Development Steps that Brought to Wi-Fi 7

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Abstract: Wi-Fi networks are globally the dominant technology for Internet access in indoor areas and are key enablers of the digital economy. Their success results from constant work on novel technical solutions and standards to provide timely responses to user demands, defined through the emergence of new applications and services. Since the adoption of the first Wi-Fi standard in 1997, the Wi-Fi development path has come to work on standardization of the seventh generation (Wi-Fi 7) of these networks. In this paper, we provide an overview of the main technical characteristics of the first six generations of Wi-Fi networks, as well as the main solutions expected to be adopted in Wi-Fi 7. Moreover, by using the ns-3 simulator, we examined the efficiency of multi-link operation (MLO) for throughput enhancement in indoor scenarios, which is one of the most significant technical innovations proposed for the Wi-Fi 7 networks.

1. INTRODUCTION

According to Cisco Annual Internet Report (2018–2023), the number of Internet users should reach 5.3 billion (about 66% of the global population) by the end of 2023 [1]. The dominant solution for Internet access in indoor environments are Wi-Fi networks. They are implemented in houses, buildings, and offices, but also in public areas, airports, shopping malls, and other open and closed spaces of this kind, thus being recognized as ubiquitous infrastructure in urban and suburban areas. Being implemented in an unlicensed spectrum, with Wi-Fi cards deployed in each smartphone, tablet, laptop, and similar devices, Wi-Fi networks are the most commonly used technology for wireless internet access for users having up to the pedestrian level of mobility. Currently, more than half of user data traffic is transmitted using Wi-Fi networks as Internet access technology [2].

Wi-Fi standards govern how to make wireless local area networks using the unlicensed part of the frequency spectrum by defining solutions for PHY (physical) and MAC (media access) levels. They have undergone numerous improvements since the first published standard more than 25 years ago. With the increase in the number of users and

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diversification of applications and services, which now include numerous IoT applications, there is a need for technical solutions that can support different requirements, which are very often diametrical and dependent on the type of application. Thus, Wi-Fi task groups are constantly working on new versions of the standards that could meet all these requirements. Since the first adopted standard in 1997, the work on Wi-Fi solutions has produced six major generations of standardized networks, with many subside standards that focus on specific technical solutions, thus not being recognized as a significant breakthrough, or new generation. Nowadays, work is ongoing on defining solutions for the seventh generation of Wi-Fi networks, denoted as Wi-Fi 7.

This paper will focus on the development steps that brought the Wi-Fi 7 standard, whose official publication is expected in the spring of 2024. It is organized as follows. In Section 2, the Wi-Fi evolution with the most common features of earlier Wi-Fi generations is given. The most important proposed technical solutions and novelties for Wi-Fi 7 are explained in Section 3, and Section 4 gives an overview of multi-link operations, one of the biggest novelties of the new Wi-Fi standard while Section 5 concludes the article.

2. OVERWIEW OF IEEE 802.11 STANDARDS

The first official IEEE 802.11 standard was created as the product of many years of research work in the area of implementing wireless communications in the unlicensed part of the spectrum. Although it had great potential, it lacked interoperability with many commercial devices since it was developed just under IEEE supervision. Thus, in 1999, several companies formed the Wi-Fi Alliance to ensure easy adoption of IEEE 802.11 standards and improve their implementation. Interoperability work between the Wi-Fi Alliance and IEEE started on the 802.11b standard. IEEE created the main standard, while Wi-Fi Alliance focused on compatibility and product designation, resulting in the creation of the Wi-Fi brand. Joint work resulted in the 802.11b standard branded as the Wi-Fi. The project was a success, and IEEE and the Wi-Fi Alliance continued to work together on new versions of the standard to meet all the upcoming user demands. Fig. 1 shows the timeline of Wi-Fi standards development, with some of their basic features. A more detailed overview of the characteristics of these standards are given in the following subsections.

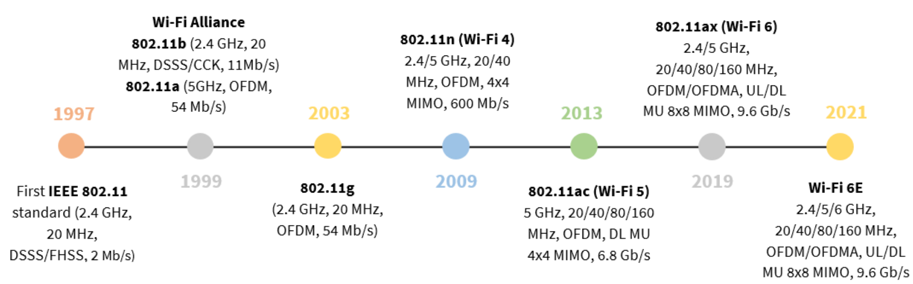

Fig. 1. Wi-Fi standards timeline

A. Wi-Fi 1, 2 and 3

The initial 801.11 standard was adopted in 1997 and then the standards denoted as 802.11b and 802.11a were announced in 1999, while the 802.11g was adopted in 2003. These standards are by retroactive decision denoted as Wi-Fi 0 (802.11), Wi-Fi 1 (802.11b), Wi-Fi 2 (802.11a and g) and Wi-Fi 3 (802.11g). For all these standards, the channel width was 20 MHz and there was still a sufficient number of non-overlapping channels.

