

IEEE 802.11be — Extremely High Throughput: The Next Generation of Wi-Fi Technology Beyond 802.11ax

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Abstract—Wireless-Fidelity (Wi-Fi) is continuously innovating to cater for the upcoming customer demands, driven by the digitalisation of everything, both in the home as well as the enterprise and hotspot spaces. In this article, we introduce to the wireless community IEEE 802.11be Extremely High Throughput (EHT), the next generation of Wi-Fi technology. We present the main objectives and timelines of this new Wi-Fi amendment, and thoroughly describe its main candidate features and enhancements. We also provide simulation results to assess the potential throughput gains brought by EHT, and cover important aspects such as the coexistence with other wireless technologies.

I. INTRODUCTION

Wireless-Fidelity (Wi-Fi) is among the greatest success stories of this new technology era, and its societal benefits are known to most of the world population. Wi-Fi has connected and entertained people, and has assisted in the creation of new technologies, industries and careers around the globe. According to a recent report from the Wi-Fi Alliance [1], more than 9 billion Wi-Fi devices are currently in use worldwide, where individuals, families, governments and global organisations depend on Wi-Fi every day. The economic value provided by Wi-Fi reached the astounding amount of nearly \$2 trillion by 2018, and is forecasted to grow to almost \$3.5 trillion by 2023. Since Wi-Fi has become an essential part of the home, and a key complementary technology for both enterprise and carrier networks, this economic value is only expected to increase beyond 2023, as the newly defined generation of more capable Wi-Fi products—Wi-Fi 6, based on the most recent Institute of Electric and Electronic Engineers (IEEE) 802.11ax specification [2]—becomes widely available.

The requirements of wireless data services, however, will continue to increase in many scenarios such as homes, enterprises and hotspots, beyond the capabilities of Wi-Fi 6. Video traffic will be the dominant traffic type in the years to come, and its throughput demand will keep growing to tens of Gbps with the emergence of more sophisticated technologies, e.g. 4k & 8k video. Simultaneously, new applications demanding both high-throughput and low-latency are also proliferating. Among these, augmented and virtual reality, gaming, remote office and cloud computing pose the stringiest requirements, including sub-5 ms latency needs. Reliability is also a major concern in the emerging digital industry, where guaranteeing that 99.9% of the data packets are correctly delivered may be the bare minimum to

replace wired with wireless communications. With these high-throughput, low-latency and high-reliability requirements, consumers will demand a further improved Wi-Fi.

To address such expectations, the IEEE 802.11 working group (WG)—responsible for the standardisation of the medium access control (MAC) and physical (PHY) layers of Wi-Fi products—has already initiated discussions on new technical features for bands between 1 and 7.125 GHz to make sure that Wi-Fi products deliver up to the highest standards. To this end, and more concretely, the IEEE 802.11 WG approved the formation of a topic interest group (TIG), and subsequently, a study group (SG) on May 2018 and July 2018, respectively. These groups have the primary objective of ensuring that the next generation of Wi-Fi—referred to as IEEE 802.11be Extremely High Throughput (EHT)—meets the peak throughput requirements set by upcoming applications [3].

In this article, we introduce the main objectives of EHT, as well as the views from different Wi-Fi stakeholders about the process and timelines to generate such amendment (Sec. II). We dive into the main candidate technical features of EHT, presenting each one of them, and describing their benefits and challenges (Sec. III). Moreover, we provide system-level simulation results that show some of the potential throughput gains that EHT may provide (Sec. IV), and discuss the important issue of coexistence (Sec. V). Altogether, this article aims to become an accessible guide to EHT for researchers and the general audience interested in Wi-Fi.

II. OBJECTIVE AND TIMELINE

The Wi-Fi community is aiming high, with the currently running EHT SG initially targeted at¹

- i) enabling new MAC and PHY modes of operation capable of supporting a maximum throughput of at least 30 Gbps, measured at the MAC data service access point (AP)—4× w.r.t. IEEE 802.11ax— using carrier frequencies between 1 and 7.125 GHz, while
- ii) ensuring backward compatibility and coexistence with legacy IEEE 802.11 devices in the 2.4, 5 and 6 GHz unlicensed bands [3].

