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The Path Towards Virtualized Wireless Communications: A Survey and Research Challenges

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Abstract

To keep up with the increasing number of connected devices in people's daily lives, it is necessary to develop intelligent mechanisms that perform the entire network management, interconnecting Wi-Fi, and the emerging beyond Fifth-Generation (5G) communications. Hence, it is essential to consider multiple usage scenarios, while managing end devices' limitations. As a result, developing a system that allows network operators to link Wi-Fi services on their main networks becomes a critical issue. These include a new paradigm that tackles optimal and dynamic resource allocation techniques. Thus, to consider in a combined way, the applications requirements, the resources available, and the different tiers involved, mechanisms such as virtualization and slicing have emerged to handle the heterogeneous context of the next-generation wireless communications. Moreover, the allocation of Radio Access Network (RAN) resources needs to be addressed. For this purpose, Open-RAN has in mind an open environment, which relies on virtualized functions and is mostly vendor agnostic. This technology will enable high data rates while maintaining adequate Quality of Service (QoS) in wireless communications. This paper advances current literature, which mainly discusses these themes individually, by providing a comprehensive survey in Next Generation Wireless Communications, highlighting their integration with beyond 5G Communications. First, we introduce the Wi-Fi evolution and explain the main standards developed over the years. Second, we present the most recent Wi-Fi standards, Wi-Fi 6 and 7, compared with 5G and beyond. Lastly, we explain the concepts related to slicing, virtualization, RAN, Open-RAN and the open research challenges.

Keywords 5G · Network slicing · Next-generation wireless networks · Virtualization · Wi-Fi

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1 Introduction

Over the years, wireless communications have evolved to support new challenges, connecting people and devices. The Wi-Fi technology assists our daily life, from education and commerce, to industries and smart cities. The Wi-Fi technology cannot answer this growing number of connected devices. The global mobile traffic volume was 7.462 EB/month in 2010, and this traffic is predicted to be 5016 EB/month in 2030 [1]. As a result, next-generation Wi-Fi will be introduced to ensure multiple simultaneous connections and enhance responsiveness. Cellular network technologies, such as beyond Fifth-Generation 5G communications, are controlled by operators and used for indoor and outdoor communications, providing coverage over long distances.

To provide a better Quality of Experience (QoE), it is necessary to analyze these technologies' integration. On the one hand, Wi-Fi can offer a lower cost to implementation, support, and scale, making it a good solution for application domains such as smart buildings. On the other hand, 5G and beyond can be used for mobile communications, car connections, and smart cities, given its long-distance communication support. Despite their technical differences, these two technologies offer complementary features that can be used together. The interconnection between Wi-Fi 6 and beyond 5G, maybe the genesis of a wireless world's story. Thus, it is essential to analyze the interconnection of different networks in a single physical interface.

Recently, the focus of study has switched to data-driven adaptive and intelligent approaches. 5G wireless networks will provide the groundwork for intelligent networks that will use techniques such as slicing. This resource partitioning technique is intended to be cost-effectively optimized for a specific purpose and/or service and respond to the different requirements of developing 5G vertical applications. Network slicing, regarded as a key component of 5G and beyond networks, allows several logical networks to be created on top of a common physical infrastructure and share resources by transforming traditional structures into customizable elements that can run on top of the traditional architecture. The capacity of 5G is expected to reach its limit by 2030 [2]. Then, only beyond 5G networks will be capable of completely intelligent network adaptation and management to provide sophisticated services. Researchers worldwide are already examining what communications will be like in 2030 and the potential drivers for success beyond 5G wireless communications. High bit rate, high reliability, high spectral efficiency, low latency, high energy efficiency, network availability, intelligent networks, communications convergence, localization, computing, and sensing are a some of the critical motivating trends driving the evolution of communication systems. However, to achieve these trends, it is necessary to define approaches where virtualization can orchestrate services over wireless networks to improve users' and network operators' experience.