The 802.11b standard continued to operate at 2.4 GHz following the example of 802.11. It introduced some new solutions and reduced prices, since the first standard was rather expensive for mass adoption. New modulations and some other changes increased the maximum data rate from 2 Mb/s (802.11) to 11 Mb/s, but this increase was not enough as user requirements began to grow. Several months later, the 802.11a standard was published. It was the first Wi-Fi standard operating at 5 GHz band and the evolutionary step was the introduction of OFDM (orthogonal division multiplexing) modulation. The maximum data rate has increased to 54 Mb/s, but the standard had a shorter range and was not compatible with the 802.11b, which had already entered mass production and had a significantly lower price, so 802.11a was not widely accepted. However, some technical solutions introduced in this standard were retained in subsequent standards in a modified form.

The upcoming 802.11g standard, released in 2003, was also OFDM based, and it used a 2.4 GHz band to be compatible with 802.11b, but could also handle dual-band connectivity for compatibility with 802.11a. The new standard achieved the same maximum data rate as the 802.11a standard (54 Mb/s). However, interference problems with other technologies (such as Bluetooth devices, microwave ovens, and baby monitors) have occurred in the unlicensed spectrum at the 2.4 GHz band. The temporary solution was to reduce the number of channels to 3 in America and 4 in Europe, but this was not optimal because the number of users was constantly increasing, thus raising an issue that this standard couldn't handle.

B. Wi-Fi 4

In 2009, the 802.11n standard, later denoted as Wi-Fi 4, was introduced, and with this standard began implementation expansion of Wi-Fi technology. Unlike its predecessors, which operated only in one band (at 2.4 GHz or 5 GHz), with this standard the operation was introduced in both bands and the possible achievable data rate reached the maximum of 600 Mbps. One of the most significant innovations in Wi-Fi 4 is the deployment of a multi-antenna system (MIMO - multiple input multiple output). With MIMO, up to 4 spatial streams could be transmitted simultaneously to improve the maximum throughput. Another advantage of using MIMO systems was their efficiency in combating the deteriorating effects of multipath fading. Wi-Fi 4 standard has also introduced different modulation and coding schemes (MCS) that can be used for mapping bits on OFDM subcarriers. The maximum code rate was increased to 5/6, but the maximum constellation rate remained 64-QAM (quadrature amplitude modulation). Through bonding two 20 MHz channels, the maximum channel width increased from 20 to 40 MHz at the 5 GHz band, which allowed the use of a gap between channels as well, so a slightly more than double throughput was achieved. Throughput increase was also possible by using shorter guard intervals between symbols (400 ns compared to 800 ns earlier) in shorter range communications, like in homes and offices. Aggregation methods introduced at the MAC level significantly reduced header costs and inter-frame spaces and also improved reliability [2]

C. Wi-Fi 5

Wi-Fi 4 has experienced widespread implementation, but as the number of users continued to grow, with novel applications demanding higher data rates, lower delays, better connection reliability, etc., novel solutions are expected to meet all these requirements. In 2007, a Very High Throughput (VHT) study group was created alongside 2 sub-groups - 802.11ac and 802.11ad, both to create standards that could achieve gigabit data rates. 802.11ad standard was supposed to work in the 60 GHz band with 4 GHz channel bandwidth, but the standard did not achieve massive application and due to the very short range, its dominant application was in peer-to-peer communications. On the other hand, the 802.11ac standard, whose operation was defined on a 5 GHz band has been widely adopted and later denoted as Wi-Fi 5.

