IEEE 802.11ax: High-Efficiency WLANs

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Abstract

IEEE 802.11ax-2019 will replace both IEEE 802.11n-2009 and IEEE 802.11ac-2013 as the next high-throughput Wireless Local Area Network (WLAN) amendment. In this paper, we review the expected future WLAN scenarios and use-cases that justify the push for a new IEEE 802.11 amendment. Then, we overview a set of new technical features that may be included in this amendment and describe both their advantages and drawbacks. Finally, we discuss the list of network-level functionalities that are required to fully improve the user experience in next-generation WLANs and note their relation with other on-going IEEE 802.11 amendments such as the IEEE 802.11ai-2016, IEEE 802.11aq-2016 and IEEE 802.11ak-2017.

Keywords: IEEE 802.11ax, HEW, WLANs

1 Introduction

IEEE 802.11 Wireless Local Area Networks (WLANs) [1] are a cost-efficient solution for wireless Internet access that can satisfy most current communication requirements in domestic, public and business scenarios.

Similar to other wireless technologies, WLANs have evolved by integrating the latest technological advances in the field as soon as they have become sufficiently mature. IEEE 802.11n-2009 adopted Single-user Multiple Input Multiple Output (SU-MIMO), channel bonding and packet aggregation. Those mechanisms were further extended in IEEE 802.11ac-2013, which also introduced Downlink Multi-user (MU) MIMO transmissions. These new features have improved the spectrum utilization efficiency and raw WLAN performance. In addition, new amendments such as the IEEE 802.11af-2013 and the IEEE 802.11ah-2017 are further expanding the application scenarios of WLANs, which include cognitive radio, long-range communication solutions, advanced power saving mechanisms, and support for Machine to Machine (M2M) devices.

Partly because of their own success, next-generation WLANs face two main challenges. First, they must address dense scenarios, which is motivated by the continuous deployment of new Access Points (APs) to cover new areas and provide higher transmission rates. Second, the current evolution of Internet usage towards real-time high-definition audio and video content will also significantly increase users' throughput needs in the upcoming years.

To address those challenges, the High-Efficiency WLAN (HEW) Study Group [2] is currently working on a new high-throughput amendment named IEEE 802.11ax-2019. This new amendment will develop new physical (PHY) and medium access control (MAC) layer enhancements to further improve the WLAN performance, with a focus on the user experience in terms of both throughput and battery duration. To achieve these goals, IEEE 802.11ax-2019 will work with other in-progress amendments such as IEEE 802.11aq-2016 (pre-association discovery of services), IEEE 802.11ak-2017 (bridged networks) and IEEE 802.11ai-2016 (fast initial link setup time). In addition, the use of more intelligent APs and coordinated multi-AP deployments will add all of the necessary features to satisfy the created expectations.

This article overviews some new technological enhancements that may be considered in the IEEE 802.11ax-2019 amendment for infrastructure WLANs and describes the potential benefits and drawbacks of each enhancement. We have grouped these enhancements into four main categories: spatial reuse, temporal efficiency, spectrum sharing and multiple-antenna technologies. Then, we describe how IEEE 802.11ax-2019 WLANs must work with other IEEE 802.11 amendments such as IEEE 802.11ai-2016, IEEE 802.11aq-2016 and IEEE 802.11ak-2017 to offer an improved user experience.

2 Scenarios, Use-cases and Requirements

The motivation to develop a new IEEE 802.11 amendment is related to the forecast user demands in the 2020-2030 decade. These user demands are primarily related to the delivery of high-definition audio-visual real-time and interactive content in dense WLAN scenarios.

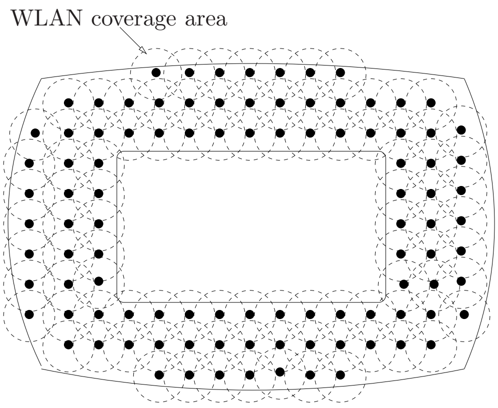
2.1 Dense WLAN scenarios

A WLAN dense scenario refers to the case in which there are multiple neighboring WLANs using overlapping channels, many stations (STAs) under the coverage of a single AP, or both. Figure 1 depicts and describes three key scenarios for next-generation WLANs: a) a stadium b) a train, and c) an apartment building. In these dense scenarios, most relevant challenges are related to interference issues, which increase the packet error rate and reduce the area throughput (i.e., the number of concurrent transmissions in a given area) by preventing neighboring WLANs from accessing the channel due to Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) rules. Additionally, the presence of many STAs in the same area increases the chances that two or more STAs simultaneously start a transmission, which results in a collision.