This study's main goal is to thoroughly compare Wi-Fi and beyond 5G networks to give insights into their characteristics, stabilising the path towards virtualized wireless communications. The study was motivated by the fact that Wi-Fi and beyond 5G networks are critical in today's wireless communication environment. Although most existing studies focus primarily on beyond 5G technologies, it is equally vital to research and comprehend the benefits and drawbacks of Wi-Fi technologies, which are still extensively utilized in various situations. By addressing the coexistence and integration of Wi-Fi and 5G networks, we want to present a comprehensive picture of the opportunities and problems faced by users and wireless service providers. To help readers understand the goal of this study, we provide a diagram in Fig. 1 that depicts the link between Wi-Fi technologies and beyond 5G networks. This paper overviews the leading technologies developed in next-generation wireless communications (Wi-Fi and beyond 5G), their characteristics, emerging mechanisms and future opportunities.

The rest of the survey is organized as follows. Section 2 establishes a related work comparison, highlighting this survey's main contributions to the literature. Wi-Fi 6—IEEE 802.11ax is drilled down in Sect. 3, explaining the Wi-Fi's evolution, and focusing on the technical mechanisms and challenges, and Sect. 4 presents a comparison between Wi-Fi 6 and 5G. WI-FI 7—IEEE 802.11be is presented in Sect. 5. Section 6 presents the main emerging mechanisms for wireless networks: Network Virtualization and Slicing. Section 7 describes the Radio Access Network (RAN), explaining how the previous concepts of Slicing and Virtualization can support RAN. Next, the new concept for RAN is explained in the Sect. 8. Section 9 outlines future research opportunities. Lastly, Sect. 10 offers the survey's conclusion. Table 1 lists the acronyms used in this paper.

2 Related Surveys

5G and beyond connections will be vital due to their high data speeds, outstanding dependability, worldwide coverage, and low latency. Furthermore, the ever-increasing need for wireless solutions demands unique solutions in this field. This survey covers the upcoming wireless communication solutions, including Wi-Fi 6 and 7 technologies, 5G and beyond mechanisms, as well as their comparison. In addition, we examine emergent technologies that enable wireless applications over cellular, wide-area, and non-terrestrial networks. Thus, we address RAN mechanisms,

Fig. 1 Beyond 5G and Wi-Fi 6 coexistence—Adapted from [3]

Table 1 Acronyms list

5G	Fifth-generation	MU	Multi user
6G	Sixth-generation	MVNOs	Mobile Virtual Network Operators
3GPP	3rd Generation Partnership Project	NFV	Network Functions Virtualization
ACK	Acknowledgment	NOMA	Non-orthogonal Multiple Access
AP	Access Point	O-RAN	Open-Radio Access Network
APs	Access Points	OFDM	Orthogonal Frequency Division Multiple
BSS	Basic Service Set	OFDMA	Orthogonal Frequency Division Multiple Access
BSSs	Basic Service Sets	PHY	Physical Layer
BSSID	Basic Service Set Identifier	QAM	Quadrature Amplitude Modulation
CSMA/CA	Carrier-Sense Multiple Access with Collision Avoidance	QoE	Quality of Experience
CU	Centralized Unit	QoS	Quality of Service
DL	Downlink	RAN	Radio Access Network
DSSS	Direct-Sequence Spread Spectrum	RIC	RAN Intelligent Controller
DU	Distributed Unit	RU	Radio Unit
E2E	End-to-End	RUs	Radio Units
EHT	Extremely High Throughput	SDN	Software Defined Network
eMBB	Enhanced Mobile Broadband	SS	Spatial Streams
FCC	Federal Communications Commission	STA	Station
FHSS	Frequency-Hopping Spread Spectrum	STAs	Stations
HARQ	Hybrid Automatic Repeat Request	TWT	Target Wake Time
IoT	Internet of Things	UL	Uplink
LAN	Local Area Network	URLLC	Ultra-Reliable and Low Latency Communications
MAC	Medium Access Control	VAPs	Virtual Access Points
MEC	Mobile Edge Computing	vRAN	Virtualized Radio Access Network
MIMO	Multiple Input and Multiple Output	WLAN	Wireless Local Area Network

network virtualization, and slicing to meet wireless Key Performance Indicators such as reliability, energy efficiency, high connectivity, and low latency.