Wi-Fi 5 was an evolution from Wi-Fi 4 and conceptually those two were very similar, but compared to Wi-Fi 4, Wi-Fi 5 went further in terms of channel bandwidth (introduction of 80 and 160 MHz wide channels), modulation order (from 64-QAM to 256-QAM) and MIMO systems (up to 8 spatial streams). Wi-Fi 5 operates only in the 5 GHz band, but a larger channel bandwidth increases the maximum achievable data rate. Some rarely used MCS schemes were disabled and deployment of 256-QAM brought using 8 bits instead of 6 per OFMD subcarrier, resulting in a 30% increased capacity. However, the improvement was achieved by imposing stricter requirements regarding error vector magnitude (EVM), and optional implementation of advanced coding techniques such as LDPC (low-density parity check) code and minimizing errors in the analog frontend to compensate even a bit for strict EVM requirements. Wi-Fi 5 also brought the adoption of beamforming which improved signal-to-noise ratio (SNR) and Multi-User MIMO technique. With Multi-User MIMO, an access point could communicate with multiple users simultaneously on the same frequency channel, by using beamforming and spatial multiplexing, which was not possible prior to Wi-Fi 5. This increased overall network capacity, reduced collisions, and improved EVM parameters.

D. Wi-Fi 6 and 6E

Wi-Fi 5 couldn't keep up with new scenarios assuming a great number of machine-type communications, i.e. IoT applications, while another shortage was operating only at the 5 GHz band. Wi-Fi Alliance introduced Wi-Fi 6 (IEEE 802.11ax) to support Wi-Fi technology in different scenarios with large user groups for various IoT applications. The highest possible modulation order has increased to 1024-QAM, as well as the number of antennas on each side up to 8, which improved the ability to realize beamforming. Also, upgraded MU-MIMO is applied both on the uplink (UL) and downlink (DL). This standard also incorporated some novel security protocols alongside old ones. To enable support for devices with limited battery supply and reduce power consumption in general, Wi-Fi 6 has introduced a new feature - target wake time (TWT). This feature is particularly useful for IoT devices, as it allows devices to be in sleep mode when there is no data transmission. When it comes to multiple access solution this standard is the first Wi-Fi standard that defines the implementation of an orthogonal frequency-division multiple access (OFDMA) scheme in Wi-Fi networks [3].

The increased number of devices and different networks led to the problem of overlapping basic service sets (OBSS), which occurs when APs from different basic service sets (BSS) communicate on the same channel(s) with their clients in a particular area. This results in a significant reduction in signal quality due to co-channel interference. To increase the spectral efficiency, spatial reuse is upgraded with a BSS coloring technique realized with a unique 6-bit identifier for all devices in a single BSS and adjusting the carrier sense threshold (CST) for inter-BSS transmissions [4].

However, as frequency resources and channels are limited and the number of devices is growing rapidly, in 2020 the Federal Communications Commission (FCC) opened the unlicensed band at 6 GHz for use, both lower (5945-6425 MHz) and upper (6425-7125 MHz) sub-bands, and those were added under Wi-Fi 6E, the extension of the Wi-Fi 6 standard. That ensures much more capacity, lower latency, and less interference. In Europe, the Middle East, and Africa (EMEA), the lower 6 GHz sub-band is adopted, while the upper 6 GHz sub-band is still under consideration [5].

3. PROPOSED TECHNICAL SOLUTIONS FOR WI-FI 7

With the Wi-Fi 6 standard, as well as its extension, the greatest focus was directed towards scenarios with densely distributed devices and networks and did not lead to significant improvements in network performance in terms of latency, data rate, and scalability [6]. In 2019, IEEE formed a working group intending to modify the physical and MAC layers of the IEEE 802.11 standard to enable operation in at least one mode that supports a maximum data rate of at least 30 Gb/s and defines at least one mode of operation that reduces maximum delay compared to the previous generation of standards. The need for this project is reflected in the growing variety of applications that use WLAN networks for data transmission, which increasingly require high data rates and delays of less than 5ms [7]. The standard is denoted as IEEE 802.11be, i.e. Wi-Fi 7, or EHT (Extremely High Throughput), and follows the same pattern as previous standards, outlining protocols and solutions at the physical and MAC levels. We describe the most significant improvements at the physical level in Subsection A, while Subsection B is devoted to the most significant improvements and new technologies at the MAC level.

A. PHY Enhancements

1) Channel bandwidth up to 320 MHz

Opening up the 6 GHz band for unlicensed use and use in Wi-Fi systems brought 1.2 GHz of additional spectrum, which created many benefits - both in terms of dense scenarios and reducing interference between different networks [8]. Such a wide spectrum allowed the TGbe to propose the usage of a channel bandwidth of 320 MHz, which would theoretically double the maximum nominal bandwidth compared to Wi-Fi 6 [2], benefiting time-sensitive networks (TSNs) and real-time applications. Although the use of the 320 MHz channel is not mandatory, it is stated in [9] that it is allowed to support channels with a width of 320 MHz but also 320/160+160 MHz. Besides this, it is possible to use the 240 MHz wide spectrum as 240/160+80 MHz or channel puncturing of 320/160+160 MHz, because the 240 MHz wide channels are not defined.

