IEEE 802.11AX: CHALLENGES AND REQUIREMENTS FOR FUTURE HIGH EFFICIENCY WIFI

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ABSTRACT

The popularity of IEEE 802.11 based wireless local area networks (WLANs) has increased significantly in recent years because of their ability to provide increased mobility, flexibility, and ease of use, with reduced cost of installation and maintenance. This has resulted in massive WLAN deployment in geographically limited environments that encompass multiple overlapping basic service sets (OBSSs). In this article, we introduce IEEE 802.11ax, a new standard being developed by the IEEE 802.11 Working Group, which will enable efficient usage of spectrum along with an enhanced user experience. We expose advanced technological enhancements proposed to improve the efficiency within high density WLAN networks and explore the key challenges to the upcoming amendment.

INTRODUCTION

Wireless networks have witnessed continuous and increasing popularity, attracting an ever growing number of users. This has resulted in a considerable increase in data consumption over all networks. As highlighted in Fig. 1, it is expected that by 2019, global data traffic will be 10 times higher than the level measured in 2014.

Since a major part of the traffic is generated and consumed indoors, indoor connectivity solutions can be instrumental in addressing the aforementioned capacity requirements.

IEEE 802.11 based WLANs, which are the most popular and successful indoor wireless solutions, have evolved as a key enabling technology to cover medium to large scale enterprises, public area hot-spots, apartment complexes, and so on. Such environments are characterized by multiple small cells with many access points (APs), and serve a large number of clients, where an increase in coverage and high data rates are the primary achievements.

In recent years there has been a major surge in WLAN deployment in geographically limited environments (encompassing multiple OBSSs). The strategic importance of WiFi technology (in terms of the expected number of WiFi-capable devices) so as to meet traffic demand by the year 2019 is highlighted in Fig. 1. The following facts about the global market size of WiFi clearly indicate the popularity of IEEE based WLAN networks. It is estimated by [2] that the global worth of the WiFi market was USD 14.8 billion in 2015, and it is projected to increase to USD 33.6 billion by 2020.

The IEEE 802.11 standardization committee has actively continued to release new draft amendments to incorporate the latest technological advances. Compared to cellular technologies, IEEE 802.11 standards/amendments are released to be backward compatible and thus pile on top of each other by adding and removing key technical aspects.

Recently, the IEEE 802.11 Working Group approved the development of a new WLAN standard: IEEE 802.11ax. Task Group 802.11ax (TGax) is currently working on the design of an extension of the IEEE 802.11ac standard, aiming to improve system capacity (and not only the supported data rates at link level). More specifically, it is intended to improve efficiency in scenarios that are interference limited (due to the high density of IEEE 802.11 devices).

In this article, we introduce the future high efficiency WiFi (i.e. IEEE 802.11ax) amendment. We first point out the necessity of the amendment. We then discuss use cases and provide an overview of key technological features proposed for the IEEE 802.11ax amendment. Then we identify two major challenges that the next generation of WiFi networks will face: coexistence with unlicensed LTE, and adoption of the IoT paradigm.

IEEE 802.11AX AMENDMENT: VISION AND REQUIREMENTS FOR HIGH EFFICIENCY WIFI

The future IEEE 802.11ax standard aims to improve spectral efficiency and area throughput in real world densely deployed WiFi environments. Since the available number of orthogonal channels for IEEE 802.11 is limited, the OBSS situation in IEEE 802.11 based networks is frequent. The collision avoidance mechanism tends to reduce network throughput and increase transmission delays where, despite acceptable collision probability, the medium is never fully utilized. Figure 2 indicates the OBSS problem. The scenario of three overlapping co-channel cells,

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each encompassing one AP and five associated stations, is simulated. With the decrease in overlapping areas, the average throughput within each cell increases (e.g., a throughput increase of more than 400 percent is visible when the overlapping area between adjacent cells decreases from 38 percent to 7 percent). The reduction of the overlapping areas could be achieved by applying different techniques introduced by IEEE 802.11ax, as discussed later. In the following sections, we highlight the need and significance of this new WLAN standard.

Basic Necessity

While the current IEEE 802.11 standards (i.e., IEEE 802.11n/ac) were developed with the goal to improve peak aggregate multi-station throughput of the network, proper mitigation of increased interference incurred has not yet been addressed. Furthermore, the channel access method in the aforementioned standards is overly protective, leading to reduced spatial reuse. In particular, this future IEEE 802.11ax standard is intended to utilize techniques that would increase the physical bit rate, but also reduce the frame error rate (FER) and improve spectral reuse by allowing highly efficient multi-user access and by mitigating/reducing interference, which would in return increase area throughput.