Moreover, we discuss technologies and solutions projected to be a part of wireless communication in the beyond 5G period. In addition, we highlight the remaining obstacles and unresolved concerns that must be handled in the future. This survey does not include traditional Artificial Intelligence (AI) methods for wireless communication. It also skips over the specifics of Internet of Things (IoT) standards and infrastructures. To the best of our knowledge, no publication surveys Wi-Fi and Beyond 5G developments. We are creating a direct literary relationship between them, analyzing other critical emerging technologies for the next generation. However, other polls and tutorials are connected to the topics addressed in this survey. Table 2 lists these surveys and their principal emphasis. Our work is far more thorough, managing practically all relationships

Table 2 Existing wireless surveys comparison

References	Year	Main topic	Spectral efficiency	Virtualization and slicing	Access network	Beyond 5G	Wi-Fi vs 5G
This survey	2022	Wireless next generation	✓	✓	✓	✓	✓
[4]	2022	6G IoT	✓	✗	✗	✓	✗
[5]	2022	6G wireless networks	✓	✗	✓	✓	✓
[6]	2021	5G network slicing	✗	✓	✗	✗	✗
[7]	2021	Wireless 5G advances and road to 6G	✗	✗	✓	✓	✗
[8]	2021	Communications for beyond 5G	✓	✗	✗	✓	✗
[9]	2021	Wireless next-generation	✓	✗	✗	✓	✗
[10]	2021	Comprehensive 5G wireless systems	✓	✗	✓	✗	✗
[11]	2020	Wi-Fi and 5G in new radio	✓	✗	✗	✓	✓
[12]	2018	Coexistence of wireless technologies in the 5 GHz	✓	✗	✗	✗	✗
[13]	2015	5G emerging technologies	✓	✗	✓	✗	✗

between Wi-Fi 6 and 5G and Wi-Fi 7 and Beyond 5G while still covering virtualization, slicing, and RAN elements. The effective use of both Wi-Fi and beyond 5G technologies has the potential to give significantly higher data rates with small latency. For the best user experience, Wi-Fi must thus coexist with 5G and beyond.

3 Wi-Fi 6—IEEE 802.11ax

Wi-Fi's evolution has continued to grow and gain more importance, providing faster, safer, and more efficient services. Wi-Fi 6 were designed to solve problems caused by the numerous terminals in restricted geographic areas, such as offices, shopping malls, houses, and airports, to answer the growing needs. Thus, Wi-Fi terminals need a wide coverage area, which requires an increase in the number of Access Points (APs) used [14].

Initially, Wi-Fi 6 only operated in the 5 GHz band. In April 2020, the Federal Communications Commission (FCC) released the 1200 MHz spectrum in the 6 GHz band for unlicensed use, addressing the problem related to the increasing number of connected devices. Due to this more spectrum in the 6 GHz band, Wi-Fi 6E was created, which technically has the same operation as Wi-Fi 6 even though it works in the 6 GHz band. Furthermore, Wi-Fi 6E represents the enhancement of Wi-Fi communications free from interference from non-Wi-Fi devices, operating in the 2.4 and 5 GHz bands. According to the Wi-Fi Alliance, the 6 GHz spectrum will be beneficial for high bandwidth and short distance communications, with the creation of wider channels, reduced interference, and increased capacity to manage more devices at the same time [15].

The Wi-Fi 6 standard, takes advantage of new modulation and coding schemes of the spectrum usage. IEEE 802.11ax, also called High-Efficiency Wireless, increases the number of simultaneously connected devices, which leads to the increase in the variety of different Stations (STAs) found nowadays. In the literature, a Station (STA) is a device capable of using an IEEE 802.11 protocol, such as a laptop or an Access Point (AP), which can be stationary or mobile.

The increase in the amount of data generated by users in the same space, associated with the services provided and stored in the cloud, represented a significant load on the Downlink (DL) and Uplink (UL) transmission services. Hence, Multi-User Multiple Input and Multiple Output (MU-MIMO) techniques were introduced to minimize these effects. However, the issue was not competently addressed even with the approaches described above. All communications had to be strictly synchronized. So, IEEE started to make some improvements in Medium Access Control (MAC) techniques and Physical Layer (PHY) management, using 4096 Quadrature Amplitude Modulation (QAM), Multiple Access Point coordination, Enhanced Link Adaptation, and re-transmission protocols, like Hybrid Automatic Repeat Request (HARQ) [16]. The next section describes the path and improvements made until Wi-Fi 6.