2) 4096-QAM modulation

4096-QAM modulation, having 12 bits per symbol, can theoretically increase the data rate by 20% compared to 1024-QAM modulation, realized with 10 bits per symbol and deployed in the sixth generation of the Wi-Fi standards. This will improve the transmission efficiency compared to the previous generation of standards but will require a tighter modulation accuracy in terms of the EVM [6]. It is considered that beamforming will be one of the key techniques for enabling the deployment of 4096-QAM modulation, i.e. for achieving the necessary SNR at the receiver side. The required SNR without the application of beamforming is above 45 dB, which cannot be achieved in the conditions of a real channel. When beamforming is used, the required SNR for 4096-QAM modulation can be lowered to about 30 dB on a channel with flat fading, if 4 transmitting antennas are used [10]. With an increase in the number of antennas, an even greater gain can be achieved, which entails the possibility of applying 4096-QAM modulation in real scenarios [10]. It is shown in [11] that the SNR requirements can be achieved using a 4x2 MIMO configuration with beamforming and 5/6 coding.

3) Multi-RU used by a Single User

Although OFDMA improved spectrum usage in Wi-Fi 6, there is still potential for further improvement in scenarios with few STAs. In the example with 2 STAs sharing an 80 MHz channel, where one STA is allocated 242-tone resource unit (RU) corresponding to 20 MHz channel bandwidth, the other STA can only get 484-tone RU (40 MHz), which leaves 25% of that channel unused [2]. The Wi-Fi 7 standard suggests assigning multiple RUs to one STA to improve spectral resource utilization and support high-speed real-time applications. RUs are divided into small-size and large-size RUs (large-size RUs contain 242 tones or more) and a combination of only the same type of RUs is allowed because combining small-size and large-size RUs will not bring significant improvement in spectrum utilization [9]. As each RU has unique parameters like MCS and number spatial streams, in [12] it is proposed that only the first assigned RU carries all the parameters, while for the other RUs, the description of the parameters is only a reference to the first RU. The complexity of scheduling would be compensated by a limited number of RU combinations [13]. The possibility of assigning more RUs to the same user will cause a much better and more flexible use of spectrum resources and will also improve real-time application support, which will be highly beneficial for Wi-Fi networks.

4) Enhanced Preamble Design

Each standard generation has a specific preamble design according to the features to be enabled and the control bits required for them. Preamble bits enable correct synchronization, automatic gain control (AGC), time/frequency correction, channel estimation, auto-detection, signaling, etc… The preamble should be small and efficient, but it should also support numerous old and new features, so TGbe proposed a new preamble design shown in Fig. 2. In contrast to previous standards' preambles, it is recommended in [14] to reuse existing functions instead of creating similar ones, such as the auto-detection mechanism developed in 11ax.

It has been decided that the structure for the Pre-EHT Preamble will be the same as for 11ax (Wi-Fi 6). This design includes the L-STF (Legacy Short Training Field), L-LTF (Legacy Long Training Field), L-SIG (Legacy Signal Field), and RL-SIG (Repeated

Legacy Signal Field) structures, along with the repetition of this part of the preamble (as well as the Pre-SIG) for every 20 MHz band [14]. Further on, [14] suggests Pre-SIG, which contains Wi-Fi version dependent and independent info to have a fixed structure of 2 symbols, which is sufficient for the accommodation of the expanded BSS color and transmission opportunity (TxOP). Other potential version-dependent bits could be carried by EHT-SIG. In [15], the authors propose having more than one content channel in both SU and MU physical layer protocol data unit (PPDU) to reduce the overhead when the bandwidth exceeds 20 MHz. This also eliminates the need to copy the EHT Preamble for each 20 MHz sub-band, which is also a significant novelty. The EHT-LTF, on the other hand, can use existing sequences to continuously estimate the channel for all channel widths, ensuring compliance with the PAPR requirements [16].