Scope of the New Amendment

The IEEE 802.11ax standard is primarily being designed to provide high efficiency WLAN operation in both indoor and outdoor environments, where paramount importance is placed on increasing the robustness outdoors as well as over the uplink transmissions. This standard aims to improve several performance metrics (such as average per station throughput, area throughput, and so on) that directly result in increased efficiency over several closely placed basic service set (BSS) deployments. Thus, the scope of the proposed amendment is to define standardized modifications of the PHY and MAC layers of legacy the IEEE 802.11 standard to improve the end user experience in densely deployed WLAN environments. The scope of the proposed amendment can be further elaborated by the following.

Improved System and User Throughputs in Dense Deployments: This amendment is expected to increase at least four times the area throughput, while targeting an increase up to 10 percent in the average throughput per station.

Maintaining and Improving Power Efficiency: While enhancing the user experience in terms of increased throughput of end users, the aforementioned standard also aims to maintain and enhance power efficiency by enabling simplified power save modes for each device.

Efficient use of Spectral Resources: The standard is expected to provide methods that would ensure efficient use of spectrum resources.

Indoor and Outdoor Operations over 1 GHz to 6 GHz Frequency Bands: IEEE 802.11ax is mainly focused on WLAN operations at 2.4 GHz and 5 GHz, but will cater the mode of operations between 1 GHz and 6 GHz.

Enabling Backward Compatibility: It is also expected to be backward compatible to support communications with any IEEE 802.11 legacy device.

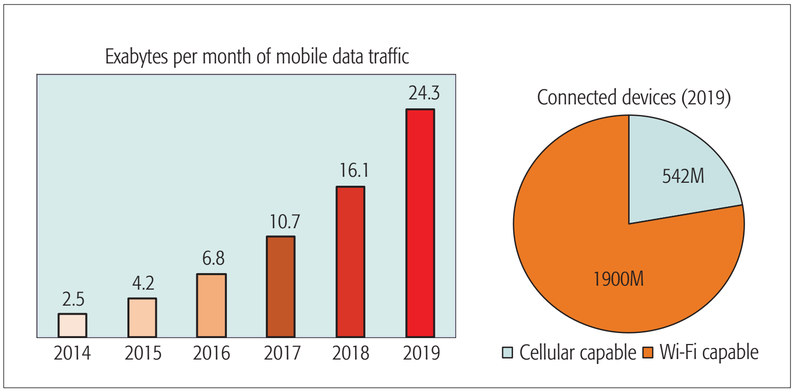

FIGURE 1. The strategic importance of WiFi technology [1].

Intended Environments/Use Cases

The IEEE 802.11ax standard aims to provide self-configuration and self-adaption abilities to increase area throughput. Therefore, TGax has prioritized the following use cases for the development and evaluation of different features.

Residential: In this environment, high density OBSSs are created when a large number of WLAN APs are installed in close vicinity such as in an apartment building. In such a scenario, an increased interference level (due to unmanaged and unplanned deployments) can greatly affect the performance of devices within the network.

Enterprise: Similar to a residential environment, enterprises/organizations are providing WiFi as their primary/only source of access to the Internet through a managed network. Interference management issues and bring your own device (BYOD) policies hold the utmost importance in these environments, as well as in scenarios where different enterprise networks are present at close proximity.

Indoor Small BSS Hotspots: This environment represents a scenario with a high density of APs and non-AP stations, where the BSS from each operator is deployed in regular symmetry (e.g., shopping malls, airports, railway stataions, and so on). Different cells of different operators can overlap and cause interference that may degrade the performance within an area.

Outdoor Large BSS Hotspots: The main objective of this scenario is to model an outdoor deployment (similar to cellular mobile networks) that consist of a high density of non-AP stations along with maximum separation among different APs. In such an environment, potential interference from different non-AP stations can severely affect the end user experience and reduce overall performance.

Vehicular: IEEE 802.11ax intends to reduce the effect of variable interference of neighboring vehicles as well as to explore possible methods to reduce the restriction on the vehicle to infrastructure communication (i.e., mobility considerations and signal directivity).

Other Notable Environments: Campuses, factory environments (where several hundred APs can be concentrated in a small area), small offices (a single BSS with a limited number of devices encountering unmanageable interference), and IoT use-cases, are also being explored by the TGax as possible use case environments.

