of all mobile traffic in 2018, and this proportion is expected to reach 74 percent in 2024 [1]. Especially in recent years, the demands for ultra-high definition video such as 4K and 8K have become increasingly intense, thus it can be predicted that ultra-high definition video traffic will become the killer scenario of the next generation wireless network [9, 10].

Furthermore, real-time application has emerged in recent years and attracts increasing attention [11]. For example, VR, AR, wireless video meeting, online games and mobile cloud computing are typical cases of real-time applications. Especially, some applications like VR and AR require both high speed and low latency. These kinds of services require the network not only to provide extremely high throughput, but also to guarantee low latency (especially worst case latency and deterministic latency) and jitter. This puts forward very stringent requirements and challenges for wireless networks.

Therefore, the ultra-high definition video traffic and real-time traffic are the target scenarios of IEEE 802.11be. To efficiently support the target scenarios, the key technical objective of IEEE 802.11be is to achieve extremely high throughput (at least 30Gbps) and to improve the worst case latency and jitter.

2.2 Key technologies of IEEE 802.11be

IEEE 802.11be focuses on a series of technical enhancements of PHY and media access control (MAC) layer, including PHY enhancements, multi-band operation, multi-AP coordination, enhanced link reliability, and latency & jitter guarantee.

2.2.1 PHY enhancements

The enhancement of PHY technology is the most direct means to improve throughput. Among them, the expansion of resource domain capability and the improvement of modulation mode are the main methods. For frequency domain, IEEE 802.11be intends to extend the maximum transmission bandwidth from 160MHz to 320MHz (240MHz is also an optional) [12–14]. Besides, we should rethink and re-design the tone-plan [15–17] and the preamble puncture scheme [18–20]. For spatial domain, IEEE 802.11be intends to increase the maximum number of spatial streams from 8 to 16 [21, 22]. Then, adopting multiple resource units (RUs) per STA is one important enhancement for IEEE 802.11be since only one RU can be used for each STA in IEEE 802.11ax. Moreover, the PHY protocol data unit (PPDU) format should be re-designed to support a series of new capabilities. For example, in recent months, the TGbe passed a motion to introduce universal signal field (U-SIG)—containing version-independent signal field (SIG) and version-dependent signal field (SIG)—and EHT SIG, which is quite different to the IEEE 802.11ax and older versions. Finally, multi-band operation, HARQ and other MAC layer protocols also require to improve the PHY technologies.

In addition to the above mentioned candidate PHY technologies discussed in TGbe, we believe that the following PHY technologies are also possible candidates. In terms of modulation mode, we consider higher order modulation such as 4096 quadrature amplitude modulation (4096-QAM) as a possible candidate technology. In the early 2020, TGbe also pays attention to 4096-QAM. Moreover, full-duplex communication technology can significantly improve throughput, thus we believe that full-duplex communication can also help achieve the goal of extremely high throughput.

It is worth noting that considering that most of the PHY enhancements of IEEE 802.11be belong to engineering technology, and in addition, due to the limited space, the following sections will not analyze the physical layer technology in detail. Readers can track TGbe's proposals on PHY to get the latest progress.

2.2.2 Multi-band operation

The IEEE 802.11be operates between 1 and 7.250 GHz. Specifically, IEEE 802.11be supports three bands: 2.4GHz, 5GHz and 6GHz. More importantly, IEEE 802.11be intends to introduce multi-band operation [23–26]. The core idea is that either AP or STAs can work in multiple bands at the same time. Efficient operations among multiple bands are introduced. Therefore, AP and STAs can use multiple band resources efficiently and dynamically, thereby achieving the goal of improving throughput and guaranteeing delay. Multi-link operation is the most important features of multi-band Operation that will be detailed in Section 3.

2.2.3 Multi-AP coordination

In order to improve area throughput, IEEE 802.11ax introduces spatial reuse technology. However, due to the lack of coordination between APs, the interference in multi-AP scenarios becomes more serious and uncontrollable. Thus, IEEE 802.11be intends to introduce multi-AP coordination technology by enabling multiple APs to exchange information, coordinate and serve STAs consistently, so as to optimize network performance from a more global perspective [27–32]. Section 4 investigates and analyzes multi-AP coordination in detail.

2.2.4 Enhanced link reliability

Since WLAN works in unlicensed band and adopts carrier sense multiple access with collision avoidance (CSMA/CA) method based on random contention, the state and quality of communication links are constantly changing, and the reliability of links is difficult to be guaranteed. Traditional WLAN uses link adaptation technology to dynamically adjust transmission rate and ARQ technology to deal with transmission failure. In order to further take into account both transmission efficiency and link reliability, IEEE 802.11be intends to introduce HARQ technology [33–37]. It is worth noting that although HARQ has been adopted in cellular networks for years, it is the first time that HARQ has been introduced into WLAN. Section 5 investigates and analyzes enhanced link reliability in detail.

2.2.5 Latency & jitter guarantee

WLAN's lack of support for delay and jitter has been criticized for a long time, which is also an important shortcoming restricting the development of WLAN. Therefore, IEEE 802.11be pays attention to the support of delay and jitter, and intends to introduce at least one mode to improve the performance of worst case delay and jitter [38–42]. Section 6 investigates and analyzes latency & jitter guarantee in detail.

2.3 Standardization roadmap of IEEE 802.11be

The standardization roadmap of IEEE 802.11be [43] is shown in Fig. 1. Before the formal establishment of the working group, the IEEE 802.11 Standards Committee first established the EHT Study Group (SG) in 2018. After thorough research and discussion of EHT SG, with the output of PAR files, the IEEE 802.11be Working Group (TGbe) was established in May 2019. Specification framework document (SFD) documentation is expected to start in 2020, and draft version 1.0 of IEEE 802.11be in 2021 will be completed. After that, it is expected that draft 3.0 and 5.0 will be completed in 2022 and 2023, respectively. Finally, it is planned to officially release IEEE 802.11be in May 2024. It can be seen that the current research of IEEE 802.11be and its key technologies is in progress.

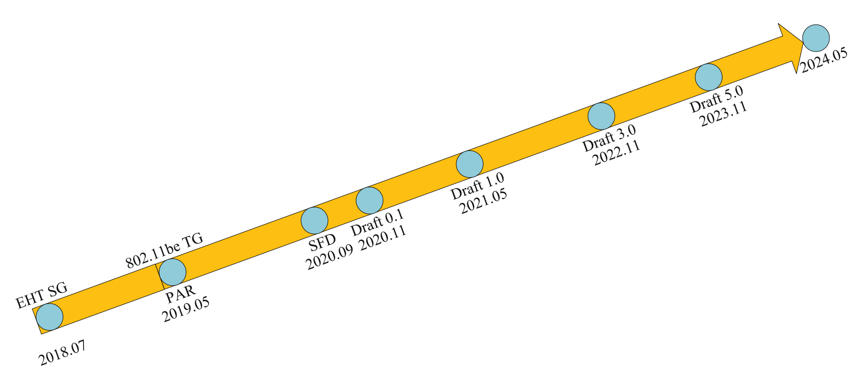


Fig. 1 Standardization Roadmap of IEEE 802.11be

In early 2020, TGbe reaches a consensus that the standardization process will be divided into two phases, thereby publishing two releases. The technologies in Phase 1 include multi-link operation, wider band such as 320MHz and 240MHz, 4096-QAM, multiple RUs per STA, and some easy designed AP coordination scheme, while other features will be studied in Phase 2.

Table 1 shows the key technologies and their phases.

3 Multi-band operation

Table 1 summarizes the different types of AP coordination.

3.1 Standards progress introduction

IEEE 802.11be operates in several bands, including 2.4 GHz, 5 GHz and the newly introduced 6 GHz. The APs and STAs of IEEE 802.11be can install multiple radios, thus enabling APs and STAs to work simultaneously on multiple bands. In fact, only one radio can also support multi-band capability, as long as the interference between adjacent bands can be eliminated sufficiently well, which is out of the space of this article. It is worth noting that it is not new to allow multiple bands to work at the same time. Legacy IEEE 802.11 has also been supported. However, the proposed multi-band capability of IEEE 802.11 is different from the multi-band capability supported by legacy IEEE 802.11.

3.1.1 Flow-level and packet-level multi-link aggregation

First of all, it is necessary to introduce the concept of "link", which refers to the communication link that can send and receive frames. Often a link corresponds to a radio frequency (RF) link. Different links can work on one band or on multiple bands, thus the concept of multi-link is a little broader than multi-band. Without special explanation, the following text will no longer distinguish between multi-band and multi-link.

IEEE 802.11be allows a logical multi-link (ML) device (MLD) to consist of a series of physical entities. As shown in the Fig. 2, a logical AP MLD consists of multiple APs, and the logical non-AP MLD (STA MLD for short in this paper) consists of multiple non-AP STAs. Different from legacy IEEE 802.11, the ML function of IEEE 802.11be proposes that only one entity connecting to the upper layer (such as the network layer), while the ML function of legacy IEEE 802.11 has several independent entities connecting to the upper layer. In other words, legacy IEEE 802.11's ML function is equivalent to several relatively independent APs or STAs encapsulated in one device.