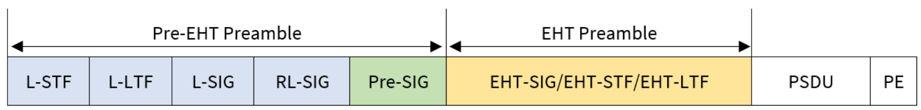

Fig. 2. Enhanced preamble design

B. MAC Enhancements

1) MIMO Enhancements

By increasing the number of spatial streams (SS) from 8 to 16, the network's capacity is theoretically doubled. MIMO deployment relies on the collection and analysis of channel state information (CSI) parameters that are necessary for proper tuning and routing of radio waves and beamforming and for some functions, like MU pre-coding. The methods used to obtain CSI parameters can be divided into two groups - implicit and explicit sounding. Implicit sounding utilizes channel reciprocity and data from the transmitting side, rather than data from the receiving side, and this technique was employed only in the fourth Wi-Fi generation. Explicit sounding, on the other hand, has been used in all generations since the introduction of the MIMO system and requires the receiver to perform a CSI assessment and then to feedback on that information to the transmitter so that it can direct the SS accordingly. With current explicit methods, the CSI feedback for 16 SS is too large, so researchers in [6] listed upgraded old as well as new proposed CSI feedback methods. As explicit sounding techniques get more complex for multiple streams, implicit sounding techniques are gaining importance. Some issues that made implicit feedback less commonly used are the need for calibration and the fact that feedback cannot be collected from beamformer with receive-only antennas. It is stated in [17] that those issues can be solved today based on numerous research efforts that occurred in the meantime. Calibration could be realized without sounding the clients using transmit-side calibration, and for the second issue, clients could send frames separately after switching, or use explicit measurements for such clients.

2) HARQ

HARQ has been used in cellular technologies for some time, but in Wi-Fi, it will find its application for the first time in Wi-Fi 7 networks. In previous years, Wi-Fi networks struggled with HARQ implementation due to inefficient protocols and the need for more computational power. In [7] it is specified that the new standard should offer greater reliability as well as improved link adaptation and retransmission. This leads to the inevitable implementation of the HARQ mechanism in Wi-Fi technologies as well.

The benefits of the implementation of HARQ in Wi-Fi networks are the improvement of link performance as a result of combining multiple re-transmissions, better coverage in low SNR areas as well as increased range, and improved link adaptation, which until now has been predominantly achieved by adapting MCS schemes based on channel quality information (CQI) feedback [18]. HARQ can boost link quality and BSS throughput, but its use in Wi-Fi networks is still being developed due to bursty interference collisions that are common in Wi-Fi networks. Thus, additional efforts are required to optimize HARQ mechanisms for Wi-Fi and adjust the design of PPDU and ACK (acknowledgment) or NACK feedback mechanisms [19].

3) Multi-AP coordination

Wi-Fi expansion leads to more networks in buildings, public spaces, etc., causing high co-channel interference. BSS coloring and spatial reuse will not be sufficient solutions for future scenarios and applications. Thus, within the Wi-Fi 7 standard, another solution is presented - multi-AP coordination, which will bring even more benefits besides the reduction of co-channel interference. To standardize the entire process and enable the most efficient and simple implementation, the TGbe working group proposes 2 types of multi-AP systems: coordinated and joint, with different levels of complexity of the implementations [20]. The main suggested solutions are coordinated beamforming (often called null steering) to avoid interference between APs, coordinated OFDMA for the most efficient use of frequency resources and the least possible interference, as well as joint processing transmissions. Coordinating methods improve efficiency, but joint transmissions are even better for enhancing both throughput and efficiency, despite being more complex. The most challenging issues are in aligning the sampling frequency, carrier frequency, transmission timing, and power balance, as stated in [19], but implementation can be simplified by restricting the number of participating APs. The joint transmission procedure includes multi-AP sounding and feedback, then dynamic AP selection is performed and joint transmission concludes the process. The sounding procedure proposed in [21] implies the existence of one master AP that coordinates joint transmission and several slave APs that participate in joint transmission.

4. MULTI-LINK OPERATIONS

One of the most significant technical innovations proposed for the Wi-Fi 7 networks is multi-link operation (MLO). Older Wi-Fi standards only allow communication on one link at one frequency band at a time, even though a lot of devices support operation on multiple bands. Wi-Fi 7 introduces multi-link operations (MLO) - communications on multiple links at different bands simultaneously. The benefits of this feature are numerous, including enhancements in total throughput, reduced delay for TSNs and real-time applications, enhanced features like fast-link switching and load-balancing, etc. Proposed technical solutions for MLO are described in Subsection A, while Subsection B shows MLO simulation results obtained through the ns3 network simulator.

A. Proposed technical solutions for MLO

1) Multi-link element

For 802.11be devices, the specification requires that APs and STAs support these MLO features: discovery procedure, setup procedures, security procedures, default mapping - all TIDs (the traffic identifiers) mapped to all links and all setup links enabled, TIM (traffic indication map) indicating BUs (bufferable units) at MLD (multi-link device) level, BA (block ACK) at MLD level, power saving per link, power state change indications per link, and BSS parameter critical update and new potential functionalities [9]. To support some of the above-mentioned features, a common multi-link element format is proposed in [22]. Multi-link element is exchanged during the association phase between AP and MLD to perform the initial multi-link (ML) setup of a specific link and carries the necessary information of all other links, but also information related to the MLO itself. Partial information from ML elements can also be included later in some other management frames to advertise individual MLO features.