3.1 The Path Until Wi-Fi 6

The first version of Wi-Fi described a primary connection of 2 Mbps, which seems irrelevant nowadays. Still, it represented a big step in what would be the development of routers and communication equipment [17]. Thus, IEEE started the standardization of IEEE 802.11 Wireless Local Area Network (WLAN)s, by defining the PHY and the MAC. Pahlavan et al. [18] present a historical perspective of Wi-Fi evolution, describing the impact of Wi-Fi technologies according to the authors' experiences over the past decades. Besides, Gures et al. [19] address the rapid growth in the number of mobile users regarding the mobility management in beyond 5G heterogeneous networks scenarios, exploring the challenges, architectures, and future opportunities of beyond 5G. Thus, Wi-Fi seeks to respond to social needs and attempts to complement fifth mobile generation networks, as shown in Sect. 4. The following are the main Wi-Fi Standards that have grown through time, as well as the key attributes of the various versions:

- IEEE 802.11b—The IEEE 802.11b standard was developed to support wireless communications between mobile nodes and communications through access points. This offered specifications of PHY and MAC layers with Carrier-sense Multiple Access with Collision Avoidance (CSMA/CA) [20].

  However, as this operated at the standard 2.4 GHz frequency, the chances of being interfered with were high since it used the same operating frequency as many appliances. Thus, this pattern was limited by distance supported between mobile users and APs, which consequently limited the wireless network topology [21], with a top link bandwidth of 11Mbps.
- IEEE 802.11a—Launched slightly after IEEE 802.11b, it uses Orthogonal Frequency Division Multiple (OFDM). It operated at the frequency of 5 GHz, which offered multiple advantages, including eliminating the interference mentioned above [22]. This new technology increased spectral efficiency without complex equalization through adaptive filtering, and reduce multipah effects and narrowband interference [23].
- IEEE 802.11g—Created to offer an improved simultaneous response capability, it uses OFDM [20, 23]. However, it only had coverage in the 2.4 GHz band, which raised questions about interference but increased the bandwidth of 54 Mbit/s, and offered support to the legacy standard [24].
- IEEE 802.11n—The IEEE 802.11n standard is 4–6 times faster than earlier versions. It aims to improve network throughput over the previous standards with a significant increase in the maximum network data rate, from 54 to 600 Mbit/s thanks to 4 Spatial Streams (SS) at 40 MHz [25]. IEEE 802.11n supports adaptive rate control, which means the transmission rate can be varied for a different client depending on the channel quality.
- IEEE 802.11ac—This standard increased the channel width from 40 to 80 MHz compared to the IEEE 802.11n standard using extended multiple wireless signals and antennas. Moreover, this standard worked in the 5 GHz frequency range and supported 8 SS instead of the 4 supported by the previous

technology. This standard allowed to direct multiple data streams to numerous customers simultaneously [26].

According to Cisco [27], for the future, even the most advanced cellular technology will need Wi-Fi capacity supportive of carrier-grade voice and video services, which are best delivered with Wi-Fi 6 and its cellular-like scheduling flexibility.

The next section will explain the Orthogonal Frequency Division Multiple Access (OFDMA), created for mobile phone networks, that aims to minimize overhead and latency and to increase the overall throughput per device by at least 4 times in dense environments. This standard also uses a 1024-QAM modulation, which allows an increase in bandwidth up to 35%, without forgetting energy consumption behavior, which is a significant concern nowadays. For this reason, Wi-Fi 6 has better programming features to achieve longer battery life with Target Wake Time (TWT) [28].

3.2 OFDMA

This improvement of the OFDM technique, called Orthogonal Frequency-Division Multiple Access, improved Wi-Fi communications. While the OFDM technique only transmits traffic to a single destination in each communication, which increases the latency for users waiting to receive their information, OFDMA allows data to be transmitted to several receivers in the same communication, dividing the traffic into smaller sub-packets to eliminate congestion. This technique was introduced to reduce transmission delay and to allow more devices to communicate simultaneously, which is useful for latency-sensitive smaller packets, such as voice and IoT applications.