As shown in Fig. 2, flow-level multi-link operation means that an AP or STA can allocate its multiple traffic streams to different links, but flow-level multi-link operation does not allow data frames from one traffic stream to be migrated to other links unless a complex processes named fast session transfer (FST) is adopted. Packet-level multi-link operation refers to that an AP or STA can dynamically transfer any of its frames to different links. This means that data frames belonging to the same traffic stream can be flexibly hosted on different links. Even as shown in the Fig. 2, if the transmission of the one frame (frame 4) fails on one link, the retransmission process can be arranged on another link. Similarly, the block acknowledgement (BA) corresponding to the transmission in one link can be sent in other links. Obviously, packet-level multi-link operation is more flexible and can further improve system performance, but more complex MAC control is needed.

Generally, there are two types of ML aggregation named synchronous and asynchronous aggregation. Wherein the synchronous ML aggregation means the different links

Table 1 Key technologies of IEEE 802.11be

Features	Detailed technologies	Phase
PHY Enhancements	Wider bandwidth such as 320MHz and 240MHz	Phase 1
	Tone plan, preamble, and PPDU format	Phase 1 and maybe Phase 2
	Multiple RUs per STA	Phase 1
	4096-QAM	Phase 1
	16 spatial streams	Phase 2
Multi-band operation	A series of schemes for multi-link operation	Phase 1
	Other technologies such as multi-band discovery	Phase 1 and maybe Phase 2
AP coordination	co-BF, co-JT, co-SR, co-TDMA, and etc.	Phase 2 and maybe Phase 1
Enhanced Link Reliability	HARQ and other potential technologies	Phase 2
Latency & Jitter Guarantee	Time-sensitive network (TSN) and other potential technologies	Phase 2
Others	Other potential technologies	Phase 2

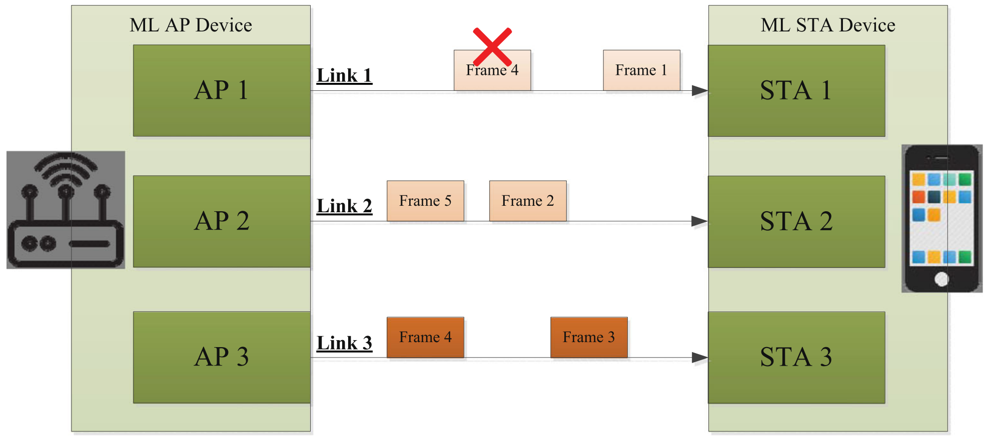


Fig. 2 Multi-band/multi-link aggregation of IEEE 802.11be

should simultaneously transmit and simultaneously receive. This type is more suitable for the APs or STAs who cannot support simultaneous transmission and reception, named non-STR capability, due to the adjacent channel interference problem. The asynchronous ML aggregation means different links can transmit and receive independently, named STR capability enabled.

A special case of synchronous ML aggregation refers to aggregating the bandwidth of multiple bands into a larger bandwidth to transmit only one PPDU. For exapmle, see PPDU 5 in Fig. 3, sender aggregates the bandwidth of multiple bands into a larger bandwidth (e.g. 320MHz) and sends only one PPDU in this larger bandwidth. This mode is similar to channel bonding (CB). The normal mode of ML aggregation is to send independent PPDUs on multiple bands, e.g. PPDU 1 & 2 as well as PPDU 3 & 4 in Fig. 3.

3.1.2 Multi-band management

Management function is an important function of IEEE 802.11, which affects the availability and efficiency of WLAN. IEEE 802.11be introduces more fine-grained multi-band operation, thus it will involve how to efficiently interoperate between multiple bands, such as multi-band scanning, multi-band association, multi-band authentication, multi-link setup and update, exchange status information, rapid traffic stream migration, and etc.

3.2 Investigation of possible technologies

To the best of our knowledge, there are few studies on multi-band operation in WLAN system. Our latest work in [8] directly faces to IEEE 802.11be and concludes that only introducing multiple bands without elaborate designs can hardly achieve the expected gain. After that, we describe several possible schemes of multi-band operation and investigate the feasibility of combining full-duplex with multi-band operation. Furthermore, we propose a unified MAC framework to support all possible multi-band operation with/without full duplex, i.e., one-fit-all. Specifically, the master AP sends an improved trigger frame (TF) which has been specified in IEEE 802.11ax to trigger the coordination between APs and/or schedule the resources between APs and STAs. This MAC framework can not only support all types of multi-band operation presented in the standard proposals, but also support AP coordination assisted and full-duplex assisted multi-band operation proposed in this study.

The authors in [44] propose a lower frequency band, i.e., 2.4GHz and 5GHz, assisted mmWave frequency transmission scheme. Operating in the 2.4/5GHz, if one

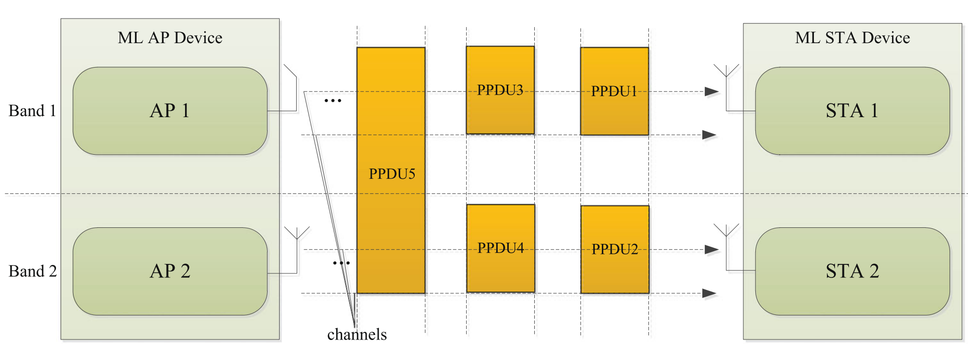


Fig. 3 Synchronous ML aggregation of IEEE 802.11be

STA is aware that its peer STA has been located in the same mmWave BSS, it will switch to mmWave to deploy the further data transmission process. In this case, the transmission capability is high since mmWave WLAN possesses much larger bandwidth. Furthermore, the overhead in mmWave WLAN such as beam scanning and neighbor discovery can be mitigated.

In [45], the authors consider the multi-band assembled WLAN system, wherein each band corresponds to one independent MAC layer. They formulate a resource allocation problem and further propose a packet scheduling algorithm in upper layer in order to minimize the transmission delay and the reorder delay.

3.3 Perspectives and open issues

1) Fast ML scanning, association, setup, and update

   Because the AP or STA of IEEE 802.11be can work in three bands at the same time, it contains lots of available channels (each channel has a bandwidth of 20 MHz). STA needs to scan the channel before it associate with one BSS, thus it will bring great challenges and costs for scanning and association. How to scan and association more efficiently becomes an important issue. After that, if STA needs to associate with each link independently, it will increase the overhead when setting up the ML relationship between AP and STAs. Therefore, how to efficiently associate and setup the ML relationship and keep fine backward compatibility is also an important issue. Finally, the ML relationship between AP and STAs may need to be updated caused by some reasons such as link ability update and link to traffic identifier (TID) mapping rule change.

2) Channel Access for synchronous and asynchronous ML operation

   If sending and receiving data packets in multiple links independently, the channel access problem is relatively simple. However, in many cases, multiple links are needed to coordinate with each other to perform channel access procedure. For example, if one PPDU needs to be sent by aggregating multiple bands, or if multiple links need to send and receive at the same time, we need to design a specific channel access method. Furthermore, if self-interference occurs between multiple adjacent links, i.e. non-STR scenario, the problem becomes more challenging.

3) Transmission Problem

   For packet-level ML operation, the frames from the same traffic stream can be sent in multiple links, even one frame can be retransmitted in other links. In this case, the acknowledgement policy and the reordering scheme need to be designed. Meanwhile, the packet allocation algorithm should be carefully designed.

4) ML Power Save

   Introducing multiple links significantly improves the maximum throughput, but it also results in high power consumption. If the power efficiency problem is not effectively solved, the quality of user experience will become worse. Therefore, IEEE 802.11be needs to find an efficient way to improve the power efficiency.