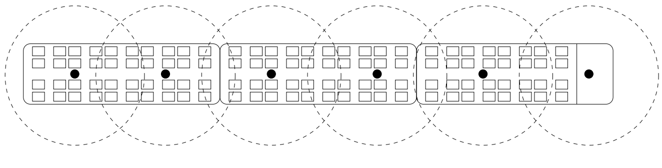
In the stadium scenario, many people are concentrated in small areas because of a fair, a conference or a sporting event. The presence of many people results in a high density of STAs and the necessity for deploying many APs to offer satisfactory service. A fundamental challenge in these scenarios is to deploy, optimize and coordinate such a large number of APs and STAs.

Public transport is also a key scenario for next-generation WLANs because trains, buses and planes will offer broadband Internet access. In these scenarios, the user density may be notably high, with several people per square meter. Then, a smart AP coordination can help

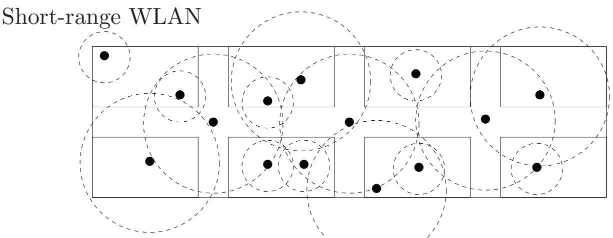
Scenario	APs	STAs	Description
Stadium	> 1000	> 50000	Large events that require many APs to provide a satisfactory connectivity service able to support video uploading/downloading.
Train	< 10	> 1000	Full coverage inside a train to provide both work and entertainment services.
Multiple Apartments	< 5	< 20	Several short-range APs deployed through the apartment, offering full coverage and high data rates for bandwidth hungry entertainment applications, as well as connectivity for house appliances.



a) Stadium



b) Train



c) Floor of a building with several apartments

Figure 1: Key scenarios in next-generation WLANs

improve the spatial reuse, and the use of an efficient medium access protocol may help support many simultaneous contenders.

Finally, in the apartment building, we can find multiple autonomous and heterogeneous WLANs overlapping, including short-range WLANs that offer high transmission rates in small spaces [3]. In this scenario, each WLAN is primarily configured independently of the others, where the channel selection, channel width and transmission power are randomly set or are simply the pre-set values. Therefore, autonomous WLANs must be able to implement smart decentralized self-configuration and self-adaption mechanisms to minimize the interference among them.

WLANs must also coexist with other wireless networks that operate in the ISM band, such as Wireless Sensor Networks and Personal Area Networks. In addition, Long-Term Evolution (LTE) operators currently consider deploying LTE networks in the ISM band [4], which is known as LTE-Unlicensed, thus opening further coexistence challenges for WLANs.

2.2 Future WLAN usages

Interactive and high-definition video applications are predicted to dominate future Internet usage. Two examples of applications that require throughputs of several Gbps are high-definition multi-party video conferences in business environments, which can help avoid unnecessary travel and meetings, and virtual reality entertainment applications at home, which include culture, films and games. Additionally, web surfing is moving further towards a multimedia experience, where rich text, images, audio and video content interact. Furthermore, file storage, management and file synchronization in the cloud are becoming the standard in terms of content management and generation. Those applications are bandwidth-demanding and require both reliability and limited delay.

2.3 Requirements

Based on the aforementioned scenarios and expected use-cases, there are four key requirements for next-generation WLANs.

1. **Coexistence**: WLANs operate as unlicensed devices in the ISM (Industrial, Scientific and Medical) bands. Therefore, they must be able to fairly coexist both with the other wireless networks that also operate there and with the licensed devices.

2. **Higher throughput**: Improving both the system and user throughput requires the improved use of channel resources. IEEE 802.11ax-2019 aims for a 4-fold throughput increase compared with IEEE 802.11ac-2013. To achieve this goal, some new wireless technologies such as Dynamic CCA (Clear Channel Assessment), OFDMA (Orthogonal Frequency Division Multiple Access), and advanced multiple-antenna techniques may be used.