2) Architecture

Two main configurations were proposed for multi-link: packet level and flow level aggregation [23]. Since packet-level aggregation is much more promising [24], a basic multi-link architecture is proposed based on this solution. The most important novelty in architecture is the introduction of Multi-Link Devices (MLDs). Architectures of MLDs at the receiver and transmitter side given in [24] are shown in Fig. 3 (a) and Fig. 3 (b).

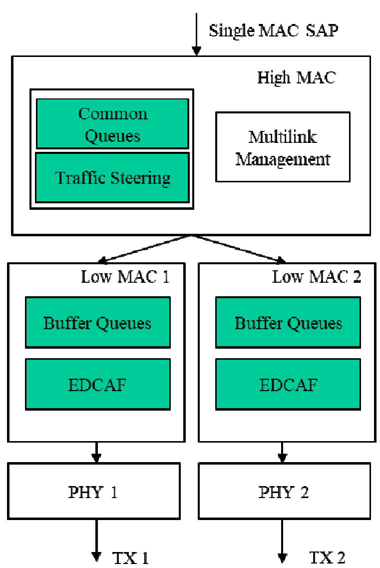

Fig. 3 (a). MLD Transmitter [24]

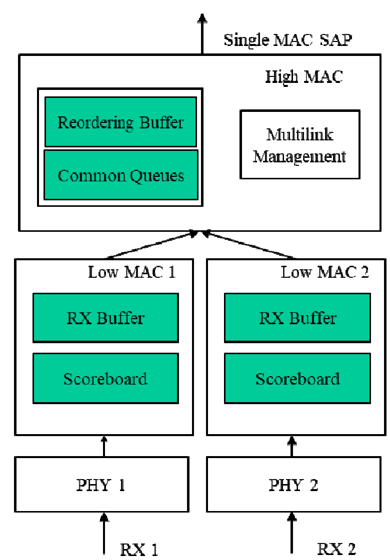

Fig. 3 (b). MLD Receiver [24]

MLDs are designed to both minimize changes to the existing infrastructure and implement MLO, while the rest of the architecture remains as in previous generations. A

MLD has one interface for controlling the logical connection, but several connected radio interfaces with separate physical and lower MAC levels that access the channels. These devices have a single MAC address and standard security and management settings, which reduces the header size, and higher MAC levels remain unchanged.

3) Channel Access

In current Wi-Fi standards, medium access mechanisms are based on per-20MHz CCA indications. Therefore, when performing MLO, we can apply channel access based on one primary channel, but this will result in less flexibility in channel selection, especially in dense deployment scenarios [6]. Channel access based on multiple primary channels is a better option in those situations and can be realized by temporarily setting secondary channels as primary.

When designing channel access schemes for MLO, it is also necessary to take into account the type of multi-link – synchronous or asynchronous. Closely related to that is the division of simultaneous transmit-receive (STR) and non-STR multi-links. Both for STR and non-STR, an MLD can simultaneously receive or transmit on all links. However, when STR is enabled, MLD can receive or perform CCA on one link, while simultaneously transmitting on the other, which is not the case in non-STR mode [25]. The downside of the STR feature is that close transmitting and receiving channels will probably cause interference due to energy leakage, impacting reception on neighboring links. To make STR feasible, researchers suggest lowering transmission power, using isolated antennas, employing high-quality low-pass filters (LPFs), and adjusting the spectral distance between channels [26]. It is suggested in [27] that AP should have STR capability for all link pairs, while other devices may or may not have it. The PPDU parameters on each link are independent and can transmit packets of different lengths, with different MCS schemes etc. In the case of unsynchronized multi-link transmission, channel access to each link can be realized independently, and therefore it is not necessary to significantly change the existing mechanisms and per-link back-off procedures can remain the same. EDCA (Enhanced Distributed Channel Access) protocol can be applied to each link, taking into account that for non-STR devices transmit and receive communications are not performed at the same time. Unsynchronized transmission has high spectrum utilization, but can lead to delays, retransmissions, and failed reception due to link quality differences and power leakage [28].

Apart from unnecessary retransmissions due to differences in link quality, synchronized transmission has no QoS issues, but transmission on all links must start at the same time. That means waiting for the CCA idle signal for each link, which requires additional schemes to keep the links free (for a limited time) until all of them are free. In [29] the use of a single primary channel was suggested for simplicity, but a couple of suggestions were also given for cases where channel access based on multiple primary channels needs to be applied.