4 Multi-AP coordination

4.1 Standards progress introduction

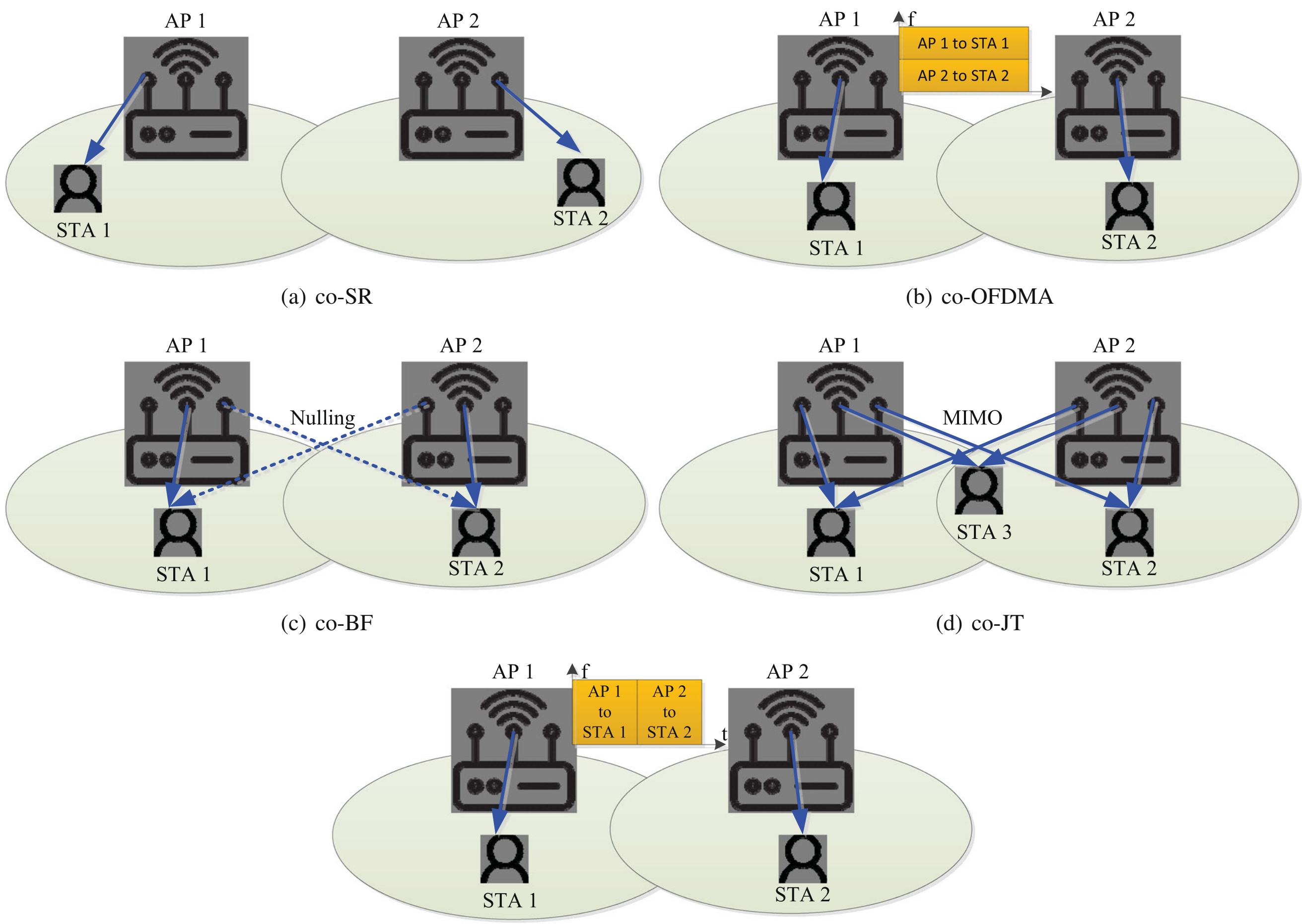
IEEE 802.11be intends to introduce multi-AP coordination so that the network resources can be used more orderly and optimally. So far, five multi-AP coordination schemes have been proposed by IEEE 802.11be proposals, which are described as follows.

4.1.1 Coordinated spatial reuse (co-SR)

As shown in Fig. 4a, co-SR refers to the downlink (DL) transmission or scheduling of uplink (transmission) to their own STAs on the same channel through information exchange and negotiation between multiple APs. Since co-SR does not use joint MIMO, there is interferences between multiple links. In order to suppress the interference, the interaction information between APS is needed to ensure that the interference between the two links is acceptable. For example, as shown in the Fig. 4a, AP1 sends DL data to STA1 on its left side, while AP2 sends data to STA2 on its right side. The interference between the two links is light, thus the data of both links can be successfully received.

4.1.2 Coordinated OFDMA (co-OFDMA)

UL and DL OFDMA was introduced by IEEE 802.11ax [46]. As shown in Fig. 4b, co-OFDMA refers to a master AP that successfully accesses the wireless channel coordinates with other APs called slave AP and allocates frequency resources among them. After that, both master AP and slave AP send DL data or schedules UL transmission simultaneously by using OFDMA. Each AP occupies a part of resource units (RU). The advantage of co-OFDMA is that there is no interference in theory before multiple links. As shown in Fig. 4b, AP sends data in RU 1 to STA 1 while AP 2 sends data in RU 2 to STA 2 by using OFDMA simultaneously.



(a) co-SR (b) co-OFDMA (c) co-BF (d) co-JT (e) co-TDMA

Fig. 4 Multi-AP coordination of IEEE 802.11be

4.1.3 Coordinated beamforming (co-BF)

As shown in Fig. 4c, co-BF refers to a master AP that successfully accesses the wireless channel coordinates with other slave APs. After that, both master AP and slave AP send DL data to their own STAs by using MIMO. As shown in Fig. 4c, AP 1 and AP 2 serve STA1 and STA2 respectively in MIMO mode. Because of the use of MIMO, the interferences of AP 1 to STA 2 and AP 2 to STA 1 have been eliminated theoretically.

4.1.4 Coordinated joint transmission (co-JT)

Co-JT is also named distributed MIMO (D-MIMO), as shown in Fig. 4d. Co-JT refers to a master AP that successfully accesses the wireless channel coordinates with other slave APs. All antenna resources from multiple APs and all users from multiple BSSs are pulled through together. After that, both master AP and slave AP send DL data to multiple STAs by using MIMO. It is noteworthy that co-JT allows AP to serve OBSS STAs and enables multiple AP to serve the same STA. As shown in Fig. 4d, AP 1 and AP2 pull-through antenna resources together and serve all STA: STA 1, STA 2 and STA 3 from two BSSs by MIMO.

4.1.5 Coordinated TDMA (co-TDMA)

Coordinated time division multiple access, as shown in Fig. 4e, refers to a master AP that successfully accesses the wireless channel coordinates with other slave APs to share the following transmission opportunity (TXOP). Different APs arrange their own AP UL/DL transmission at different time period in the TXOP. as shown in Fig. 4e, in the same TXOP, AP 1 deploy DL transmission first while AP 2 following.

Table 2 summarizes the different types of AP coordination.

Table 2 Summary and comparison between different types of AP coordination

	co-SR	co-OFDMA	co-BF	co-JT	co-TDMA
Resource	spatial reuse	frequency domain	spatial (antenna) domain	spatial (antenna) domain	time domain
Direction	UL & DL	UL & DL	DL only	DL only	UL & DL
Backhaul	little need	little need	medium traffic requirement	high traffic requirement	little need
Served STA	own BSS	own BSS	own BSS	cross-BSS	own BSS
Sync Requirements	little	little	medium	very strict sync and re-sync	little
Possible gain	Good	a little	Good	Very Good	a little
Signalling overhead	little	little	medium	high	little

4.2 Investigation of possible technologies

4.2.1 Coordinated spatial reuse

Many studies focus on the improvements of spatial reuse by AP coordination. The first class is centralized solutions. The authors in [47] proposes a cooperative scheduling scheme for uplink OFDMA of IEEE 802.11ax in high-dense OBSS scenario. It divides all BSSs into several groups. The interferences between BSSs in the same group is very low. Therefore, the scheme controls the trigger frames of different groups to be sent in different time, and the trigger frames of the same groups can be sent in the same time. This enhances the spatial reuse capability, thereby improving the area throughput. Jiang et al. [48] assumes a software-defined network (SDN) like environment, and proposes a game theory based scheme for APs to control their transmitting power. The propose scheme achieves less interferences between BSSs. Similarly, [49] designs a SDN based WiFi network architecture, and further proposes a global downlink scheduling scheme.

For the distributed solutions, in [50], the authors propose a joint CCA and transmitting power adjusting scheme based on AP coordination. Specifically, APs exchange statistical information carried in the Beacon frame with each other. After that, the APs adjust their CCA level and transmitting power to guarantee the throughput fairness between APs. Chen et al. [51] propose a distributed coordination opportunistic transmission scheme for mmWave WLAN. To avoid interfering ACK frame caused by different simultaneous transmission links, the sender of the first link sends a short synchronization frame. After the sender of the second link receives the synchronization frame, it can transmit simultaneously with the first link, but the data transmission time should be aligned to avoid the ACK frame conflict. This scheme improves the spatial reuse capability.

4.2.2 Coordinated joint transmission

Coordinated joint transmission is also named as D-MIMO. Some studies focuses on the algorithms and protocols for D-MIMO. The authors in [52] assume that several APs form a group, within which there is a centralized controller. A user selection algorithm and a aggregate rate maximizing scheduling algorithm are proposed, respectively. After that, the authors extend their study in [53] by considering the scheduling for multiple time-slots. In [54], to minimize the CSI feedback overhead and to maximize the overall throughput, several D-MIMO groups are established. The APs in the same group utilize D-MIMO while different groups utilize orthogonal resources to avoid interferences. After that, joint AP grouping and STAs association algorithm are proposed.