3. **Improved user experience**: The user experience is directly related to provisioning users with the resources required for a smooth and pleasant operation, which implies that the network must be able to allocate sufficient resources for each user based on his/her specific traffic and usage patterns. In addition, the energy efficiency-related aspects, such as improving the battery duration of the nodes, are a fundamental part of the user experience. The target in IEEE 802.11ax-2019 is - at least - to not consume more than the previous amendments, considering the aforementioned 4-fold throughput increase, which requires both new low-power hardware architectures [5] and new low-power PHY/MAC functionalities.

4. **Backward Compatibility**: Because IEEE 802.11ax-2019 WLANs must support any IEEE 802.11 device, mechanisms must also be implemented to make it backward compatible (i.e., common frame headers and transmission rates), although it is a clear source of inefficiency. Alternatively, vendors may opt to implement multiple WLAN networks in the same AP and distribute the active STAs among them according to the latest amendment that they implement.

3 New Features and Concepts

The IEEE 802.11ax-2019 amendment may include some new technical features compared with the IEEE 802.11ac-2013 amendment. A brief description of the most relevant features and some insights into their potential performance gains are introduced below.

3.1 Spatial reuse

In dense scenarios, the combined use of CSMA/CA, a conservative Clear Channel Assessment (CCA) and a high transmit power level may result in scenarios with limited spatial reuse. A conservative configuration of both parameters minimizes the interference among the WLANs, which supports higher transmission rates. However, the number of concurrent transmissions is reduced, which may decrease the achievable area throughput. The alternatives that can be used to reach an optimal tradeoff and maximize the area throughput include adapting the transmit power level, CCA level and directional transmissions.

Figure 2(a) shows three neighboring WLANs. The channels that each WLAN uses are shown in Figure 2(b). Because WLANs A and C, and B and C, partially share their channels, they overlap. The three APs are inside the carrier sense range of the others as shown in Figure 2(a), which pauses their backoff if either of the other two transmits. Although WLAN C uses the widest channel, it achieves the lowest throughput because it overlaps with WLANs A and B that are independent between them (Figure 2(c)).

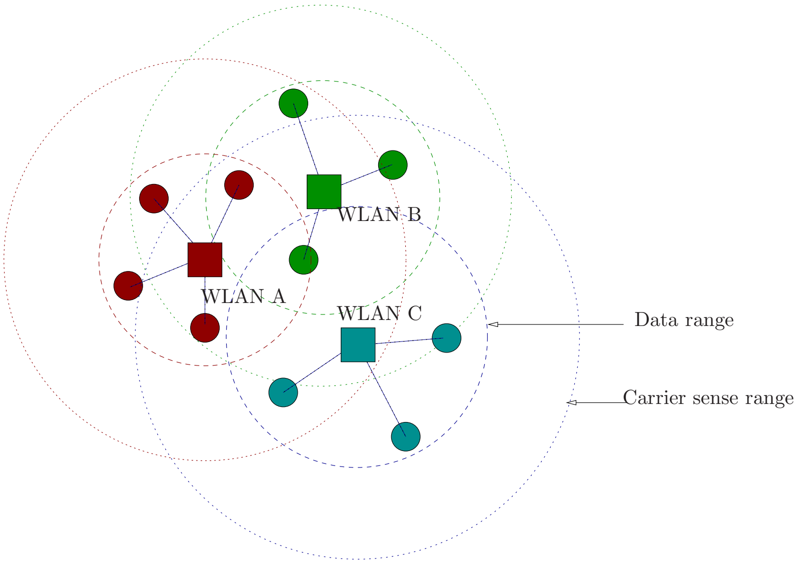
3.1.1 Dynamic transmit power and CCA levels

Reducing the used transmission power in a WLAN reduces its influence area, which benefits the spatial reuse. However, it may result in a larger number of packet errors and lower transmission rates in that WLAN because the Signal to Noise and Interference Ratio (SNIR) is also reduced. In addition, not all nodes in the same WLAN can listen to an on-going transmission, which potentially increases the number of hidden nodes.