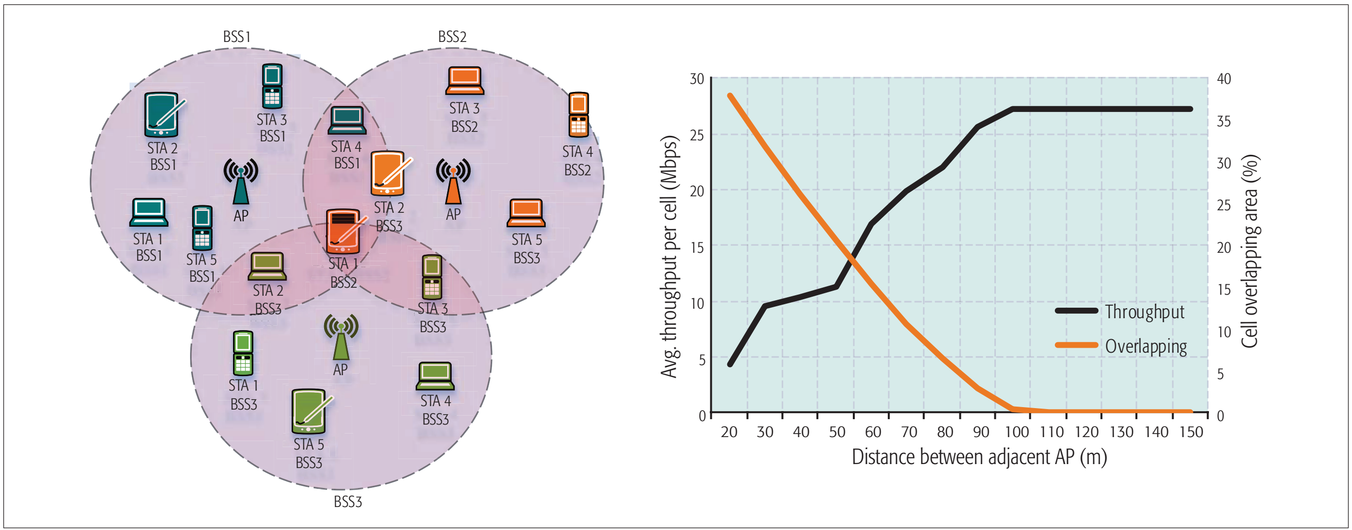

FIGURE 2. High density scenario where numerous WiFi enabled devices coexists with overlapping BSS problem.

Overview of Key Technological Features of the High Efficiency WiFi Amendment: IEEE 802.11ax

In order to improve the user experience by reducing interference as well as to provide improved aggregate multi-station throughput, the IEEE 802.11ax amendment is being developed that aims to significantly improve WLAN efficiency along with system level performance in dense deployments. TGax intends to introduce radio technology based on multiple-input multiple-output (MIMO) and orthogonal frequency-division multiple access (OFDMA), so that more bits can be transmitted per transmission opportunity (TXOP).

In this section, we provide a thorough overview of important features proposed for the IEEE 802.11ax amendment. We organize proposals into the following four categories; PHY, MAC, multi-user, and other notable features. With the help of Fig. 3, we highlight the expected improvements (in-terms of system throughput) of the four aforementioned categories (where multi-user techniques indicate the largest gain). It is pertinent to mention that the expected percentage improvement of each proposal is inferred by the studies submitted and discussed at the TGax. Table 1 summarizes the main features introduced by TGax as detailed in this section.

PHY Layer Enhancements

Although IEEE 802.11ax is an evolution of the IEEE 802.11ac standard, it aims to adopt new technologies while being backward compatible. For example, IEEE 802.11ax physical layer convergence protocol (PLCP) protocol data unit (PPDU) intends to include a legacy preamble duplicated on each 20 MHz subchannel so as to solve the backward compatibility and coexistence challenge. In addition, TGax is also contemplating the design of new preamble types needed to support new features. The noteworthy amendments proposed at the physical layer for IEEE 802.11ax are explained as follows.

Physical Coding Decision (LDPC and BCC): The default forward error correction (FEC) scheme proposed for IEEE 802.11n and IEEE 802.11ac is based on binary convolutional coding (BCC) with frequency interleaving per orthogonal frequency division multiplexing (OFDM) symbol. Using low density parity check (LDPC) is optional and has not yet received much attention from the WLAN due to its high computational cost. However, it has been shown that LDPC codes can provide significant gains (in-terms of capacity) when compared to BCC [3]. IEEE 802.11ax proposes to use LDPC when using large bandwidth (i.e., channel bonding) and to use BCC in narrower bandwidths.

1024-QAM: One of the solutions proposed by TGax to achieve a four-fold increase in average throughput is to incorporate a very high optional modulation scheme (i.e., 1024-QAM) where each symbol encodes a larger number of data bits when using such a dense constellation.

Enhancement for Outdoor Communication: In order to improve the spectral efficiency of stations over the intended use cases, TGax intends to utilize four times larger FFT size than that used for IEEE 802.11ac. This larger FFT size is proposed to increase robustness outdoors as well as to improve the average indoor throughput.