Some studies pay attentions to the system design of D-MIMO. Hamed et al. [55] designs and implements a real-time D-MIMO system. Specifically, the authors propose a mathematical model and a protocol to achieve real-time channel update by using channel reciprocity. After that, coordinated power control scheme is proposed. The authors in [56] propose a D-MIMO system and focus on solutions to synchronization, channel status feedback, and STAs grouping problem. Hamed et al. [57] designs a fully distributed D-MIMO system by introducing self-organized architecture. Shepard et al. [58] proposes a design and implementation of D-MIMO system and corresponding beamforming algorithm. Gan et al. [59] proposes an OFDMA based synchronization protocol for D-MIMO. A D-MIMO protocol and device are designed in [60].

4.2.3 Coordinated beamforming

Coordinated Beamforming is not a quite new topic, and a series of related studies focus on it and achieve some fundamental results [61–63]. However, applying coordinated beamforming into WLAN has only attracted attention in recent years. Osama et al. [64] proposes a coordinated beamforming method for IEEE 802.11. The primary AP sends feedback trigger frame first, and receives the feedback information including the channel status from the candidate STAs. After that, the coordinated beamforming based transmission can be deployed. Yang et al. [65] details a coordinated beamforming method that after measuring the channel status and service requirements of STAs belonging to multiple BSSs, Each AP beamforms signals to a specific area while canceling other APs' signals. The authors in [66] utilize coordinated beamforming to solve hidden terminal problem in WLAN which is an inherent problem of CSMA/CA based wireless system.

4.2.4 Coordinated network management

Some studies focus on the network management such as operating channels management and association management based on AP coordination. Bouhafs et al. [67] proposes a centralized solution based on SDN architecture. The controller collects and evaluates the interference information of each channel. Joint considering the interference information and users' requirement, the controller optimized determine the operating channels and the transmitting power of each AP. Yang et al. [68] proposes a multiple AP association method for IEEE 802.11ax to improve the edge users' throughput. Ma et al. [69] enables two-hop distance STAs associating with AP and assigning different operating channels for the first-hop and the second-hop. Furthermore, it allows the STAs to associate with multiple APs for the purpose of load balance. Karowski et al. [70] proposes a coordination scheme for neighbor discovery in WiFi networks by using multiple transceivers.

Some researchers try to use AP coordination to support mobile handoff. The authors in [71] face to the handover problem of WiFi, which is an important problem for high-dense deployed scenario. To improve the handover performance when STAs move from BSS to BSS, a network coding scheme is propose by sending additional coded frames. In [72], the authors allow the STAs to associate with multiple BSSs and introduce a AP clustering based handoff protocol for IEEE 802.11ay.

4.3 Perspectives and open issues

1) AP coordination grouping and master AP selection
   Several APs should probably form a coordination group, otherwise the coordination information is untrusted. Thus, how to automatically and efficiently form a coordination group is a fundamental problem to be addressed. Furthermore, master AP is necessary for many multi-AP coordination modes, thus the master AP selection is also an important problem to be solved.
2) Access and transmission for AP coordination
   For different multi-AP coordination modes, the process of negotiation between multiple APs is different, and the information of interaction between multiple APs is also different. Therefore, the cooperation process between multiple APs is the technical premise of multi-AP coordination, which needs to be solved first.
   Moreover, it is an important question that needs to be answered and carefully designed whether each coordination mode uses an independent protocol process or all coordination modes use an unified process.
3) Inter-AP Backhaul
   Co-JT needs one AP to send STAs' buffer data to other APs, resulting in very huge amount of backhaul data. How to transfer data to other APs more quickly without incurring much air interface overhead is an important issue. Wired network backhaul is a solution, but it puts forward additional requirements for network deployment.
4) Sounding and measurement
   Each multi-AP coordination scheme needs to measure and acquire some information. For example, co-SR needs to measure the interference information between different links, and co-BF and co-JT need to deploy channel sounding. Therefore, how to collaborate and efficiently accomplish measurement tasks in multiple AP environments is a challenge. Moreover, the sounding and measurement feedback is overhead for IEEE 802.11. Therefore, how to find a tradeoff between measurement performance and feedback overhead is also an open problem to be solved.
5) Synchronization
   Different multi-AP coordination schemes have different requirements for synchronization between APs. The most stringent one is co-JT, which requires strict time, frequency and phase synchronization. In addition, due to the rapid channel changes in wireless environment, how to deal with out-of-step and resynchronization is also an important issue to be concerned.

5 Enhanced link reliability

5.1 Standards progress introduction

Link reliability is an important factor affecting throughput. Legacy IEEE 802.11 introduces two mechanisms. a) Retransmit mechanism. When a data frame transmission fails, the sender needs to re-contend the channel and retransmit the data frame until the transmission succeeds or the maximum retransmissions time is reached. b) Link adaptation (LA) mechanism or algorithm. The sender or the receiver (usually the sender) adjusts the modulation and coding scheme (MCS) level adaptively according to the historical transmission results or some information such as Signal to Interference and Noise Ratio (SINR) to adapt to the current air interface environment. However, the traditional retransmit mechanism and LA mechanism will lead to low efficiency and throughput suppression. As shown in the Fig. 5, when a MAC protocol data unit

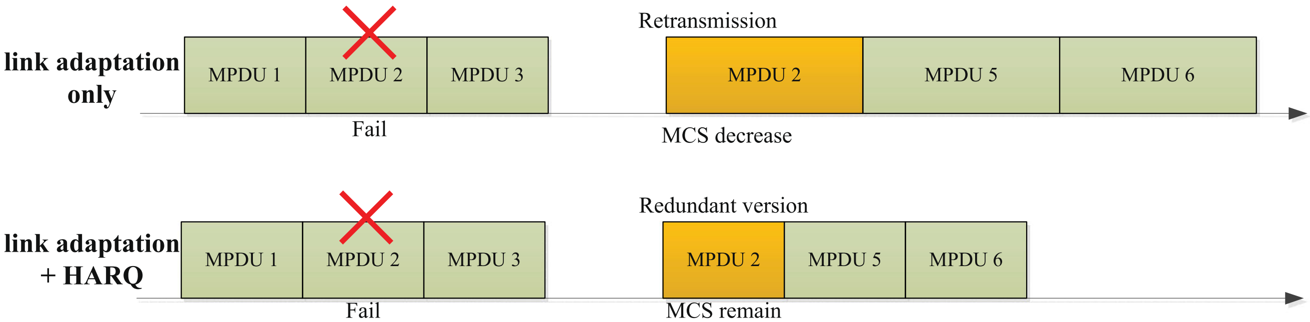


Fig. 5 HARQ enabled transmission for IEEE 802.11be

(MPDU) transmission fails, according to the LA algorithm, the sender may reduce the MCS, so that all MPDUs transmitted at the next transmission have to use the lower MCS. Moreover, and every information bit of the failed data has to be retransmitted, which is costly.

HARQ enables the retransmission frame to just contain part of information bits of failed frame and coded bits with or without the MCS decrease. In this case, as shown in the Fig. 5, for the retransmission, the sender transmit all the MPDUs by using the same MCS as the last transmission, while an HARQ redundant version of the failed MPDU 2 is transmitted. Therefore, the throughput can be guaranteed.

5.2 Investigation of possible technologies

HARQ has been adopted by cellular network for years. However, the technical details in WLAN and cellular network are quite different. Specifically, a) cellular network is scheduling based system while WLAN is contention based system, resulting in that the MAC layer procedures including HARQ of these two wireless networks are quite different. b) The frame format of these two systems are quite independent and different. c) The WLAN works on unlicensed band, thus the air interface environment is quite complicated comparing with cellular network. The reasons of unreliable transmissions are also complex. For example, channel fade loss, collision, and etc. This further increased difficulty in HARQ design for WLAN. Therefore, only in recent years, some scholars began to pay attention to HARQ technology in WLAN.

In [73], the authors propose an incremental redundancy HARQ (IR-HARQ) MAC protocol with fine backward compatibility. Specifically, the receiver replies clear-to-send frame (CTS) instead of acknowledgement frame (ACK) to declare that the transmission is error, and the network allocation vector (NAV) in the CTS indicate the retransmission time. Here the CTS frame represents NAK. After the sender successfully receive CTS/NAK, it should retransmit the data according to the retransmission time carried in NAV field. The authors extend the scheme into multi-band scenario in [74] to further improve the latency. The authors in [75, 76] combine chase combining HARQ (CC-HARQ) with NACK based channel reservation to improve the transmission reliability for WLAN. The NACK frame carries NAV and reserve the channel for HARQ retransmission. Kim et al. [77] proposes a detailed HARQ transmission method and design the frame format based on IEEE 802.11ac. Wang et al. [78] proposes a general HARQ method including the transmission scheme and the information indication scheme based on IEEE 802.11ax. It allows the ACK/NAC information to be aggregated with data frame. Furthermore, it also details the frame aggregation and block acknowledgement (BA) method.

Some related works study the HARQ scheme for unlicensed band networking. For example, [79] and [80] propose scheduling based uplink HARQ scheme in unlicensed band. Liu and Song [81] focuses on the ACK feedback scheme for HARQ and channel status feedback for unlicensed band in cellular network. Fang and Babaei [82] proposes an upplink HARQ scheme for listen before talk system. Based on the above, however, these related works are more suitable for cellular network such as Long Term Evolution Unlicensed (LTE-U) rather than WLAN.