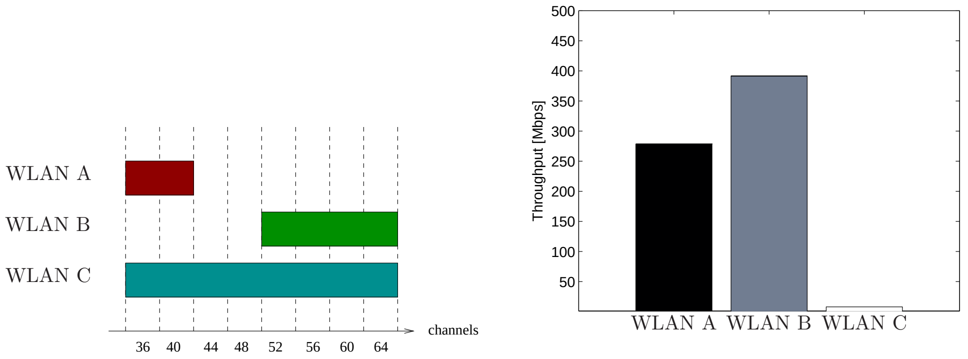
Alternatively, to reduce the area of influence of neighboring WLANs and increase each WLAN's chances to transmit, the nodes in a WLAN may increase their CCA level and require a higher energy level to be detected in the channel for the channel to be considered busy and the node to pause the backoff. In [7], significant throughput gains are achieved by tuning the CCA level in a multi-cell WLAN scenario. The downside of increasing the CCA level is again the higher interference that a node may suffer, which may be detrimental in some cases.

3.1.2 Beamforming

Omnidirectional transmissions homogeneously spread the transmitted energy in all directions, which fills the channel with energy in areas where it is not required. Concentrating the energy towards the desired destination improves the spatial reuse and SNIR at the target destination because the devices that are placed in other directions will observe the channel as being empty. Therefore, the use of beamforming may also reduce the WLANs' influence area and allow



(a) Three overlapping WLANs. Dashed lines represent the carrier sense-range



(b) Channel used by each WLAN

(c) Throughput achieved by each WLAN

Figure 2: Throughput unfairness between overlapping WLANs. The throughput plot is obtained using the analytical model and the parameters presented in [6], that correspond to those defined in the IEEE 802.11ac-2013 amendment.

concurrent transmissions from neighboring WLANs. However, the number of potential hidden nodes may be higher since nodes outside the energy beam will detect the channel as empty.

3.2 Temporal Efficiency

The backoff process, packet headers, interframe spaces, collisions and retransmissions are an intrinsic part of the Enhanced Distributed Channel Access (EDCA) protocol, but they significantly decrease the time that a node spends transmitting data every time it accesses the channel. IEEE 802.11ax-2019 may include several solutions to mitigate such overheads.

3.2.1 Control Packets

The overheads caused by the exchange of control packets may result in large overheads, particularly because they are usually transmitted at a low rate. Common control packet exchanges between the AP and STAs include the RTS/CTS exchange to avoid hidden nodes and ACKs to acknowledge the reception of data packets.

Additionally, some of the new technical features described in next sections that enable multi-user transmissions may require an initial exchange of control packets to synchronize all involved STAs, hence also increasing the control packets overheads.

3.2.2 Packet Headers, Aggregation & Piggy-Backing

Packet aggregation was introduced in IEEE 802.11n-2009 to reduce temporal overheads by combining short packets into a longer one. Using packet aggregation, multiple packets can be transmitted with a single backoff, DIFS, SIFS, PHY header and ACK.

The packet header overheads can be reduced by supporting variable size headers and using only the minimum required fields for every packet. Additionally, the use of shorter identifiers instead of the full MAC address is considered.

Moreover, the piggybacking of ACKs with DATA will improve the efficiency, although some changes in the current setting of the Network Allocation Vector (NAV) are required because the full transmission duration is unknown to the transmission initiator.

3.2.3 Efficient retransmissions

Packet errors are also a source of overhead because they currently require the full retransmission of the data packet. Further work about the use of incremental redundancy-based ARQs can reduce the time spent in retransmissions, although it implies some extra complexity in both transmitter and receiver firmware.

3.2.4 Simultaneous Transmit and Receive

By allowing the AP and STAs to simultaneously transmit and receive (STR), the channel capacity can be theoretically doubled [8]. However, when the EDCA is used, the probability that the AP and STA to which the AP transmits a packet simultaneously finish the backoff is notably low. Only when the number of active STAs is low, they have bidirectional and saturated flows and use a small backoff contention window; here, the use of STR can result in some gains. Alternatively, the STR capability can allow WLANs to replace the Collision Avoidance (CA) feature, which is currently used in EDCA with the Collision Detection (CD) feature, because collisions can be promptly detected and resolved.