While reaching an agreement on such daring objectives was relatively easy, the discussion among Wi-Fi stakeholders on the process and timelines to generate the EHT amendment

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¹ It is important to note the EHT SG has not specified any objectives in terms of latency and/or reliability so far, and a more detailed analysis on this matter is being carried out by the real time application (RTA) TIG, running in parallel.

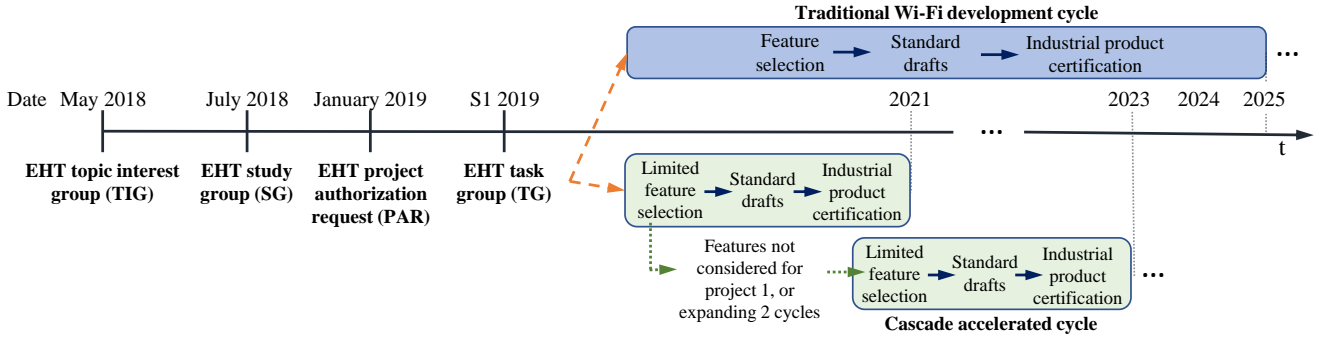


Figure 1: Illustration of the different standardization cycles considered by 802.11 stakeholders.

was much more lively. Traditionally, major IEEE 802.11 amendments, such as IEEE 802.11n or IEEE 802.11ax, have taken 6+ years to complete, with

- i) a development process effectively serialised—task group (TG) formation, feature set definition, draft development and certification process—, and
- ii) no major overlap between subsequent amendments, as illustrated at the top of Fig. 1.

However, in light of *i)* the fast developing pace of new coexisting technologies, and *ii)* to maintain the relevance of Wi-Fi, drive more frequent improvements, and provide a clearer product roadmap to the market, there is an increasing desire to accelerate this process, and move into a two- or three-year cadence (in resemblance to the third generation partnership project (3GPP)). For instance, as shown in Fig. 1, the camp in favour of such change has proposed a cascade approach between subsequent amendments [4]. With this formula, a new project would start once the current one reaches feature maturity, and not when it completes, and the development of more complicated features would expand multiple projects.

The camp against such change, however, sees clear benefits on sticking to the current—and so far successful—amendment development model, i.e. having one five year next generation project at a time. With this larger time budget, a project is more likely to deliver massive—and not just moderate—enhancements on many fronts for IEEE 802.11 multitudinous customers and use cases. In turn, this also enables the Wi-Fi Alliance to develop appropriate certifications of high profile features in a manner that is timely to satisfy market needs [5].

As of now, this topic is a subject of debate, and the approach to be adopted for EHT remains to be decided. Regardless of the outcome, it is agreed that the EHT TG—and thus the more technical discussions—should start on May 2019.

III. CANDIDATE TECHNICAL FEATURES

A variety of candidate technical features have been discussed in the EHT fora during the initial TIG and SG phases. In the following, we describe those that have attracted the most attention.