5.3 Perspectives and open issues

1) The reason of transmission failure

   Since WLAN works in unlicensed band, the reasons for transmission failure are complex, such as channel deep fading and random interference. Different failure reasons have different coping methods. If the packet loss is caused by channel deep fading, it is not appropriate to use HARQ only, and LA should also be used together. If the packet loss is caused by random interference, HARQ is more appropriate, and it may not need to reduce the MCS. Therefore, how to accurately identify the cause of transmission failure in WLAN is an important issue.

2) Chase combining (CC) or incremental redundancy (IR)

HARQ has two basic implementation approaches: CC and IR, each with its own advantages. The advantage of CC lies in its simple implementation, but its disadvantage lies in its limited performance gain. The advantage of IR is that it has better performance gain, but the disadvantage is that the implementation is more complex. Therefore, IEEE 802.11be needs to further study the implementation complexity and performance gain of these two approaches, and seek a tradeoff.

3) Protocol and PHY and MAC frame design

Since it will be the first time for IEEE 802.11 to introduce HARQ, the MAC protocol supporting HARQ needs to be designed carefully. For example, for acknowledgement, legacy IEEE 802.11 only has positive ACK, that is, to reply to ACK after the recipient successfully receives the data frame. If the frame is not received successfully, no frame is replied. However, HARQ requires the receiver to reply ACK after receiving the data frame correctly and NAK after not receiving the data packet correctly. Therefore, IEEE 802.11be needs to support ACK and NAK functions. Moreover, the PHY frame also needs to be designed especially the HARQ information indication in the signal field in EHT preamble.

4) HARQ and link adaptation algorithm

HARQ and link adaptation is highly correlative. The sender should adjust the HARQ mode and MCS dynamically according to the channel status, packet loss status, and QoS requirements. But it is quite difficult to obtain the global and realtime information. Operating in unlicensed band exacerbates this problem. Therefore, designing an efficient joint HARQ and link adaptation algorithm is quite important for implementation.

6 Latency & jitter guarantee

6.1 Standards progress introduction

Since legacy IEEE 802.11 has little corresponding supports for latency and jitter guarantees, and IEEE 802.11be has just started research on latency and jitter, no consensus has yet been reached.

Time-sensitive network (TSN) is a series of standards specified by IEEE 802.1. In order to guarantee delay and jitter, it consists of a series of functions. a) Time synchronization. All nodes involved in time-sensitive services need strict time synchronization. b) Resources Reservation. In order to guarantee delay, TSN reserves resources. c) Time gated queue and priority queue. Adding a gate to the queues can restrict or open the function of queue output packet by controlling ON/OFF. In addition, different queues have different priority. However, since TSN is standardized in IEEE 802.1, its design does not consider compatibility and adaptability with IEEE 802.11, thus how to adapt TSN to IEEE 802.11 is still a challenge [83–85]. Some studies focus on the TSN solutions for IEEE 802.11 [86, 87].

Moreover, a series of other potential technologies are proposed in TGbe to guarantee the low latency and jitter. For example, some proposals consider that multi-link operation is one potential solution for low latency, some proposals try to introduce preemption scheme, and some others focus on priority guarantee and channel access based solutions. It is worth noting that the solutions for worst case latency in IEEE 802.11be are still unclear.

6.2 Investigation of possible technologies

6.2.1 Redundancy transmission and preemption

Redundancy is an important option to enhance the transmission reliability, thereby improving the average latency. Rentschler and Laukemann [88] inroduces multi-radio redundant schemes to enhance the reliability and further improve the latency of WLAN by connecting the single wired network interface of one device to its doble IEEE 802.11 channels and adopting Parallel Redundancy Protocol (PRP). Halloush [89] proposes an interference (named jamming) detection scheme to detect the transmitting jamming before the time deadline. If the jamming is detected for a packet, it will be retransmitted in other channel named safe channel.

In [90], the authors introduces a narrow-band channel for the STAs to send busy tone to report the real-time requirements. If other STAs successfully receive the requirements, they will stop transmitting in the main channel, while the STA who sends requirements should preempt channel resource in the main channel.

6.2.2 Scheduling based solutions

Scheduling is an efficient technology since AP is the core element of WLAN especially IEEE 802.11ax enhances the schedule capability. The authors in [91, 92] focus on the real-time application support in hybrid OFDMA based transmission including explicit scheduling access and random access. Specifically, the authors propose a cyclic resource allocation algorithm for IEEE 802.11ax and a group resource allocation algorithm for IEEE 802.11be. The necessary protocol modification is also described. VR is the killer application for the near future wireless network. To decrease the UL delay of VR device, [93] introduces a scheduling based scheme by using UL OFDMA protocol of IEEE 802.11ax. The UL contention of VR devices are disabled by the AP. After that, AP periodically schedules UL transmission of multiple VR users. Li et al. [94] focuses on the stream video traffic in the hign-dense scenario, and proposes a QoE aware scheduling scheme. A new metric named packet importance index carried in the ToS field is introduced to indicate the importance of one packet, and then the authors improve the gradient based scheduling by considering the metric. The authors in [95] propose a hybrid scheme combining transmission and retransmission scheduling, redundancy, and bandwidth allocation to guarantee the real-time requirements.

Some studies focus on the static or quasi static configurations of WiFi. The authors in [96] proposes a scheme which regulate the traffic from MAC to the queue in PHY based on contention situation. The scheme guarantees that the delay-sensitive frame can avoid the queuing process. The authors in [97] introduce a decision tree to study the WiFi factors that influence the latency. After that, AP can change some configurations such as the transmission power, operating channel, and AP location to improve the latency. The authors in [98] focus on the load balancing for several BSSs. Packet deadline is considered for the AP change determination, and a game theory based AP selection algorithm is proposed.

The authors in [99] studies the scheduling scheme in polling or named contention-free based IEEE 802.11 MAC and propose a two-level priority queues to reduce the delay. Vishalakshi and Nagaraja [100] proposes a highest urgency first scheduling algorithm in contention-free mode of WLAN.

For WLAN based mesh or multi-hop network, the authors in [101] propose a hybrid coordination function (HCF) controlled channel access (HCCA) based scheduling scheme. It firstly estimates a series of metrics, e.g., the packet loss rate, future queue size, and etc. After that, the most urgent packets in the queue are scheduled in the next TXOP. Similarly, [102] proposes a packet scheduling scheme by adjusting the packet length according to the estimated link conditions.

6.2.3 Channel access optimization

Lin et al. [103] introduces neural networks to model the relationship between STAs' performance, such as throughput and delay, and STAs' EDCA channel access parameters. Then, the AP can optimally adjust and broadcast the EDCA parameters to all STAs to guarantee the differentiated QoS. Nguyen et al. [104] faces two types of services: delay-sensitive services and throughput-sensitive and proposes a proportional tradeoff scheme by adjusting the STAs' TXOP limit and the minimum contention window to satisfy both types' QoS. The authors in [105] propose a fast retransmission scheme for VoIP service. Specifically, if a VoIP frame encounters collision, the node will send a non-data packet named energy burst immediately after AIFS to let other nodes know such collision. After that, the collided frame can be retransmitted after a short backoff period while other nodes increase their backoff counter to guarantee the retransmission. Syed and Roh [106] proposes an algorithm to dynamically change the contention window of each AC based on the STA number. Similarly, the authors in [107] also adjust the contention window by Q-learning algorithm. In [108], the authors propose a new channel access protocol scheme to mitigate the tail latency of WiFi. The proposed protocol introduces a new concept named "Round", during which only one frame is allowed to sent for each STA by modifying the backoff and contention window strategy.

Some works focus on the combination of energy efficiency and delay guarantee. Liu et al. [109] optimizes the sleep time and the wake-up time under the constraints of STA's delay requirements to maximize energy-efficiency and to avoid the access contention when any STA wakes up. Meanwhile, [110] differentiates delay-sensitive service and other service. Immediate transmission is adopted for delay-sensitive service, while packets should be buffered for other services.

6.2.4 Transmission optimization

Optimizing the frame aggregation scheme is one important direction in transmission optimization. Zheng et al. [111] studies the performances of video traffic with the variation of per MPDU size and the retransmission time when frame aggregation is adopted. Furthermore, the authors find the optimal parameters under specific channel condition. Similarly, the authors in [112, 113], and [114] try to find the optimal aggregation sizes towards different QoS types. In [115], the authors study the retransmission scheduling algorithm for A-MPDU considering the delay-sensitive requirements.

Bobarshad et al. [116] studies the interaction relationship between expired frame dropping rate and the buffer overflow dropping. Furthermore, the authors propose a retransmission time adaption algorithm to improves the video traffic performance. The authors in [117] classify the packet loss situation into three types: collision, congestion, and channel errors. After that, a link adaptation algorithm is proposed. Khavasi and Suk [118] studies the link adaptation scheme for MU-MIMO in IEEE 802.ac to gurantee the real-time video services. Tramarin et al. [119] formulates an optimizing problem considering the deadline of packets, and then solve the problem by optimizing the transmission rate. The authors in [120] propose a deadline-constrained backoff scheme for periodic real-time services. Specifically, the STAs double their backoff counters not only when the collisions occur, but also when the channel is busy.

Furthermore, a intra-AC_VO differentiation is introduced by modifying the retransmission time of periodic real-time flow. In [121], the authors propose an online reinforcement learning algorithm for the STAs to determine their MCS according to the channel status and buffer status in order to guarantee the energy efficiency and the delay-sensitive requirements.