To subdue the large path loss and channel delay suffered in outdoor large hotspots, TGax defines a new high efficiency PPDU (HE-PPDU) format, called Extended Range Single User (SU) PPDU, in which the fields that contain the information required to interpret packets are repeated.

Frequency Selective Scheduling: OFDMA systems benefit from frequency selectivity in terms of frequency diversity and frequency selective scheduling (FSS). In TGax, FSS is being actively pursued to provide throughput gains to far away stations (with respect to AP) by allocating physical resource blocks with the least amount of fading for their transmissions. Furthermore, IEEE 802.11ax intends to adapt dual sub-carrier modulation (a scheme that modulates the same information on a pair of far apart sub-carriers) to improve FER performance and robustness against narrow-band interference under dense deployments.

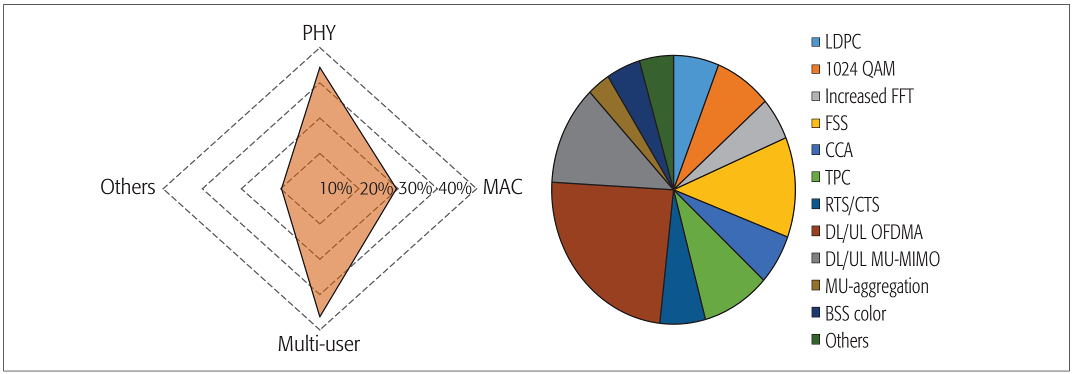

FIGURE 3. Expected improvements by different novel methods proposed for TGax in order to increase the efficiency of WLAN networks.

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Parameter	IEEE 80 2.11ac	IEEE 802.11ah Draft 10	IEEE 802.11ax Draft 0.4
Spectrum	<6 GHz, excluding 2.4 GHz	863–868 MHz Europe and 902-928 MHz US	Between 1 and 6 GHz
Bandwidth	20 to 160 MHz	1 to 16 MHz	20 to 160 MHz
Modulation	BPSK to 256 QAM	BPSK to 256 QAM	BPSK to 1024 QAM
FFT size	64 to 512	32 to 512	256 to 2048
OFDM symbol duration	3.2μs + 0.8/0.4 μs GI	32μs + 8/4 μs GI	12.8μs + 0.8/1.6/3.2μs GI
Pilot sub-carriers	4/6/8/16	2/4/6/8/16	2/4/6/8/16
Subcarrier spacing	312.5 kHz	31.25 kHz	78.125 kHz (smaller value to increase range/coverage for OFDMA systems)
Number of spatial streams	1 to 8	1 to 4	1 to 8
MIMO	SU and DL-MU	SU and DL-MU	SU and DL-UL-MU
Guard interval	Long and short	Long and short	Long, additional guard interval durations for outdoor channels, short guard not available
Backward compatibility	IEEE 802.11a/n	NA	IEEE 802.11a/b/g/n/ac
Mechanism to reduce power consumption	NA	TWT	TWT

TABLE 1. Comparison of IEEE 802.11ax amendment with IEEE 802.11ac and 802.11ah amendments.

MAC LAYER ENHANCEMENTS

TGax is working on the following notable MAC enhancements.

Improving Spatial Reuse (PHYCCA Modifications): The legacy IEEE 802.11 utilizes physical clear channel assessment (PHYCCA) modules to sense state of the channel (i.e., either busy or idle) by measuring the received energy. The IEEE 802.11ax proposed amendment aims to formally embrace the dynamic PHYCCA modifications. These methods allow multiple concurrent transmissions to coexist and thus increase spectral reuse. The intuition to include these modifications lies in the fact that, in dense deployments, stations may end up always assuming the channel to be occupied (due to fixed carrier sensing range), even though multiple concurrent transmissions might still be possible. TGax has been actively involved in the design of PHYCCA modification schemes, where the dynamic sensitivity control (DSC) algorithm has been proposed as one of the key innovative technologies that can increase the overall throughput.