3.2.5 Collision-free MAC protocols

Collisions represent an important waste of channel resources in WLANs. IEEE 802.11ax-2019 may consider enhancing or changing the underlying CSMA/CA protocol in the EDCA to minimize collisions. There are two possibilities: moving to a centralized solution or enhancing the current CSMA/CA protocol. Because centralized options such as the Hybrid coordination function Controlled Channel Access (HCCA) were never adopted in WLANs, a focus on enhancing

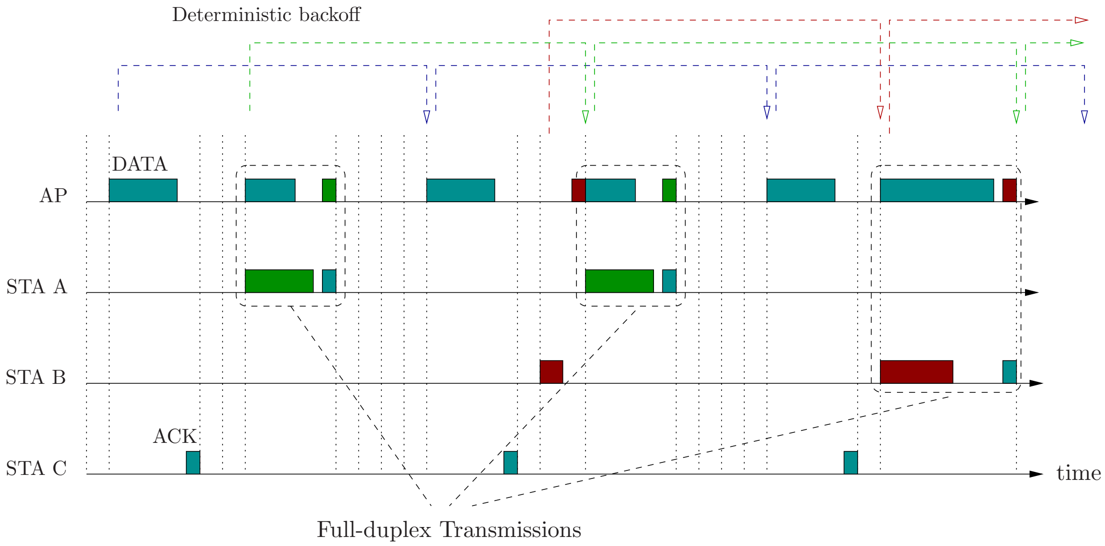


Figure 3: CSMA/ECA operation. It can be observed how the use of a deterministic backoff allows to predict when a node will transmit after it has transmitted successfully.

the CSMA/CA appears more plausible. CSMA/ECA is a particularly good candidate to replace CSMA/CA because it is backward compatible, is easily implemented and outperforms CSMA/CA in all cases [9].

Figure 3 shows the basic operation of CSMA/ECA with STR. Compared with CSMA/CA, the main difference observed for CSMA/ECA is its use of a deterministic backoff after successful transmissions. This deterministic backoff guarantees that after some time, a collision-free schedule can be achieved. In addition, because the AP can learn when the STAs will transmit, the use of STR can provide huge performance gains.

3.3 Spectrum Sharing

An unplanned deployment of WLANs results in a chaotic and fragmented spectrum occupancy, which causes many inefficiencies and undesirable interactions among neighboring WLANs. In addition, the use of channel bonding to obtain better WLAN performance exacerbates them [6]. To improve the spectrum usage efficiency, two main approaches can be considered in IEEE 802.11ax-2019: dynamic channel bonding and OFDMA.

3.3.1 Dynamic Channel Bonding

To adapt to the instantaneous channel occupancy, IEEE 802.11ax-2019 may consider the use of a packet-based dynamic spectrum access, which extends the Dynamic Bandwidth Channel Access (DBCA) scheme in [10]. Using DBCA, only the available channel width is used at each transmission, which allows the WLANs to adapt to the instantaneous spectrum occupancy. This mechanism helps fill most spectrum gaps and share them fairly them among neighboring WLANs.

3.3.2 OFDMA

The use of OFDMA adds a new degree of flexibility to the use of channel resources by dividing the channel width into multiple narrow channels. Then, these narrow channels can be used to transmit to multiple users in parallel [11]. A basic implementation of OFDMA in WLANs may simply consider the use of multiple independent 20 MHz channels. This approach is shown in Figure 4: when channel bonding is used, each 20 MHz subchannel can be independently allocated to a different user. The RTS' packet has been extended to announce the subchannels allocation to the STAs. Additionally, OFDMA may enable the use of non-contiguous channel bonding and remove the requirement to use only 20 MHz consecutive channels.