6.2.5 Admission control

Charfi et al. [122] and Inaba et al. [123] propose frame aggregation based admission control algorithm and fuzzy-based admission control algorithm, respectively, to guarantee the existing STA's latency and throughput. The authors in [124] propose a model to estimate the performance if a new flow is admitted to access. After that, admission control result is decided by the AP.

6.3 Perspectives and open issues

1) TSN adapted to IEEE 802.11

   TSN can effectively guarantee latency and jitter, but the technologies of TSN itself do not match 802.11 well. Thus, how to extract some appropriate features from TSN technologies and design appropriate mechanisms to make it naturally adapt to 802.11 is a great challenge.
2) Multi-band supported latency guarantee

   Since APs and STAs of IEEE 802.11be have multi-band capabilities, it is worth studying whether and how multi-band capabilities can support delay and jitter.
3) Enhanced AP scheduling

   An important reason for the poor latency and jitter guarantee of IEEE 802.11 is that distributed random access makes conflict and interference uncontrollable. The global scheduling capability of AP has been greatly enhanced since IEEE 802.11ax. Therefore, how to utilize AP's powerful scheduling capability to support latency and jitter is a noticeable direction.
4) 5G inspired latency guarantee scheme

   Since 5G significantly improves the latency performance by a series of solutions such as improved protocol stack and flexible slot configuration. Therefore, the solutions or the research thought of 5G might be the inspirations for WLAN.

7 Conclusions

In this article, we investigates and analyzes the key technologies of the next generation WLAN: IEEE 802.11be, established in May 2019, and further provides our perspectives and insights on it. We summarize that the target scenario of IEEE 802.11be is the ultra-high definition video traffic and real-time traffic. To efficiently support the target scenario, the key technical objective of IEEE 802.11be is to achieve extremely high throughput (at least 30Gbps) and to improve the worst case latency and jitter. After that, we further investigate and analyze the technical characteristics and challenges of multi-band operation, multi-AP coordination, enhanced link reliability, and latency & jitter guarantee, respectively. To the best of our knowledge, this is the first work to investigate, analyze and provide insights on IEEE 802.11be. Future work is to study the key technologies of IEEE 802.11be

Acknowledgments This work was supported in part by the National Natural Science Foundations of CHINA (Grant No. 61871322, No. 61771390, No. 61501373, and No. 61271279), the National Science and Technology Major Project (Grant No. 2016ZX03001018-004), and Science and Technology on Avionics Integration Laboratory (20185553035).

References

1. Ericsson (2019) The power of 5g is here and will continue to spread across the globe in the coming years. Ericsson Mobility Report
2. Cisco (2019) Global mobile data traffic forecast update. Cisco Visual Networking Index: White Paper
3. Yang M, Li B, Yan Z (2019) Mac technology of ieee 802.11ax: Progress and tutorial (acepted). Mobile Networks and Applications
4. Qu Q, Li B, Yang M, Yan Z, Yang A, Deng D-J, Chen K-C (2019) Survey and performance evaluation of the upcoming next generation wlans standard - ieee 802.11ax. Mobile Networks and Applications
5. Deng DJ, Lien SY, Lee J, Chen KC (2016) On quality-of-service provisioning in ieee 802.11ax wlans. IEEE Access 4:6086–6104
6. IEEE 802.11ax Task Group (2019) Ieee p802.11ax d4.3. Telecommunications and information exchange between systems local and metropolitan area networks—Specific requirements?, pp 1–746
7. IEEE 802.11be Task Group (2019) Project authorization request. Part 11: wireless LAN medium access control (MAC) and physical layer (PHY) specifications amendment: enhancements for extremely high throughput (EHT), pp 1–2
8. Yang M, Li B, Yan Z, Yan Y (2019) Ap coordination and full-duplex enabled multi-band operation for the next generation wlan: Ieee 802.11be (eht). In: The 11th International Conference on Wireless Communications and Signal Processing, pp 1–7
9. Qiao J, He Y, Shen XS (2018) Improving video streaming quality in 5g enabled vehicular networks. IEEE Wireless Commun 25(2):133–139
10. Fan Q, Yin H, Min G, Yang P, Luo Y, Lyu Y, Huang H, Jiao L (2018) Video delivery networks: Challenges, solutions and future directions. Comput Electrical Engineering 66:332–341
11. Zhao G, Imran MA, Pang Z, Chen Z, Li L (2019) Toward real-time control in future wireless networks: Communication-control co-design. IEEE Commun Mag 57(2):138–144
12. Park E, Lim D, Kim J, Choi J (2019) Phase rotation for 320mhz. doc.: Ieee 802.11-19/1493r0. IEEE TGbe Proposal, pp 1–11

13. Park E, Lim D, Kim J, Choi J (2019) Non-ofdma tone plan for 320mhz. doc.: Ieee 802.11-19/1492r0. IEEE TGbe Proposal, pp 1–12
14. Chen A, Yang L, Tian B, Kim Y, Vermani S, Shellhammer S (2019) 320mhz channelization and tone plan. doc.: Ieee 802.11-19/0797r0.IEEE TGbe Proposal, pp 1–10
15. Park E, Lim D, Kim J, Choi J (2019) Tone plan discussion. doc.: Ieee 802.11-19/1066r1. IEEE TGbe Proposal, pp 1–16
16. Yu J, Gan M (2019) 11be tone plan. doc.: Ieee 802.11-19/1487r1. IEEE TGbe Proposal, pp 1–10
17. Park E, Lim D, Kim J, Choi J (2019) Non-ofdma tone plan for 320mhz. doc.: Ieee 802.11-19/1492r1. IEEE TGbe Proposal, pp 1–12
18. Son J, Ko G, Kwak JS, Kim S, Murti W, Yun JH, Oh YS (2019) Preamble puncturing and sig-b signaling. doc.: Ieee 802.11-19/1606r0. IEEE TGbe Proposal, pp 1–14
19. Redlich O, Shilo S, Hencinski O, Klausner O, Yu J, Xin J (2019) Improved preamble puncturing in 802.11be. doc.: Ieee 802.11-19/1190r2. IEEE TGbe Proposal, pp 1–11
20. Tian B, Yang L, Kim Y (2019) Preamble puncturing and ru aggregation. doc.: Ieee 802.11-19/1869r2. IEEE TGbe Proposal, pp 1–11
21. Lee WB, Duan R, Ibrahim M, Kandala S, Ranganath A (2019) 16 spatial stream support. doc.: Ieee 802.11-19/1877r0. IEEE TGbe Proposal, pp 1–7
22. Lee WB, Duan R, Ibrahim M, Kandala S, Ranganath A (2019) Further discussion on feedback overhead reduction. doc.: Ieee 802.11-19/1495r0. IEEE TGbe Proposal, pp 1–16
23. Huang PK, Cariou L, Stacey R, Bravo D, Klein A, Park M, Cordeiro C (2019) Extremely efficient multi-band operation. doc.: Ieee 802.11-19/0822r0. IEEE TGbe Proposal, pp 1–21
24. Patil A, Cherian G, Asterjadhi A, Ho D (2019) Multi-link aggregation. doc.: Ieee 802.11-19/0823r0. IEEE TGbe Proposal, pp 1–2
25. Li Y, Guo Y, Huang G, Zhou Y, Gan M, Liang D (2019) Channel access in multi-band operation. doc.: Ieee 802.11-19/1116r1. IEEE TGbe Proposal, pp 1–25
26. Naribole S, Kandala S, Lee WB, Ranganath A (2019) Multi-link aggregation considerations. doc.: Ieee 802.11-19/1181r0. IEEE TGbe Proposal, pp 1–9
27. Guo Y, Huang G, Yu J, Loc P (2019) Ap coordination in eht. doc.: Ieee 802.11-19/0801r0. IEEE TGbe Proposal, pp 1–12
28. Nan L, Bo S, Chen J, Fang Y (2019) Consideration on multi-ap coordination. doc.: Ieee 802.11-19/1219r0. IEEE TGbe Proposal, pp 1–8
29. Guo Y, Huang G, Yang B (2019) A unified transmission procedure for multi-ap coordination. doc.: Ieee 802.11-19/1102r0. IEEE TGbe Proposal, pp 1–8
30. Doostnejad R, Cariou L, Chen X, Kenney T (2019) Multi-ap collaborative bf in ieee 802.11. doc.: Ieee 802.11-19/0772r0. IEEE TGbe Proposal, pp 1–18
31. Yang B, Lv Y, Chen P (2019) Consideration on joint transmission. doc.: Ieee 802.11-19/1595r0. IEEE TGbe Proposal, pp 1–12
32. Verma L, Cherian G, Wentink M (2019) Coordinated ap time/frequency sharing in a transmit opportunity in 11be. doc.: Ieee 802.11-19/1582r0. IEEE TGbe Proposal, pp 1–12
33. Duan R, Ibrahim M, Lee BW, Kandala S (2019) Discussion on harq. doc.: Ieee 802.11-19/1172r0. IEEE TGbe Proposal, pp 1–13
34. Shilo S, Basson N, Melzer E, Arie YB, Reich M, Ezri D (2019) An harq transmission scheme for 11be. doc.: Ieee 802.11-19/1587r0. IEEE TGbe Proposal, pp 1–14
35. Shellhapmer S, Doan Z, Chen A, Tian B (2019) Harq simulation results. doc.: Ieee 802.11-19/1078r0. IEEE TGbe Proposal, pp 1–23
36. Zhang Y, Zhang H, Srinivasa S, Chu L, Cao R, Yu M (2019) Comparisons of harq transmission schemes for 11be. doc.: Ieee 802.11-19/0792r0. IEEE TGbe Proposal, pp 1–30
37. Latif I, Schelstraete S, Dash D, Wang H (2019) Harq framing. doc.: Ieee 802.11-19/0873r0. IEEE TGbe Proposal, pp 1–20
38. Kim S, Choi J, Kim J, Jang I, Song T (2019) Latency enhancement for eht. doc.: Ieee 802.11-19/1524r0. IEEE TGbe Proposal, pp 1–13
39. Zuo X, Meng K, Huang L, Chitrakar R, Ding Y, Urabe Y (2019) Use of uplink persistent allocation for rta. doc.: Ieee 802.11-19/1538r0. IEEE TGbe Proposal, pp 1–8
40. Kim S, Choi J, Kim J, Jang I, Song T, Park S (2019) Performance evaluation of deterministic service for eht. doc.: Ieee 802.11-19/1523r0. IEEE TGbe Proposal, pp 1–23
41. Lu L, Yuan L (2019) Multi-band/multi-channel operation for low latency and jitter. doc.: Ieee 802.11-19/1615r0. IEEE TGbe Proposal, pp 1–9
42. Zeng T, Wang E, Zhao Y, Si X (2019) Use auto repetition in low latency queue. doc.: Ieee 802.11-19/1622r0. IEEE TGbe Proposal, pp 1–17
43. Cariou L, Stacey R, Cordeiro C, Vegt RD, Tian B, Erceg V, Porat R (2019) 802.11be timeline proposal. doc.: Ieee 802.11-19/0787r2. IEEE TGbe Proposal, pp 1–16
44. Singh H, Hsu J, Verma L, Lee SS, Ngo C (2011) Green operation of multi-band wireless lan in 60 ghz and 2.4/5 ghz. In: 2011 IEEE Consumer Communications and Networking Conference (CCNC), pp 787–792
45. Goya S, Le T, Chincholi A, Elkourdi T, Demir A (2018) On the packet allocation of multi-band aggregation wireless networks. Wireless Netw 24(7):2521–2537
46. Li B, Qu Q, Yan Z, Yang M (2015) Survey on ofdma based mac protocols for the next generation wlan. In: 2015 IEEE Wireless Communications and Networking Conference Workshops (WCNCW), pp 131–135
47. Kawamura K, Inoki A, Nakayama S, Wakao K, Takatori Y (2019) Cooperative control of 802.11ax access parameters in high density wireless lan systems. In: 2019 IEEE Wireless Communications and Networking Conference (WCNC), pp 1–6
48. Jiang C, Zhang Y, Yuan J, Ren Y, Han Z (2016) Cooperative wifi management: Nash bargaining solution and implementation. In: 2016 IEEE Wireless Communications and Networking Conference, pp 1–6
49. Lei J, Wang Y, Xia Y (2019) Sdn-based centralized downlink scheduling with multiple aps cooperation in wlans. Wireless Commun Mobile Comput 2019
50. Iwai K, Ohnuma T, Shigeno H, Tanaka Y (2019) Improving of fairness by dynamic sensitivity control and transmission power control with access point cooperation in dense wlan. In: 2019 16th IEEE Annual Consumer Communications Networking Conference (CCNC), pp 1–4
51. Chen B, Yang Q, Li B, Yang M, Yan Z (2018) Multi-cell cooperative transmission for the next generation millimeter-wave wifi network. In: International Conference on Internet of Things as a Service (IoTaaS 2018), pp 246–254
52. Ge M, Blough DM (2017) High-throughput and fair scheduling for access point cooperation in dense wireless networks. In: 2017 IEEE Wireless Communications and Networking Conference (WCNC), pp 1–6
53. Ge M, Blough DM (2018) High throughput and fair scheduling for multi-ap multiuser mimo in dense wireless networks. IEEE/ACM Trans Netw 26(5):2414–2427