The basic idea of the DSC scheme is to optimize the existing deployments by appropriately tuning the carrier sense threshold (CST) for each node in a distributed manner. DSC tries to confine the increase and decrease of CST for a station in a bounded area so as to avoid both extremely aggressive and conservative behavior. The throughput gains achieved by DSC are more than 20 percent [4] on average when combined with optimal channel selection (gain increases beyond 40 percent when stations use slow bit rates and send long frames).

Improving Spatial Reuse (Transmit Power Control): TGax is contemplating the standardization of per link transmit power control (TPC) mechanisms with the aim of reducing interference as well as increasing spatial reuse. The goal of the power

OFDMA operates on top of OFDM, where the base station allocates the subset of carriers to each user so as to accommodate multiple simultaneous transmissions. OFDMA uses a synchronous medium access that results in reduced contention (i.e. less collisions).

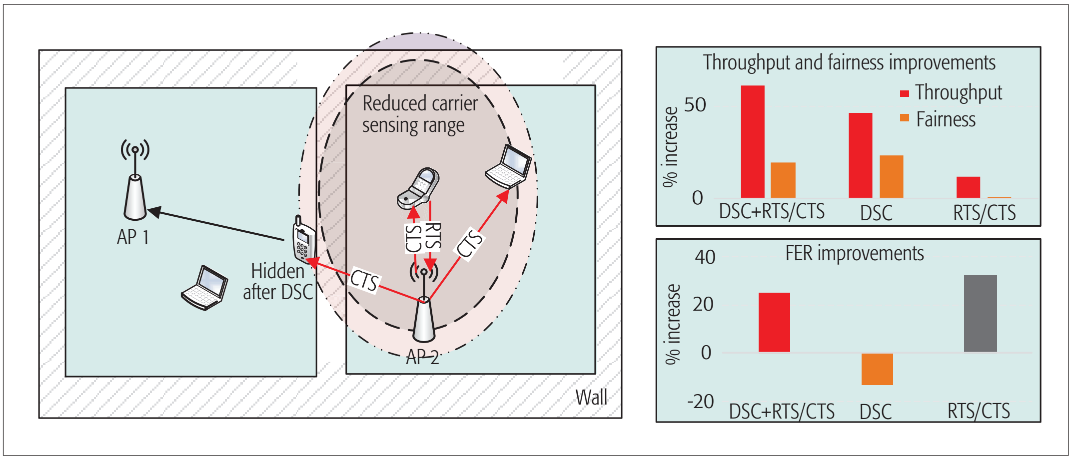

FIGURE 4. TGax proposal for CCA modification and controlled use of RTS/CTS mechanisms.

control mechanism is to dynamically adjust the lowest possible power for stations with the highest path loss with the intent to reach a target signal to interference plus noise ratio (SINR) (enough to correctly decode the received frames).

The TPC method in IEEE 802.11ax also constitutes the change of transmit power control of non-AP stations based on the RSSI of beacon signals received from the associated AP. IEEE 802.11ax envisions the utilization of TPC along with PHYCCA modifications so as to avoid excessive interference from stations that reduce their carrier sensing range to allow more concurrent transmissions.

Improving Spatial Reuse (BSS Color): This is an innovative scheme to increase throughput of dense WLAN networks, where each BSS is assigned a specific color (in-terms of bits designated in the L-SIG field of the physical header). Upon receiving frames from a neighboring BSS, a station can abandon the reception process, assuming the channel is idle during that transmission, thus increasing transmission opportunities. This scheme was initially proposed for the IEEE 802.11ah standard, but has also shown remarkable improvements when used for IEEE 802.11ax use cases.

Improving Spatial Reuse (Multiple NAVs for Spatial Reuse): In legacy IEEE 802.11, virtual carrier sensing is used to solve the collision problem associated with hidden nodes. This technique operates by reserving the wireless channel with the help of request to send/clear to send (RTS/CTS) handshakes (that precede the data frames). The neighboring overhearing stations upon receiving the RTS/CTS frames set a timer (called the network allocation vector (NAV)) that blocks them from transmitting for a specific time.

The IEEE 802.11ax amendment proposes to utilize two NAV timers at each station (one identified as an intra-BSS NAV and the second called a regular NAV) where the intra-BSS NAV is reset or increased only by the frames from that BSS. Thus, spatial reuse can be increased by allowing the station to ignore RTS/CTS frames transmitted from the OBSS.

Interference Management: Since conventional interference management techniques, when applied to dense deployments, also ease overall network conditions, IEEE 802.11ax aspires to intelligently utilize the RTS/CTS method based on observed channel conditions on a per node basis (i.e., an AP can use novel mechanisms to remotely enable RTS/CTS for any of its associated stations). If transmissions are hampered by the suspected existence of hidden nodes (e.g., due to the use of carrier sense adaptation mechanisms such as with DSC), stations can then opt to use the aforementioned method.