4) Multi-link transmission

Implementing MLO not only increases network capacity but also enables new features, like quick link switching or reserving a link for control plane operations [6]. Fast switching between the links already exists in the IEEE 802.11 specifications, but MLO will allow a more efficient implementation. This function can help to achieve more efficient load balancing to improve QoS, where traffic of a certain category can be quickly directed to another (or better) link, without the currently existing lengthy cross-talk procedures for transition to transmission over another link. In addition, dynamic and fast switching is expected to find its application in reducing interference between neighboring nodes. Fast link switching is expected to enable efficient traffic transfer to idle high-quality links [6].

Allocating one link for the control plane and control bits can be advantage, especially for applications with sizable control packets. Such a concept is proposed in [30], where the authors claim that the separation of control and data planes in Wi-Fi systems can significantly improve performance and reliability. In this way, one or more links can be intended for data transmission, while one link takes control of packets needed for channel access, data transmission scheduling, as well as numerous network management tasks.

5) Power Saving

Introducing transmission over multiple links increases power consumption per device. Therefore, one of the very important components when it comes to MLOs is the power-saving mode. In [31], the authors show that enabling multiple links with independent power-saving modes for MLOs might not be the preferred power-saving option. Thus, the proposal suggests introducing an extremely low-power multi-link operation mode with one designated Anchor link that can be fixed and changed dynamically. In that way, the advantages of MLO can be efficiently used and when the link is not used, the extremely low power mode is deployed. Changing the power state must be fast and efficient, so it is proposed for non-AP MLDs to use a new switch frame to enter or exit extremely low power mode, unlike previous generations that used per-link enable/disable messages and power state indications. For AP MLDs, it will be necessary to improve the entire power management. One of the possible solutions is the intelligent change of transmit power based on machine and deep learning models that predict user requirements and activities as well as conditions on the channel and then accordingly adjust the transmitted power and power consumption itself [6].

B. Simulation of Multi-link operations

Before presenting the simulation results, we will demonstrate how the basic MLO takes place, which will help in understanding how improvements in terms of total throughput and average delay are obtained, based on the example given in [32]. The presented MLO operation is also the basis of the implemented MLO, which is simulated below. In the first phase of the standard's adoption, we anticipate carrying out basic MLO implementations such as the represented one, while other features with MLO implementation will come gradually.

Fig. 4 illustrates packet transmission with two links and compares it to one link. What we can conclude based on the image is that the package is transmitted via the first available link, unless otherwise defined. During the back-off procedure, if a busy link is detected, it pauses and then continues after detecting an available link. Additionally, we can observe that MLO can cause longer delays for certain individual packets (such as Packet #1), but it significantly reduces the overall delay. This is expected to play a very large role in both improving overall throughput and reducing latency for individual users, and TSN and real-time applications.

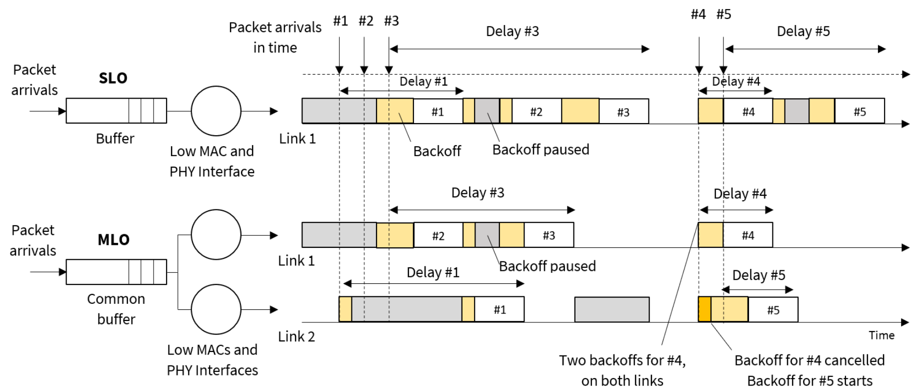

Fig. 4. Differences between SLO and MLO transmissions. Grey slots indicate occupied channels, yellow/light orange indicates ongoing backoffs, orange indicates cancelled backoff, and white slots indicate successful transmissions.

The overall throughput enhancements provided by MLO in an indoor scenario are quantified through simulations conducted in ns-3. Within the latest ns-3 release, the basic 802.11be functionalities of the physical level, multi-link elements, and multi-link devices are modeled. To evaluate the performance of MLO we consider a single BSS with a variable number of MLDs and examine how MLO affects total throughput and latency. Only downlink traffic is considered, there is no traffic class prioritization and the AP and MLDs use the same channel access parameters for the best-effort traffic. A fixed MSC is applied and all MLDs are within the AP coverage area for that MSC. The BSS is located in a building with no obstacles between the AP and the MLDs and no other interference sources because here we mainly focused on the MLO functionality. The evaluation parameters are shown in Table I and are adapted to the general user scenario, in which the devices do not have sufficient processing power for high modulation orders (like 1024- and 4096-QAM) and the availability of a wide channel bandwidth for a single link/band.