54. Wong W, Chan SG (2018) Distributed joint ap grouping and user association for mu-mimo networks. In: IEEE INFOCOM 2018 - IEEE Conference on Computer Communications, pp 252–260
55. Hamed E, Rahul H, Abdelghany MA, Katabi D (2016) Real-time distributed mimo systems. In: Proceedings of the 2016 ACM SIGCOMM Conference, SIGCOMM '16. Association for Computing Machinery, New York, NY, USA, pp 412–425
56. Wang T, Yang Q, Tan K, Zhang J, Liew SC, Zhang S (2018) Dcap: Improving the capacity of wifi networks with distributed cooperative access points. IEEE Trans Mob Comput 17(2):320–333
57. Hamed E, Rahul H, Partov B (2018) Chorus: Truly distributed distributed-mimo. In: Proceedings of the 2018 Conference of the ACM Special Interest Group on Data Communication, SIGCOMM '18. Association for Computing Machinery, NewYork, NY, USA, pp 461–475
58. Shepard C, Yu H, Anand N, Li E, Marzetta T, Yang R, Zhong L (2012) Argos: Practical many-antenna base stations. In: Proceedings of the 18th Annual International Conference on Mobile Computing and Networking, Mobicom '12. Association for Computing Machinery, New York, NY, USA, pp 53–64
59. Gan L, Li B, Yang M, Yan Z, Yang Q (2019) Ofdma based synchronization protocol for distributed mimo in the next generatio wlan. In: International Conference on Internet of Things as a Service (IoTaaS 2019), pp 1–11
60. Hou J, Montojo J Method and apparatus for supporting distributed mimo in a wireless communication system, 2016-05-22
61. Dahrouj H, Yu W (2010) Coordinated beamforming for the multicell multi-antenna wireless system. IEEE Trans Wireless Commun 9(5):1748–1759
62. Shen C, Chang T, Wang K, Qiu Z, Chi C (2012) Distributed robust multicell coordinated beamforming with imperfect csi: An admm approach. IEEE Trans Signal Process 60(6):2988–3003
63. He S, Huang Y, Jin S, Yang L (2013) Coordinated beamforming for energy efficient transmission in multicell multiuser systems. IEEE Trans Commun 61(12):4961–4971
64. Osama AM, Au KS, Suh JH System and methods for enabling coordinated beamforming in overlapping basic service set in wlan, 2016-11-22
65. Yang K, Calin D, Ozge A, Yiu S Method and apparatus for coordinated beamforming, 2013-12-12
66. Shrestha S, Fang G, Dutkiewicz E, Huang X (2014) Addressing hidden terminals in wlans with zero forcing coordinated beamforming. In: 2014 14th International Symposium on Communications and Information Technologies (ISCIT), pp 249–253
67. Bouhafs F, Seyedebrahimi M, Raschella A, Mackay M, Shi Q (2019) Per-flow radio resource management to mitigate interference in dense ieee 802.11 wireless lans. IEEE Trans Mobile Comput PP(9):1–1
68. Yang M, Li B, Yan Z, Zuo X, Ji L (2016) Multi-bss association for edge users throughput improvements. doc.: Ieee 802.11-16-0590-00-00ax. IEEE TGax Proposal, pp 1–12
69. Ma Y, Li J, Li H, Zhang H, Hou R (2016) Multi-hop multi-ap multi-channel cooperation for high efficiency wlan. In: 2016 IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), pp 1–7
70. Karowski N, Willig A, Wolisz A (2017) Cooperation in neighbor discovery. In: 2017 Wireless Days, pp 99–106
71. Ghanem SAM (2018) Network coded Handover in IEEE 802.11 arxiv 2018:1–13
72. Li Y, Zhao P, Li B, Yang M, Yan Z (2019) Multi-cell cooperative transmission for the next generation millimeter-wave wifi network. In: 12th EAI International Wireless Internet Conference (Wicon 2019), pp 1–10
73. Yofune M, Sonobe S, Sugitani A, Amezawa Y, Sato S (2017) Low latency ir-harq scheme for wlan system. In: 2017 IEEE 13th Malaysia International Conference on Communications (MICC), pp 271–275
74. Masanori Y, Satoshi S, Atsuhiko S, Yasuharu A, Shin-Ich S (2018) Low latency ir-harq for multiband wlan system. IEICE Communications Express 7(6):189–194
75. Kim J, Kim SH, Sung DK (2018) Hybrid arq-based uplink/downlink fairness enhancement in wlan. IEEE Trans Veh Technol 67(10):10107–10111
76. Kim J, Kim SH, Sung DK (2018) Hybrid arq-based fairness enhancement in uplink wlan. IEEE Trans Wireless Commun 17(7):4362–4373
77. Kim J, Kim Y, Mujtaba SA System and method for performing hybrid automatic repeat request (harq) in a wlan system, 2017-04-11
78. Wang X, Zhang G, Olesen RL, Lou H, Ghosh M, Xia P, Shah NB, Oteri O Systems and methods for smart harq for wifi, 2017-08-10
79. Ahn J, Yang S, Kim S Method and device for supporting harq in unlicensed band, 2018-10-30
80. Pazhyannur R, Chandrasekhar V, Kwan RYC Wireless shared spectrum access contention based on harq feedback, 2018-10-16
81. Liu J, Li S, Song X, Harq/csi ack feedback method over unlicensed carrier 2018-08-28
82. Fang JA, Babaei A Hybrid automatic repeat request (harq) in listen before talk systems, 2018-05-31
83. Cavalcanti D, Venkatesan G, Cariou L, Cordeiro C (2019) Tsn support in 802.11 and potential extensions for tgbe. doc.: Ieee 802.11-19/1287r0. IEEE TGbe Proposal, pp 1–22
84. Finn N (2019) Wireless + tsn = part of the picture. doc.: Ieee 802.11-19/1266r1. IEEE TGbe Proposal, pp 1–12
85. Farcas J (2019) Ieee 802.1 tsn –an introduction. doc.: Ieee 802.11-19/1298r1. IEEE TGbe Proposal, pp 1–18
86. Adame T, Carrascosa M, Bellalta B (2019) Time-sensitive networking in ieee 802.11be: On the way to low-latency wifi 7
87. Cavalcanti D, Cordeiro C, Doostnejad R Methods to enable time sensitive applications in secondary channels in a mmwave ieee 802.11 wlan
88. Rentschler M, Laukemann P (2012) Towards a reliable parallel redundant wlan black channel. In: 2012 9th IEEE International Workshop on Factory Communication Systems, pp 255–264
89. Halloush RD (2019) Transmission early-stopping scheme for anti-jamming over delay-sensitive iot applications. IEEE Internet Things J 6(5):7891–7906
90. Bankov D, Khorov E, Lyakhov A, Sandal M (2019) Enabling real-time applications in wi-fi networks. Int J Distribut Sensor Netw 15(5):1550147719845312
91. Avdotin E, Bankov D, Khorov E, Lyakhov A (2019) Enabling massive real-time applications in ieee 802.11be networks. In: 2019 IEEE 30th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), pp 1–6
92. Avdotin E, Bankov D, Khorov E, Lyakhov A (2019) Ofdma resource allocation for real-time applications in ieee 802.11ax networks. In: 2019 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom), pp 1–3
93. Ahn J, Kim YY, Kim RY (2017) Delay oriented vr mode wlan for efficient wireless multi-user virtual reality device. In: 2017 IEEE International Conference on Consumer Electronics (ICCE), pp 122–123
94. Li M, Tan PH, Sun S, Chew YH (2016) Qoe-aware scheduling for video streaming in 802.11n/ac-based high user density networks. In: 2016 IEEE 83rd Vehicular Technology Conference (VTC Spring), pp 1–5