In Fig. 4, we indicate simulation results of a network that encompasses DSC and an intelligent RTS/CTS mechanism. Uplink transmissions under saturation condition was assumed where each station was continuously transmitting frames of maximal duration (i.e., the worst case environment scenario was assumed). The details of the simulation environment can be found in [5].

Figure 4 indicates considerable gains when DSC (i.e., around 40 percent throughput gain) and DSC with an intelligent four-way handshake mechanism (i.e., around 60 percent throughput gain) are combined in a dense residential environment.

MULTI-USER (MU) ENHANCEMENTS

An overview of multi-user techniques proposed by TGax is as follows.

Downlink and Uplink OFDMA: OFDMA operates on top of OFDM, where the base station allocates the subset of carriers to each user so as to accommodate multiple simultaneous transmissions. OFDMA uses a synchronous medium access that results in reduced contention (i.e., fewer collisions).

Thus, the IEEE 802.11ax Task Group has defined the uplink and downlink OFDMA (where the minimum size of a resource unit (RU) comprises 26 subcarriers) as the key multi-user feature to improve physical layer efficiency. Different stations in dense environments that inefficiently contended for the shared resources, are allocated to dedicated sub-channels that increase the average end user throughputs. In [6], the authors propose an OFDMA based multi-user access framework for IEEE 802.11ax.

In order to amicably allow the operation of OFDMA, IEEE 802.11ax proposes to utilize a specific HE-PPDU format, called HE trigger-based PPDU, which allows the announcement of scheduling decisions. This feature helps to reduce synchronization complexity. The channel allocation mechanism (consisting of methods to allocate available RUs at the downlink and the uplink) is managed by the AP.

At the uplink, IEEE 802.11ax defines an OFDMA based distributed random access mechanism that randomly selects resource units assigned by the AP for transmission of uplink PPDUs. The trigger frame includes a parameter to initiate random access at the uplink.

Downlink and Uplink Multi-User (MU) MIMO: Downlink MU-MIMO has already been introduced in the IEEE 802.11ac standard. In [7], the authors provide a thorough and updated overview of different MU-MIMO MAC schemes proposed in the literature for IEEE 802.11 standards and amendments.

In MU-MIMO, transmissions to several stations are overlapped in the same time-frequency resources (i.e., several stations simultaneously communicate with a base station equipped with multiple antennas) by exploiting the spatial diversity of the propagation channel.

TGax intends to add uplink MU-MIMO to operate along with downlink MU-MIMO. In uplink MU-MIMO, multiple stations are allowed to transmit simultaneously over the same frequency resources to the receiver. Similar to OFDMA, a trigger based PPDU is used to indicate to the transmitting stations when to transmit the uplink MU-MIMO PPDUs.

Multi-User Aggregation: Frame aggregation was introduced in IEEE 802.11n to reduce overhead by allowing the transmission of multiple data frames in a single channel access (provided that they have the same destination). IEEE TGax aims to further extend the aggregation procedure by defining a multi-user aggregation scheme that will allow a single access to send frames to multiple recipients. This scheme operates to reduce transmission overheads.

Other Notable Features

Energy Efficiency Techniques: In order to decrease/maintain the utilized energy, TGax is actively working to refine the current sleep state and incorporate power saving techniques that might either extend sleep time or allow awake time to be reduced. These mechanisms will assist in high density network conditions as well as for low power mode of operation.

In addition, the TGax is also exploring the possibility to reuse different energy efficiency techniques proposed for the upcoming IEEE 802.11ah standard (such as target wake time (TWT), where a routine and schedule for sleep is permitted by the AP to the associated stations).

Expected Challenges Posed to High Efficiency WiFi

Since IEEE 802.11ax is most likely to be used along side advanced cellular wireless technologies, such as Long Term Evolution (LTE), or its advanced version (LTE-A), in this section, we highlight the expected coexistence challenge. Furthermore, the IEEE 802.11ax amendment is also being explored as a viable communication network to support the Internet of Things (IoT) paradigm. Therefore, we discuss the expected opportunity and challenges for TGax within IoT scenarios.

The Challenge of LTE in Unlicensed Spectrum

Apart from WiFi networks, other wideband access technologies are considering to start competing in the unlicensed spectrum arena. LTE in the unlicensed band has been evaluated by the LTE-U forum and the 3rd Generation Partnership Project (3GPP) to meet the explosive growth of traffic volume.