A. 320 MHz bandwidth and more efficient utilisation of non-contiguous spectrum

Spectrum is the air that wireless networks breath, and any new generation of radio technology always attempts to leverage the usage of new spectrum bands, as they become

available. EHT is no exception and, following the initial steps of IEEE 802.11ax, Wi-Fi stakeholders embrace the usage of the 6 GHz band as an immediate approach to increase Wi-Fi's peak throughput, as shown in Fig. 2. In this regard, discussions about the most efficient approaches to operate the up to 1.2 GHz of potentially accessible unlicensed spectrum between 5.925 and 7.125 GHz—which more than doubles the available bandwidth in the 5 GHz band—are ongoing.

The adoption of 160 MHz and 320 MHz communication bandwidth per AP in the 6 GHz band as mandatory and optional features, respectively, seems a sensible choice, building on IEEE 802.11ax, where 160 MHz bandwidth per AP is already an option [7]. Moreover, a minimum channel size of 40 or even 80 MHz in the 6 GHz band also seems appropriate when compared to the 20 MHz one used in the 2.4 and 5 GHz bands, given the focus on extremely high throughput.

While the benefits of using the 6 GHz band to enhance peak and system throughputs are obvious, the usage of a new band also opens up new networking approaches. For example, there are on-going discussions on whether EHT-compliant APs should always schedule uplink transmissions in the 6 GHz band—thereby reducing the time spent on channel contention. Moreover, it is likely for STAs implementing 802.11ax to also be present in the 6 GHz band. For this reason, channel coordination schemes between 802.11ax and EHT devices are also being considered, e.g., allowing EHT devices to enforce channel selection changes in 802.11ax APs.

B. Multi-channel/multi-band aggregation and operation

With the emergence of dual-radio non-AP STAs and tri-band APs, capable of simultaneously operating at 2.4, 5 and 6 GHz, one of the main objectives of EHT is to make a more efficient use of these multiple bands [8]. We describe four of the most appealing techniques being considered by EHT in the following.

- a) *Multi-band data aggregation.* The aggregation of 5 and 6 GHz spectrum for data transmission or reception is a feature fully aligned with EHT's fundamental objective of enhancing Wi-Fi's peak throughput. Effectively, this aggregation requires Wi-Fi devices to synchronise the start of the transmission opportunity (TXOP) in different bands, therefore making this approach more efficient in sparsely populated scenarios where contention for channel access is generally smooth.

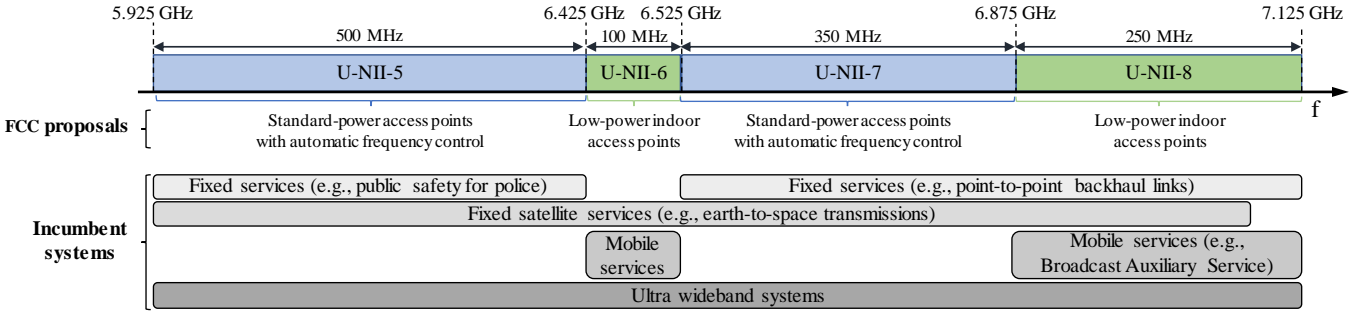


Figure 2: Frequency allocation in the 6 GHz band proposed by the Federal Communications Commission (FCC) [6].