95. Seno L, Cena G, Scanzio S, Valenzano A, Zunino C (2017) Enhancing communication determinism in wi-fi networks for soft real-time industrial applications. IEEE Trans Ind Inf 13(2):866–876
96. Pei C, Zhao Y, Liu Y, Tan K, Zhang J, Meng Y, Pei D (2017) Latency-based wifi congestion control in the air for dense wifi networks. In: 2017 IEEE/ACM 25th International Symposium on Quality of Service (IWQoS), pp 1–10
97. Pei C, Zhao Y, Chen G, Tang R, Meng Y, Ma M, Ling K, Pei D (2016) Wifi can be the weakest link of round trip network latency in the wild. In: IEEE INFOCOM 2016 - The 35th Annual IEEE International Conference on Computer Communications, pp 1–9
98. Cheng Y, Yang D, Zhou H (2018) Det-lb: A load balancing approach in 802.11 wireless networks for industrial soft real-time applications. IEEE Access 6:32054–32063
99. Vishalakshi PH, Nagaraja GS (2018) Delay-sensitive smart polling in dense ieee 802.11n network for quality of service. IUP J Telecommun 10(1):7–9
100. Vishalakshi PH, Nagaraja GS (2017) Highest urgency first scheduling adapted in ieee 802.11n to support quality of service. In: 2017 2nd IEEE International Conference on Recent Trends in Electronics, Information Communication Technology (RTEICT), pp 1521–1525
101. Saheb SM, Bhattacharjee AK, Dharmasa P, Kar R (2012) Enhanced hybrid coordination function controlled channel access-based adaptive scheduler for delay sensitive traffic in ieee 802.11e networks. IET Netw 1(4):281–288
102. Zhu R, Qin Y, Lai CF (2011) Adaptive packet scheduling scheme to support real-time traffic in wlan mesh networks. IET Netw 5(9):1492–1512
103. Lin P, Chou W, Lin T (2011) Achieving airtime fairness of delay-sensitive applications in multirate ieee 802.11 wireless lans. IEEE Commun Mag 49(9):169–175
104. Nguyen SH, Vu HL, Andrew LLH (2013) Service differentiation without prioritization in ieee 802.11 wlans. IEEE Trans Mobile Comput 12(10):2076–2090
105. Tüysüz MF, Mantar HA (2011) Fast retransmission mechanism and end to end qos support for voip applications over ieee 802.11e wlans. In: ICIMU 2011 : Proceedings of the 5th international Conference on Information Technology Multimedia, pp 1–5
106. Syed I, Roh B (2016) Delay analysis of ieee 802.11e edca with enhanced qos for delay sensitive applications. In: 2016 IEEE 35th International Performance Computing and Communications Conference (IPCCC), pp 1–4
107. Wu C, Ohzahata S, Ji Y, Kato T (2014) A mac protocol for delay-sensitive vanet applications with self-learning contention scheme. In: 2014 IEEE 11th Consumer Communications and Networking Conference (CCNC), pp 438–443
108. Kim D, Yeom I, Lee T-J (2018) Mitigating tail latency in ieee 802.11-based networks. Int J Commun Syst 31(1):e3404. e3404 dac.3404
109. Liu L, Cao X, Cheng Y, Niu Z (2014) Energy-efficient sleep scheduling for delay-constrained applications over wlans. IEEE Trans Veh Technol 63(5):2048–2058
110. Chen B, Li X, Zhou X, Liu T, Zhu Z (2014) Towards energy optimization based on delay-sensitive traffic for wifi network. In: 2014 IEEE 11th Intl Conf on Ubiquitous Intelligence and Computing and 2014 IEEE 11th Intl Conf on Autonomic and Trusted Computing and 2014 IEEE 14th Intl Conf on Scalable Computing and Communications and Its Associated Workshops, pp 252–259
111. Zheng H, Chen G, Yu L (2010) Video transmission over ieee 802.11n wlan with adaptive aggregationscheme. In: 2010 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), pp 1–5
112. Hajlaoui N, Jabri I, Taieb M, Benjemaa M (2012) A frame aggregation scheduler for qos-sensitive applications in ieee 802.11n wlans. In: 2012 International Conference on Communications and Information Technology (ICCIT), pp 221–226
113. Charfi E, Gueguen C, Chaari L, Cousin B, Kamoun L (2017) Dynamic frame aggregation scheduler for multimedia applications in ieee 802.11n networks. Trans Emerg Telecommun Technol 28(2):e2942. e2942 ett.2942
114. Azhari SV, Gurbuz O, Ercetin O, Daei MH, Barghi H, Nassiri M (2018) Delay-sensitive smart polling in dense ieee 802.11n network for quality of service. Wireless Netw 26(3):1949–1968
115. Qian X, Wu B, Ye T (2017) Qos-aware a-mpdu retransmission scheme for 802.11n/ac/ad wlans. IEEE Commun Lett 21(10):2290–2293
116. Bobarshad H, van der Schaar M, Aghvami AH, Dilmaghani RS, Shikh-Bahaei MR (2012) Analytical modeling for delay-sensitive video over wlan. IEEE Trans Multimedia 14(2):401–414
117. Tüysüz MF, Mantar HA (2011) A link adaptation scheme for improving voice quality and overall throughput over wlans. In: ICIMU 2011 : Proceedings of the 5th international Conference on Information Technology Multimedia, pp 1–6
118. Khavasi AA, Suk J (2016) Link adaptation strategies for real-time video transmission over ieee 802.11ac dl-mu. IEEE Trans Commun 64(10):4425–4433
119. Tramarin F, Vitturi S, Luvisotto M (2016) An innovative approach to rate adaptation in ieee 802.11 real-time industrial networks. In: 2016 IEEE World Conference on Factory Communication Systems (WFCS), pp 1–4
120. Tian G, Camtepe S, Tian Y (2016) A deadline-constrained 802.11 mac protocol with qos differentiation for soft real-time control. IEEE Trans Indus Inf 12(2):544–554
121. Mastronarde N, Modares J, Wu C, Chakareski J (2016) Reinforcement learning for energy-efficient delay-sensitive csma/ca scheduling. In: 2016 IEEE Global Communications Conference (GLOBECOM), pp 1–7
122. Charfi E, Fourati LC, Kamoun L (2014) Qos support of voice/video services under ieee 802.11n wlans. In: 2014 9th International Symposium on Communication Systems, Networks Digital Sign (CSNDSP), pp 600–605
123. Inaba T, Sakamoto S, Oda T, Ikeda M, Barolli L (2016) A qos-aware admission control system for wlan using fuzzy logic. In: 2016 30th International Conference on Advanced Information Networking and Applications Workshops (WAINA), pp 499–505
124. Taher NC, Doudane YG, El Hassan B, Agoulmine N (2014) Towards voice/video application support in 802.11e wlans: A model-based admission control algorithm. Comput Commun 39:41–53. Research advances and standardization activities in WLANs