The legacy IEEE 802.11 utilizes the PHYCCA based listen before talk (LBT) process before transmitting a data frame. PHYCCA is composed up of physical carrier sensing (PHYCS) and physical energy detection (PHYED) methods. The PHYCS method is employed to detect and decode the preamble of other WiFi stations' frames: if the energy level of the detected preamble is above the CST, the channel is sensed busy. PHYED (first introduced in IEEE 802.11a to counter the noise generated from OFDM transmitters, and later evolved to detect any signal over the shared channel) operates to detect whether any energy (regardless of the type of signal or noise) is present in the channel. The ED threshold is generally assigned a value greater than CST (i.e., 20 dB greater).

Unlike WiFi, in which devices use a distributed mechanism to contend for access to the wireless medium, LTE relies on base stations as central schedulers for medium access of all associated nodes in a cell. Since operation in unlicensed bands is non-exclusive, medium access inherently needs to employ means for fair spectrum sharing.

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In order to shorten the time to market of a first wave of 5 GHz compatible LTE devices, the initial LTE-U framework seeks a minimal impact on current specifications and does not rely on LBT. Instead, LTE-U incorporates a dynamic on/off scheme called carrier-sensing adaptive transmission (CSAT). CSAT allows LTE-U transmissions to be scheduled according to a duty cycle (where the off period is selected based on the sensed channel activity). Early studies on the coexistence between WiFi and unlicensed LTE indicate inconsistencies in simulation and demonstration results. Some results show that the absence of LBT in LTE-U causes a coexistence issue [8], whereas other results point to negligible or no impact [9]. However, spectrum regulations defined in European Telecommunications Standards Institute (ETSI) EN 301 893 require the use of LBT in the 5 GHz industrial, scientific, and medical (ISM) radio band band across Europe.

The 3GPP variant of unlicensed LTE is called license assisted access (LAA-LTE). LAA-LTE aims to design LTE specifications for global harmonization that allow for fair co-existence with IEEE 802.11. LAA-LTE employs a medium access scheme similar to IEEE 802.11's enhanced distributed channel access (EDCA). EDCA utilizes carrier sensing and a priority based backoff mechanism that require changes in LTE specifications.

With context to the coexistence challenge, both CSAT and LBE techniques appear to be aggressive. While the CSAT technique might result in overlap of WiFi with LTE transmissions, the nodes using LBE utilize a static range for backoff procedures (unlike WiFi, where an exponential backoff process based on contention windows is used). Therefore, the coexistence impact on fair-

The most essential part of IoT infrastructure is the wireless communication system that acts as a bridge for the delivery of data and control messages. However, the existing cellular technologies lack the ability to support a huge amount of data exchange from many battery-driven devices spread over a wide area.

Parameter	IEEE 802.11ax	LTE-U and LAA-LTE
Design architecture	Distributive	Centralized
Channel bandwidth (MHz)	20, 40, 80, 160	1.25, 2.5, 5, 10, 15, 20
Highest order modulation scheme	1024 QAM	256 QAM
Access technology	CSMA/CA	TDD based OFDMA
Handover	Client-driven, network-assisted	Network-driven, client assisted
Interference problems	Collisions, hidden and exposed node problem, partially overlapping channels	Co-channel co-tier, cross tier interference, For LAA-LTE (additional interference due to collisions)
Scheduling	Contention based de-centralized, EDCA	For LTE-U (base station controlled without contention), for LAA-LTE (contention based de-centralized, EDCA)
Range	Possible methods under consideration to improve range	Better range characterization as compared to legacy IEEE 802.11
Rate control	Vendor specific algorithms (implicit and explicit feedback based on probing, lack of acknowledgments, etc.)	Constant channel feedback
MAC and PHY layer protocol overheads	In-band signaling (e.g. RTS/CTS, sounding, null data, etc.), headers, pilot symbols, etc.	Control channel signaling, LBT (non-adaptive backoff range), CSAT (channel oblivious duty cycle), pilot symbol, transmission scheduling etc.
Integration with current 4G networks	Requires mobile core integration (MCI) for mobile offload	No requirements
Coexistence with other technologies	Based on LBT	For LTE-U (CSAT and optional LBT), for LAA-LTE (Based on LBT)
Potential market	Belongs to IEEE 802.11 family and is a natural evolution	Motivation for operators to enable/extend services to unlicensed spectrum without the need to integrate with a non-LTE technology

Table 2. Comparison of IEEE 802.11ax amendment with LTE in unlicensed spectrum.

ness and throughput with respect to LTE, which needs further evaluation, can be considered a current challenge for the IEEE 802.11ax standard.

In summary, whereas LAA-LTE and IEEE 802.11 use similar medium access mechanisms, and thus compete in comparable conditions, LTE-U uses a dissimilar approach not suited for all regulatory domains. However, with the upcoming LTE-U specification introducing LBT into CSAT, coexistence studies between IEEE 802.11ax and LTE-U will need to be revisited. Building on the argument, the authors in [10] highlight the latest trends regarding those coexistence problems. They propose radio resource management based on comprehensive network monitoring and centralized scheduling within a software-defined networking paradigm to solve the coexistence challenges.