Figure 4(a) shows an example where Dynamic Channel Bonding and OFDMA operate together. The upper part of Figure 4(a) shows a snapshot of the spectrum occupancy for a group of neighboring WLANs. The lower part of Figure 4(a) shows two transmissions: a node in the target WLAN transmits to a single user via a bonded channel of 40 MHz (left), and a node uses a bonded channel of 80 MHz and OFDMA to transmit to three different users (right). Figure 4(b) shows the AP throughput when OFDMA is used to split a 160 MHz channel into multiple subchannels. The parallelization of temporal overheads clearly improves the throughput.

3.4 Multiple Antennas

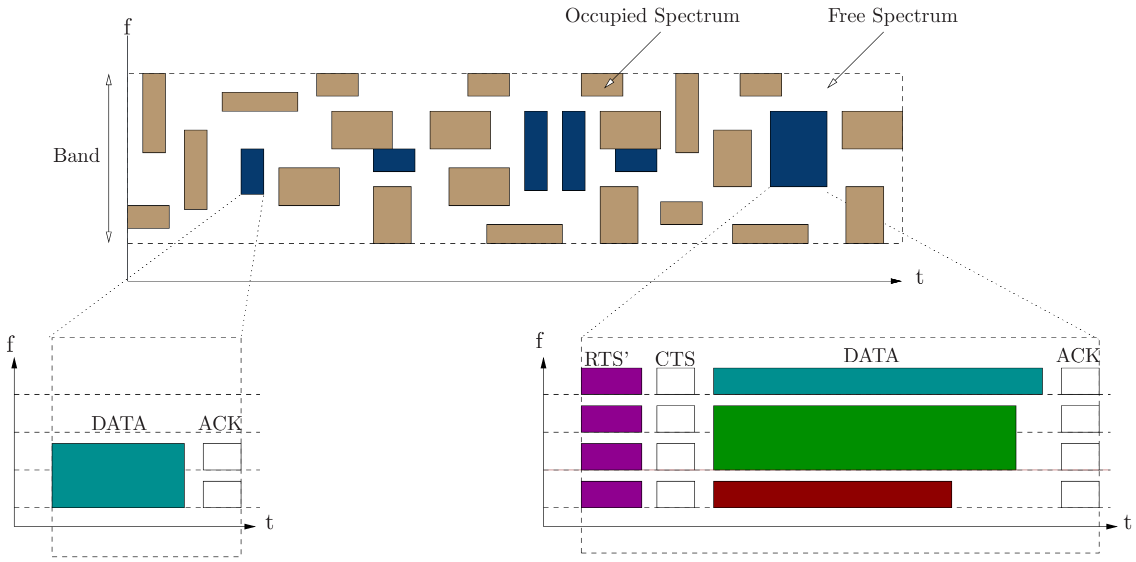
Spatial Multiplexing using multiple antennas at both AP and STAs remains one of the key technologies to achieve high transmission rates in WLANs. IEEE 802.11ax-2019 will continue implementing both SU-MIMO and Downlink MU-MIMO, as in IEEE 802.11ac-2013. However, it may also include or provide support for Uplink MU-MIMO, Massive MIMO and Network MIMO.

3.4.1 MIMO

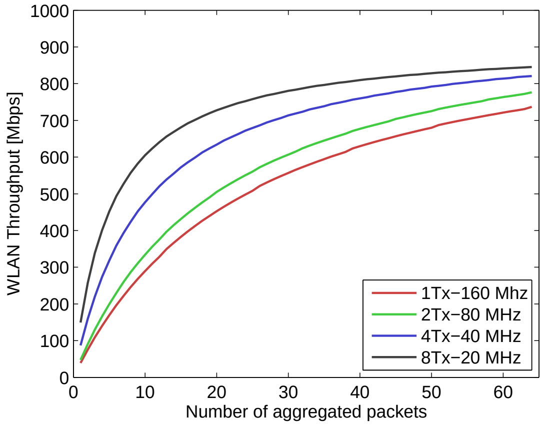
Multi-user MIMO enables multiple simultaneous transmissions to different users in both downlink and uplink. In the uplink, MU-MIMO transmissions can be used to mitigate the collision probability by allowing multiple STAs to simultaneously transmit. A survey of MU-MIMO MAC protocols for WLANs is shown in [12], where both uplink and downlink MU-MIMO MAC proposals for WLANs are reviewed. The use of SU-MIMO will be maintained as a mechanism to increase the transmission rate in point-to-point communications.

A challenge for IEEE 802.11ax-2019 is to reduce the channel sounding overheads when the same explicit approach as in IEEE 802.11ac-2013 is considered. The overhead caused by the explicit channel sounding protocol depends on the channel sounding rate and number of sounded STAs, which can result in an unacceptable overhead in dense scenarios with many STAs. The solutions used to reduce these large overheads require the use of smart schedulers that maximize the CSI availability and consider the instantaneous buffer occupancy and other QoS requirements from the users.