- b) *Simultaneous transmission and reception in different bands.* This feature, also commonly referred to as multi-band full duplex, has the potential of reducing the communication latency and enhancing the throughput by enabling an asynchronous and simultaneous uplink/downlink operation in separate bands. If this feature is to be included in EHT, the TG will likely set a minimum separation between the downlink and uplink channels to prevent uplink to downlink and downlink to uplink interference [8].
- c) *Simultaneous transmission and reception in the same band.* In parallel to the EHT SG, the IEEE 802.11 WG also approved the formation of a TIG in January 2018 to examine the technical feasibility of in-band full duplex operation for Wi-Fi [9]. The TIG finished its activity in December 2018, concluding that full duplex operations can be realised with minor modifications to the 802.11 standard, and can yield various benefits such as increased throughput per STA, reduced latency, collision detection, and hidden node mitigation within a densely populated basic service set (BSS). Accordingly, at this point, it seems likely that the in-band full duplex efforts continue under the EHT TG umbrella.
- d) *Data and control plane separation.* EHT devices with multi-band full duplex capabilities also have the unprecedented opportunity of separating the data and management planes. For instance, the STA buffer status feedback is currently performed using the same channel dedicated to data transmission and reception, therefore introducing delays and overheads that translate into suboptimal scheduling decisions and throughput losses. These issues could be mitigated by dedicating a band to data transmission/reception and a complementary one to provide frequent and reliable control information updates.

C. 16 spatial streams and multiple-input multiple-output (MIMO) protocol enhancements

More antennas and better spatial multiplexing capabilities have been consistently added to Wi-Fi APs over the years to satisfy the stringent traffic demands generated by the increasing number of devices with wireless connectivity. Currently, the majority of high-end APs in the market, based on IEEE 802.11ac, are already equipped with four antennas, and can multiplex up to four spatial streams in a given time/frequency resource, while many STAs already have more than one

antenna [10]. IEEE 802.11ax upgraded these capabilities, enabling multi-antenna APs to spatially multiplex up to eight devices in downlink and uplink, through multi-user MIMO.

Consistent with this trend, and due to the EHT stringent requirements, many Wi-Fi stakeholders foresee the need of further enhancing the APs' spatial multiplexing capabilities to accommodate for up to sixteen spatial streams [7], [10]. This upgrade has the potential of doubling EHT spectral efficiency w.r.t. IEEE 802.11ax, taking full advantage of both the high speed backhaul provided by fiber-to-the-home (FTTH) solutions and the rich scattering in the indoor environments where Wi-Fi systems typically operate.

Such spatial multiplexing gains, however, could be hindered by the overhead of the channel sounding process, which is crucial to acquire accurate channel state information (CSI). Doubling the number of spatial streams while reusing the same explicit CSI acquisition procedure currently specified in IEEE 802.11ax may not be scalable. For this reason, EHT is considering to introduce an implicit channel sounding procedure that relies on STA-transmitted pilots and exploits uplink/downlink channel reciprocity [7]. Implicit sounding would likely require APs to implement a calibration method to prevent potential hardware mismatches that could break channel reciprocity.

D. Multi-access point coordination

Enabling some degree of collaboration among neighbouring EHT APs will permit a more efficient utilisation of the limited time, frequency and spatial resources available, and thus is also an appealing approach to enhance system performance. Below we discuss three of the main alternatives considered within EHT, following an increasing order of coordination complexity.

- a) *Coordinated OFDMA.* As illustrated in Fig. 3(a), in coordinated OFDMA, collaborative APs synchronise their data transmissions, and use orthogonal time/frequency resources. This coordinated resource assignment diminishes the collision probability with respect to the case when APs implement independent contention-based channel access procedures [7]. Coordinated OFDMA is particularly attractive to minimise the latency of short packet data transmissions, since it allows an efficient sharing and full occupation of the band by collaborating neighbouring nodes, which otherwise would require multiple contention processes, and would not utilise the available resources up to their full potential.