Table I
Evaluation parameters

Parameter description	**Value**
Carrier frequency	2.4/5/6 GHz
Bandwidth	40 MHz
MSC scheme	9 (256-QAM, 5/6 code rate)
AP/STA Tx power	16 dBm
AP/STA noise level	7 dB
CCA sensitivity	-82 dBm
Payload size	1500 B
Guard interval	800 ns
Simulation time	10 s

Fig. 5 (a) and 5 (b) show total throughput and average packet delay, respectively and both figures present results for SLO and for MLO with two and three links. As for total throughput, we can see that transmission on 2 links simultaneously gives almost 100% enhancements compared to transmission on 1 link or legacy SLO. In comparison, transmission on 3 links brings an improvement of about 140% compared to 1 link, but only about 20% compared to MLO on 2 links. To ensure fairness, we introduced a normalized traffic load based on the maximum throughput of one link in this BSS. This prevents any link from becoming a bottleneck. MLO noticeably reduces the average packet delay compared to SLO, benefiting larger networks and enabling real-time applications on common user devices. Thus, for example, for the normalized traffic load around 0.9 (or 180 Mb/s), MLO brings about 5 times delay reduction (from 1.5 ms to 0.3 ms). From Fig. 5 (b) we can also see that adding a third link also results in certain performance improvement in terms of delay, compared with the two-link scenario. For the same normalized traffic load of 0.9, adding the third link results in a 33.34% reduction in delay compared to the two-link scenario (from 0.3 ms to 0.2 ms). For the higher traffic load values, approaching the maximum throughput of the two links, delay reduction is becoming more noticeable.

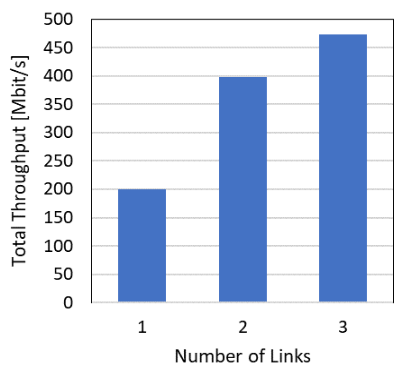

Fig. 5 (a). Total throughput

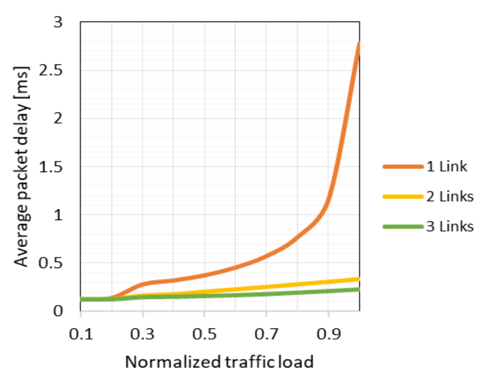

Fig. 5 (b). Average delay per packet

5. CONCLUSION

Implementation expansion and success of Wi-Fi networks is mainly due to easy deployment in unlicensed frequency bands, advanced technical solutions which enable fulfilment of users' demands, and strong support of industry, which provided Wi-Fi certified chips deployment in a plethora of different types of communication devices and smart IoT devices.

In this paper we have presented the main PHY and MAC level technical features of the first six Wi-Fi generations, and we introduced the expected technical solutions of the seventh generation of these networks (Wi-Fi 7), which should be standardized during 2024. Additionally, through the ns-3 simulation tool, we examined multi-link operation (MLO), considered to be one of the main advancements of the new generation of Wi-Fi networks.

The results show that deploying MLO in Wi-Fi 7 networks is necessary. Adding a second link in an indoor building propagation scenario doubles the total throughput and brings significant delay reduction, which is especially high (multiple times reduction) in the region of high traffic loads. Adding a third link in this scenario brings certain improvements of the total throughput and average delay per packet compared to having two links. If any of the link is close to its maximal throughput, i.e. if packet drop can occur, the performance improvement achieved with introducing the third link becomes more significant. Having in mind that besides MLO, 320 MHz channel is planned to be used, 4096-QAM modulation, HARQ, enhanced MIMO, multi-AP coordination, etc., it can be said that the Wi-Fi 7 networks have all the prerequisites to successfully fulfill demands of the current and upcoming data services and applications.

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