Apart from the MAC layer, other notable differences between IEEE 802.11ax and LTE in unlicensed spectrum are highlighted in Table 2.

Therefore, since LTE is a centralized scheduling scheme, it will change the ecosystem within unlicensed spectrum. Furthermore, as highlighted in Table 2, the difference in technologies would lead to no common control channel between LTE and WiFi. The novel techniques proposed within the IEEE 802.11ax amendment will help WiFi in combating added interference by and to fairly share the medium with LTE unlicensed.

In spite of the aforementioned coexistence challenge, developing seamless methods to allow the foregoing technologies to operate by aggregating their capabilities can provide users with a compelling experience. LTE and WiFi link aggregation (LWA) is another proposition put forward by 3GPP. Unlike LTE-U and LAA-LTE, LWA does not introduce a new coexistence mechanism; rather, it introduces an interworking framework. The most important aspect of LWA is that it could be enabled with straightforward software upgrades, and it will allow user data to be simultaneously streamed through both WiFi and LTE interfaces, making use of specific transport protocols such as multipath TCP (MPTCP).

Opportunities and Challenges from the IoT Paradigm

The most essential part of IoT infrastructure is the wireless communication system that acts as a bridge for the delivery of data and control messages. However, the existing cellular technologies lack the ability to support a huge amount of data exchange from many battery-driven devices spread over a wide area. IEEE based WLANs (due to their ease of deployment and cost efficiency) could be used as a viable alternative technology for IoT only if the limitations of high power consumption, range, number of associated stations, and efficiency problems (due to diversity of loads) are overcome.

In terms of ongoing enhancements to the IEEE 802.11 standard, the proposed IEEE 802.11ah amendment [11] (focused on operations in the sub 1 GHz band) is specifically being designed for IoT applications. The key aspects of IEEE 802.11ah, summarized in Table 1, are improved energy-saving (e.g., through TWT and longer sleep periods), better coverage (utilizing a lower frequency band and more robust modulation and coding), and the ability to simultaneously handle more than 8,000 nodes. However, as highlighted by [12], the recent delays in the development process might lead to a situation where IEEE 802.11ah will face heavy competition upon its arrival from other already introduced and promising technologies (such as SIGFOX, LoRa, BLE, some IEEE 802.15.4 variants, and so on) that seek to operate in the same IoT market.

The aforementioned challenge has resulted in new proposals being explored by TGax to accommodate the IoT use cases. Most recently, the IEEE 802.11 Working Group has created a new topic interest group, called Long Range Low Power (LRLP), to address the needs of machine to machine (M2M) communications, IoT, energy management, and sensor applications. This group intends to develop methods to provide longer range operation of WiFi on the 2.4 GHz band. This new development poses a new coexistence challenge for the next generation of WLANs.

Two approaches have been discussed within the LRLP and TGax:

- Introducing narrow band orthogonal frequency division multiple access (OFDMA) transmissions with smaller subcarrier spacing.
- Accommodating LRLP transmissions in the form of single carrier modulations within a new OFDMA scheme, combined with smart link adaptation.

Table 1 provides an overview of the key technical features of IEEE 802.11ax as compared to IEEE 802.11ac and IEEE 802.11ah amendments.

Conclusion

In this article, we provided a thorough overview of IEEE 802.11ax, a future high efficiency WiFi standard being designed to increase capacity within high density and outdoor deployments. After we discussed the necessity and scope of the proposed amendment, we introduced the most important technological improvements that will form the basis of the next generation of WLANs. Finally, we highlighted the expected coexistence challenge of IEEE 802.11ax with LTE-U. In addition, we highlighted the expected opportunities and challenges for TGax within IoT scenarios.

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Biograhies

Muhammad Shahwaiz Afaqui received his bachelor degree in computer engineering from COMSATS University, Pakistan, and his masters degree in electrical engineering (wireless systems) from the Royal Institute of Technology (KTH), Sweden, in 2004 and 2009, respectively. In 2012 he joined the Wireless Networks Group at Technical University of Catalonia, BarcelonaTech (UPC) as a Ph.D. student, and is carrying out his research under the direction of Dr. Eduard Garcia-Villegas and Dr. Elena Lopez-Aguilera. His research interests include network security, performance analysis and optimization of current and next-generation wireless networks.

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In terms of ongoing enhancements to IEEE 802.11 standard, the proposed IEEE 802.11ah amendment is specifically being designed for IoT applications. The key aspects of IEEE 802.11ah, are improved energy-saving, better coverage (utilizing lower frequency band and more robust modulation and coding), and the ability to simultaneously handle over 8,000 nodes.