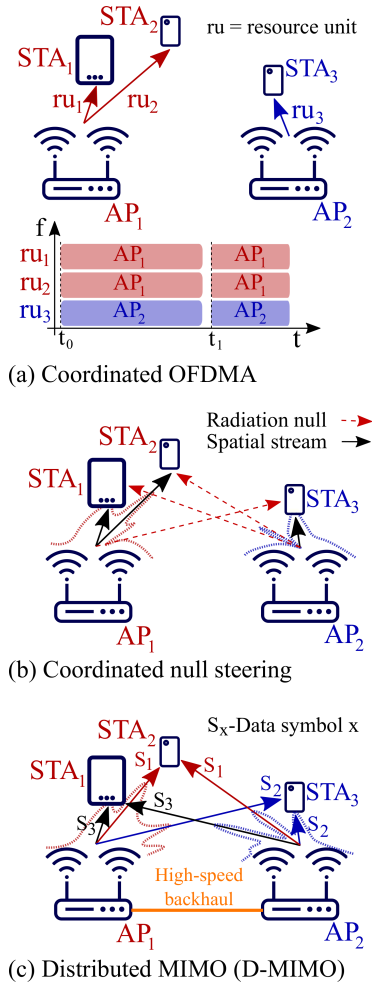


Figure 3: Multi-AP coordination techniques considered for EHT. (a) coordinated OFDMA, (b) coordinated null steering, and (c) distributed MIMO (D-MIMO).

- b) *Coordinated Null Steering*. Multi-antenna APs typically use their capabilities for spatially multiplexing STAs in the same time/frequency resources, and/or to provide useful signal power gains through beamforming. Alternatively, APs can also leverage their antennas to place spatial radiation nulls from and towards non-associated devices in their neighbourhood, as shown in Fig. 3(b). This approach is referred to as coordinated null steering, and is targeted at further boosting spatial reuse by enabling the simultaneous data transmission—using the same time/frequency resources—of devices within the same coverage area [7]. When compared to coordinated OFDMA, coordinated null steering generally requires a further degree of cooperation among overlapping BSSs to organize scheduling decisions and facilitate the acquisition of CSI from non-associated devices, which is essential for the effective placement of radiation nulls.
- c) *Distributed MIMO (D-MIMO)* The most intricate solution in terms of coordination complexity being considered by EHT is D-MIMO, where multiple non-located APs perform a joint data transmission and/or reception from multiple STAs reusing the same time/frequency resources [11], [12]. When compared with systems com-

prised of independent APs, the tight inter-AP collaboration of D-MIMO can provide an extended coverage, thanks to the additional beamforming gains, and an improved spatial multiplexing, as neighbouring APs are turned from interferers to servers [7]. A D-MIMO cluster is also more likely to use the up to 16 spatial streams that may be available in EHT. Achieving these gains requires inter-AP collaboration to jointly process both the data and the CSI of all STAs involved in the data transmission/reception, thus raising the need for a high-capacity, low-latency wired (e.g. fibre) or wireless (e.g. millimetre wave) backhauling network.

Importantly, the implementation of D-MIMO in EHT would require the design of new distributed carrier-sense multiple access with collision avoidance (CSMA/CA) mechanisms, compliant with regulations, to optimise channel access and guarantee a fair coexistence with independent APs deployed in the same coverage area [11]. This aspect, together with the stringent time, frequency and phase synchronisation-related constraints imposed by Wi-Fi's PHY layer numerology, have led a number of EHT contributions to propose D-MIMO implementations, consisting of a master AP that must be visible to all collaborating APs and oversees the cluster operation [12]. While theoretically compromising performance gains, the presence of a master AP could greatly simplify the coordination requirements, e.g. by enabling an efficient over-the-air synchronisation through the transmission of a control trigger frame to collaborating devices.