Figure 5(a) shows an AP with three STAs. In the left side, we have three downlink MU-



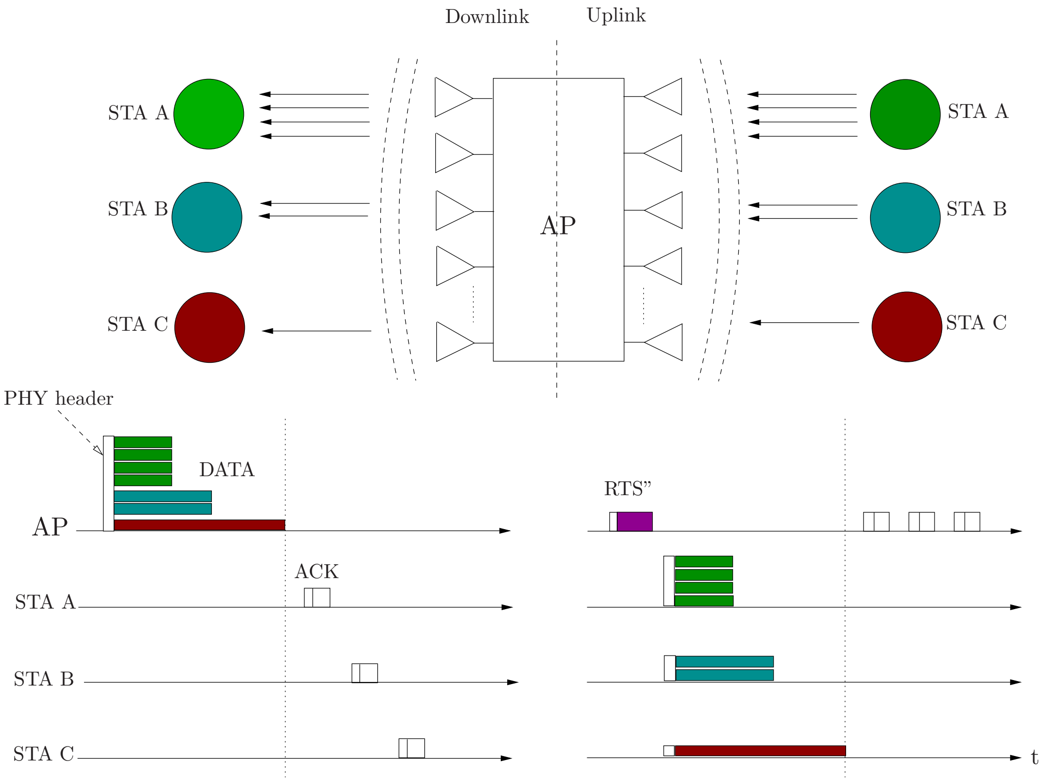
(a) Dynamic Channel Bonding and OFDMA.



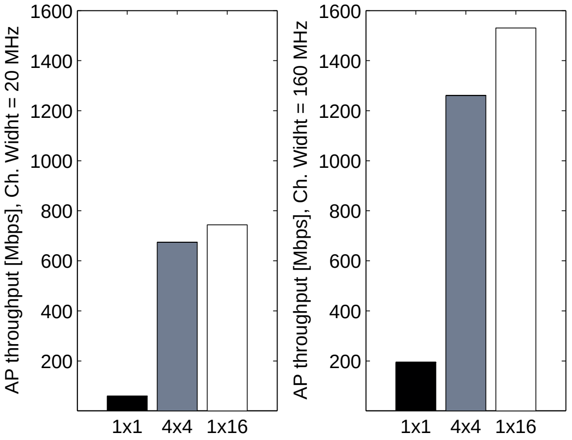
(b) Throughput using a channel width of 160 MHz and OFDMA.

Figure 4: Dynamic Spectrum Access with and without OFDMA. The RTS' size is $120+56\cdot N_{\text{tx}}$, with N_{tx} the number of OFDMA subchannels. The rest of the parameters, as well as the throughput model, are obtained from [6].