E. Enhanced link adaptation and retransmission protocol

Current Wi-Fi systems rely on the retransmission of MAC protocol data units (MPDUs) when these are not successfully decoded at the receiver or an acknowledgement (ACK) is not received at the transmitter. In this automatic repeat request (ARQ) approach, the receiver discards the failed MPDU before receiving its retransmitted version, thus not allowing soft-combining. With the requirements on enhanced reliability and reduced latency, multiple companies advocate that EHT should evolve towards hybrid ARQ (HARQ) capabilities. As illustrated in Fig. 4, HARQ-capable devices attempting to decode a retransmitted MPDU do not ignore the previous unsuccessful MPDU/s, but instead combine their soft-bits to improve the likelihood of correct decoding. The HARQ mechanism—already implemented in cellular systems and previously discussed during the standardisation of Wi-Fi 5 & 6—can provide signal-to-interference-plus-noise ratio (SINR) gains of approximately 4 dB with respect to ARQ in the ideal additive white Gaussian noise (AWGN) channel [13].

While the gains of implementing HARQ are clear in an ideal additive white Gaussian noise channel, some Wi-Fi stakeholders have reservations regarding the potential throughput gains achieved by HARQ when considering that Wi-Fi scenarios frequently suffer from bursty interference due to collisions [10]. Additionally, from a computational standpoint, the soft combining operation of HARQ requires extra computational capabilities as well as memory requirements for storing past transmissions. At this stage, further studies

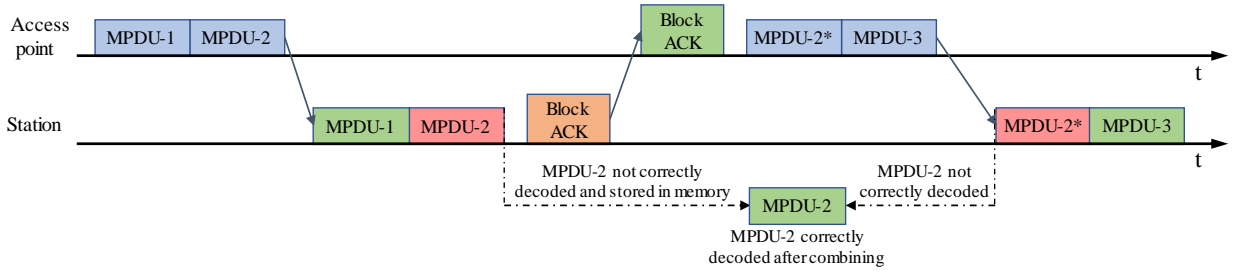


Figure 4: Illustration of the HARQ process. The receiving STA is capable of correctly decoding an erroneous MPDU received twice (MPDU-2) after combining the soft-bits.

are expected to evaluate the performance and complexity requirements of HARQ in Wi-Fi scenarios/use cases.

IV. EHT PERFORMANCE EVALUATION

In this section, we present the results of detailed system-level simulations performed on a typical enterprise scenario, to assess the actual throughput gains that EHT may bring over 802.11ax under realistic conditions. Specifically, we adopt the view of a company residing in a $40\text{ m} \times 40\text{ m}$ building, which aims at upgrading their 16 802.11ax APs—deployed in a square grid fashion and reusing 4 channels—with newer APs that implement a key subset of the EHT technical features introduced in Sec. III, namely:

- 1) *More bandwidth*: EHT-capable APs support 160 MHz transmissions in the 6 GHz band, a feature likely to be mandatory in EHT, whereas 802.11ax APs perform 80 MHz transmissions.
- 2) *More antennas and spatial streams per AP*: EHT-capable APs incorporate 16 antennas, and can spatially multiplex up to 16 STAs in downlink and uplink—doubling the number of antennas and spatial streams w.r.t. 802.11ax APs.
- 3) *Implicit CSI acquisition*: EHT-capable APs rely on STA-transmitted pilots to estimate the channel. This allows EHT to reduce the overhead introduced by the explicit CSI acquisition procedure of 802.11ax².

A detailed list of the most relevant system parameters can be found in Table I.

Fig. 5 shows the cumulative distribution function (CDF) of the aggregate downlink and uplink throughput per AP for both 802.11ax and EHT deployments. In this enterprise scenario, it can be observed that STAs generally experience smaller throughputs in the downlink than in the uplink despite of the identical downlink/uplink traffic generation ratio, which is a consequence of *a)* the power division that APs perform in downlink when performing spatial multiplexing, *b)* that STAs have a larger noise figure than APs—which leads to reduced downlink SINRs—, and *c)* that the uplink-to-downlink (STA-STA) interference is generally larger than that downlink-to-uplink one (AP-AP), since STAs are equipped with a single omnidirectional antenna and do not spatially suppress interference.

² For simplicity and to facilitate the comparison, we consider that there are no CSI acquisition errors in both EHT and 802.11ax systems.

Table I: Detailed system-level parameters

Parameter	Description
Deployment	
Floor size	40 m \times 40 m
AP positions	16 ceiling-mounted APs equally spaced ($d_x = d_y = 10\text{ m}$)
AP/STA heights	$h = 3/1\text{ meters}$
STA distribution	512 uniformly deployed STAs
AP-STA association criterion	Strongest average received signal
PHY & MAC	
Carrier frequency	5.18 GHz (.11ax) / 6.2 GHz (EHT)
System bandwidth	320 MHz (.11ax) / 640 MHz (EHT)
Channel size	80 MHz (.11ax) / 160 MHz (EHT)
AP/STA maximum TX power	$P_{\max} = 24/15\text{ dBm}$
Number of antennas per AP	4×2 (.11ax) / 4×4 (EHT)
Number of antennas per STA	1
AP and STA antenna elements	Omnidirectional with 0 dBi
CCA energy detection threshold	$\gamma_{\text{LBT}} = -62\text{ dBm}$
Signal detection threshold	$\gamma_{\text{preamble}} = -82\text{ dBm}$ with -0.8 dB of minimum SINR
MCS selection algorithm	Minstrel
AP/STA noise figure	$F_{\text{dB}} = 7/9\text{ dB}$
Maximum # of scheduled STAs	8 (.11ax) / 16 (EHT)
STA scheduling	Round Robin with semi-orthogonal user selection (SUS)
Downlink power allocation	Equal power assigned per STA
MPDU payload size	1500 bytes
Maximum TXOP length	4 ms
Channel model	
Path loss and LOS probability	3GPP 3D InH [14] for all links
Shadowing	Log-normal with $\sigma = 3/8\text{ dB}$ (LOS/NLOS) [14]
Fast fading	Ricean with log-normal K factor
Thermal noise	-174 dBm/Hz spectral density
Traffic model	
Traffic model	FTP model 3 with a packet size of 0.5 MBytes
Traffic generated per STA	75 Mbits/s
DL/UL traffic ratio	0.5/0.5

As envisioned, Fig. 5 demonstrates that EHT provides notable throughput gains w.r.t. 802.11ax, in more detail, $3.2\times$ and $2.7\times$ in median for downlink and uplink, respectively, and $4.6\times$ and $2.2\times$ in 5%-tile downlink and uplink throughputs, respectively. This is thanks to the larger transmission bandwidths and enhanced spatial multiplexing capabilities of EHT. Interestingly, the throughput gains provided by EHT in this realistic scenario do not always reach the maximum theoretical gain of $\approx 4\times$ w.r.t. 802.11ax because *a)* cell-edge STAs might not actually benefit from the larger bandwidth available in EHT, since their SINRs—and, consequently, their

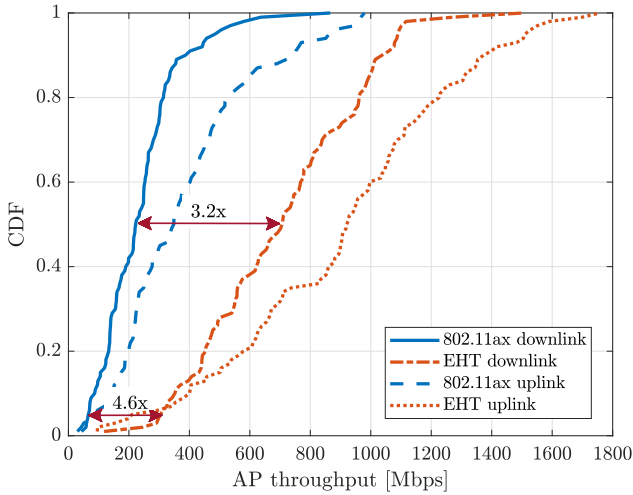


Figure 5: CDF of the downlink and uplink aggregate throughput per AP [Mbps] in the considered 802.11ax and EHT enterprise scenarios.