MIMO transmissions. The ones directed to STAs A, B and C contain four, two and one spatial streams, respectively. To start a downlink transmission, the AP omnidirectionally sends the PHY header with information about the group of selected STAs and the number of spatial streams that are transmitted to each STA. It is also observed that increasing the number of streams sent to the same destination (i.e., SU-MIMO) can reduce the packet transmission duration. On the right side, we show an uplink MU-MIMO transmission. In IEEE 802.11ax-2019, uplink MU-MIMO transmissions may be started by the AP to maximize the WLAN efficiency using a special RTS" packet because several STAs are unlikely to finish their backoff countdowns at the same slot. Then, the selected STAs will simply transmit in parallel and wait to receive the corresponding ACKs. Figure 5(b) shows the AP throughput when it is equipped



(a) Downlink and Uplink MU-MIMO transmissions in WLANs



(b) Downlink Throughput. The AP is equipped with sixteen antennas.

Figure 5: Multi-user spatial multiplexing. The considered parameters, as well as the throughput model, are obtained from [6].

with 16 antennas and transmits a single stream to a single user (1:1), four streams to four users (4:4) and one stream to sixteen different users (1:16) using 20 and 160 MHz channels.

3.4.2 Massive MIMO

Massive MIMO refers to the case where the AP has many more antennas than STAs and uses them to create a nearly identical number of point-to-point links as the number of active STAs [13]. In addition to the cost of APs, the extra processing complexity and higher energy consumption, other open challenges for massive MIMO include obtaining the CSI information; WLANs may require switching to an implicit channel feedback approach.

3.4.3 Network MIMO

In coordinated WLAN deployments, network MIMO can be used to minimize the interference among simultaneous transmissions from different APs. The idea behind network MIMO is that different APs can coordinate the transmissions as if they were a large array of antennas, which reduces the inter-transmission interference and increases the spatial reuse [14]. However, effectively solving the tight synchronization requirements among the APs remains an open challenge.

4 WLAN-Level Improvements

The user experience will not be simply improved by increasing the achievable network and user throughput as previous technical features do. Some sources of inefficiency can only be removed by adding new functionalities to allow neighboring WLANs to coexist and cooperate whenever possible. The case of uncoordinated WLAN deployments is particularly interesting because the design of smart decentralized algorithms for channel allocation when wider channels are used, CCA and TPC adaption remains an open challenge.

In scenarios where multiple APs of the same administration domain are used to offer a large coverage area or higher data rates by overlapping multiple WLANs, a mechanism that enables a fast hand-off among the APs is required because the current large delays when a STA switches to a new AP are unacceptable for providing a high user experience. The IEEE 802.11ai-2016 amendment targets this challenge. It aims to provide a handoff duration below 100 msecs by implementing preemptive channel sensing and user authentication. Other alternatives based on a centralized virtual AP that balances the users and manages handoffs among the APs are also interesting solutions.

Device-to-device (D2D) communications, which are also known as Wifi Direct in the IEEE WLAN context, will also be a key element in next-generation WLANs [15]. Examples of D2D communications are file synchronization with an external hard disk and instantaneous file exchange between a mobile phone and a projector/smart television. The use of D2D communications will reduce the amount of airtime required for each transmission by allowing higher data rates and avoiding the use of the AP as a relay. Beamforming is an interesting feature for D2D communication because it may allow concurrent transmissions inside the same WLAN. If two STAs in the same WLAN cannot directly communicate, the use of Network Coding can also help reduce the number of transmissions.

IEEE 802.11ax-2019 aims to operate in the range of 1-6 GHz, which supersedes and integrates IEEE 802.11n-2009, IEEE 802.11ac-2013 and IEEE 802.11ah-2016. In a few years, every single AP will most likely implement two IEEE 802.11ax-2019 instances that independently operate at 2.4 and 5 GHz with a IEEE 802.11ah-2016 WLAN at 1 GHz for M2M and long-range communications and one IEEE 802.11ad-2012 WLAN at 60 GHz for notably fast point-to-point communications. In this situation, the STAs of any of those networks should be able to communicate with the STAs in another WLAN. This goal is the aim of the IEEE 802.11ak-2018 amendment, which focuses on bridging multiple operating WLANs in the same AP.

Finally, IEEE 802.11ax-2019 WLANs will use traffic differentiation, flow admission control and groupcast mechanisms from the IEEE 802.11e-2007, IEEE 802.11ae-2012 and IEEE 802.11aa-2012 amendments to support multimedia traffic with the required QoS to achieve an improved user experience.

5 Conclusion

We have reviewed some technological options that can be included in the IEEE 802.11ax-2019 amendment for WLANs to further improve the throughput. Moreover, we believe that the most disruptive performance and user experience improvements for next-generation WLANs will be related to the integration of IEEE 802.11ax-2019 with other recently approved or ongoing amendments and by developing efficient and smart mechanisms to improve the coexistence and cooperation among WLANs.

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