MCSs—diminish due to the larger noise power, which grows proportionally with the transmission bandwidth, *b*) in spite of generally scheduling a larger number of STAs than 802.11ax APs, EHT APs are not always able to spatially multiplex 16 STAs, and *c*) the per-STA SINRs generally degrade when more STAs are spatially multiplexed, since the spatial correlation of their channels increases.

To reach the maximum theoretical gain of $\approx 4\times$ that EHT can bring w.r.t. 802.11ax—thanks to doubling the bandwidth and the spatial streams—some degree of coordination between APs will be required, urging for the need of examining further such techniques in EHT.

V. COEXISTENCE IN THE 6 GHz BAND

EHT is eager to make full use of the 1.2 GHz of spectrum available in the 6 GHz band, as discussed in Sections III-A and III-B. However, to access these enticing frequency resources, Wi-Fi will have to coexist with other technologies operating in the same band. Two major types of technologies are foreseen to share the 6 GHz band:

- Existing—and to be deployed—fixed and mobile services, which can be considered as incumbents, and
- Newcomers, where we can distinguish between IEEE-based technologies, such as IEEE 802.11ax or EHT, and 3GPP-based ones, such as New Radio-Unlicensed (NR-U).

Based on this classification, it is likely that regulatory bodies define new coexistence requirements to guarantee that newcomers do not generate harmful interference to incumbent services in the 6 GHz band, as shown in Fig. 2 [6]. For instance, in the USA, it seems sensible that incoming technologies guarantee a peaceful coexistence with the more than 44,000 fixed access links deployed today, since the latter represent an important component of current and future cellular technologies, where they mostly serve as a backhaul solution. While some coexistence schemes have been already proposed by several stakeholders, such as that in [15]—based on a proactive geolocation and database-based approach and some

a posteriori interference detection and mitigation techniques—the definition of the coexistence technique of choice is still under discussion within the relevant regulatory bodies at the time of writing this article [6]. In this regard, it is worth noting that regulators have already specified coexistence techniques that may also be of value for the 6 GHz operation, e.g. the dynamic frequency selection method applied in the 5 GHz band, the geo-location database-based approach used in the television white spaces, or the spectrum access system (SAS) employed in the citizens broadband radio service (CBRS) [6].

In contrast, coexistence between new comers, such as IEEE 802.11ax/EHT and NR-U, is likely to be governed by listen-before-talk [2]. However, and differently to the 5 GHz coexistence case, IEEE 802.11ax/EHT may not to be treated as an incumbent technology, and thus no advantages in terms of energy detection threshold may be given. Within this space, the use of a common preamble among multiple technologies to realise a cross-technology virtual carrier sense-like mechanism has also been considered to enhance coexistence. These and other inter-technology aspects are already under discussion, and is expected that the IEEE and the 3GPP can leverage their previous experiences in the 5 GHz band to smoothly find efficient coexistence solutions.

VI. CONCLUSION

In this paper, we have presented a comprehensive overview of the initial steps taken towards the creation and standardisation of EHT: the next generation of Wi-Fi technology beyond IEEE 802.11ax. In more detail, we have covered EHT’s main objectives and expected timelines, shared the viewpoints of different Wi-Fi stakeholders, and discussed its main candidate features—providing insights on their benefits and challenges as well as system-level simulation results in a typical enterprise scenario. The EHT standardisation process has just started and everything is still open, please come and join us in making a better Wi-Fi.

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