In the IEEE 802.11ax standard, the fact that the communication channels' resources are allocated over time and frequency, associated with the OFDMA transmission, which is frame organized, allows each of these to be able to transport information to several STAs. OFDMA enables bandwidth sub-carriers to be organized into smaller parts of the channel called Resource Units. These individual Resource Units are allocated to separate stations, allowing access points to be used concurrently during DL and UL transmissions. This suggests that a Resource Unit is composed of a set of tones that correspond to the subcarriers split into granular components [30]. Thus, according to Cisco [29], the number of tones for different bandwidths, i.e., the number of tones, should be the bandwidth (in MHz) divided by the subcarrier spacing. The subcarrier spacing for Wi-Fi 6 corresponds to 0.078125 MHz. Based on this, we can obtain the following formula for the Number of Tones = (Bandwidth in MHz) ÷ (0.078125 MHz). Thus, we obtain 256, 512, and 1024 tones for the channels of 20 MHz, 40 MHz, and 80 MHz, respectively. Table 3 shows the correlation between Resource Units and Channel bandwidth, representing the subcarriers per channel width mapping. It essentially provides the number of OFDMA users for a specific tone at a specified bandwidth for example, with 26 tone Resource Unit's at 20 MHz, a maximum of 9 users will be supported.

Table 3 Resource unit map—Taken from [29]

Resource unit	20 MHz BW	40 MHz BW	80 MHz BW	80 + 80/160 MHz BW
26-tone	9	18	37	74
52-tone	4	8	16	32
106-tone	2	4	8	16
242-tone	1	2	4	8
484-tone	NA	1	2	4
996-tone	NA	NA	1	2
2X996-tone	NA	NA	NA	1

However, not all of these tones are used for data transmission. Some of them are used as pilots to carry out the supervision, control, and synchronization of communications.

Figure 2 shows the difference between OFDM and the OFDMA technique, where it is possible to observe the channel division in Resource Units.

Due to MU-MIMO techniques, up to eight different customers can be allocated to each Resource Unit. Thus, it is possible to ensure that several clients with varying bandwidth uses can be served simultaneously through a spectrum division that allocates each sub-channel to a different client, satisfying the needs of several customers simultaneously.

3.3 MU-MIMO

The Multiple Input and Multiple Output (MIMO) technique had already been introduced in Wi-Fi 5 (IEEE 802.11ac), creating 4-lane highway from a single communication channel. The MU-MIMO system improves MIMO expanding the communication to an 8-lane freeway. Thus, this technology reduces latencies by introducing more

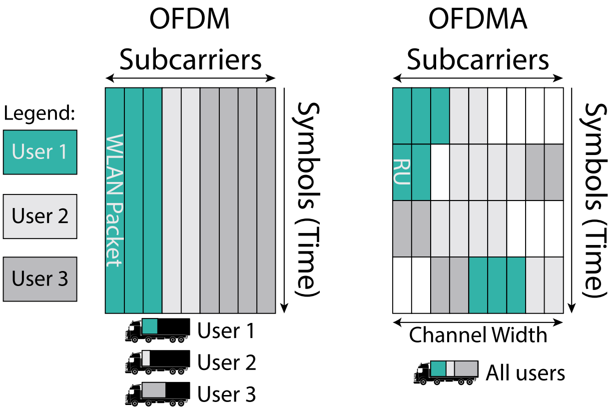

Fig. 2 OFDM vs OFDMA

communication channels for users, designed for large data communication applications, such as streaming videos or large data files. However, it continues to support Single User systems [31].

While in Single User mode, each STA only communicates with one user. Thus, the Single User system benefits from interference reduction, while the Multi User (MU) system benefits from multiplexing gains. In MU mode, each STA can separate communications for more than one user, which provides capacity gains but reduces the data delivery rate to each user. Therefore, Wi-Fi 6 brings more advanced technology, allowing MU services to operate in the UL direction, which involves several simultaneous transmissions of data, from several STAs to a single AP.

Together with OFDMA, the presented techniques formed the “DL & UL MIMO-OFDMA” technique, which increases the scope of Wi-Fi [28]. According to [31], Downlink multi-users means data sent, simultaneously, from the same AP to several associated STAs. One of the main fundamentals that led to the creation of the DL MU-MIMO technique is Beamforming, which includes the emission of audible signals before generating transmissions in the STAs spectrum to understand the communication conditions environment [32]. The UL MU-MIMO technique is executed based on Multi-Point to Point commands. Thus, one of the challenges of this technique is the STAs synchronization to work in a coordinated manner, which raises problems related to the power variation received in the APs and symbolic interference. This feature is handy in dense and closed environments, being one of the main reasons that supported the creation of smart-buildings, providing flexibility so that the various APs can respond to all customers’ needs. Hence, Fig. 3 shows the available bandwidth division into several smaller Resource Units to simultaneously transport several services.

With combinations of OFDMA, 8 × 8 MIMO, different guard intervals values, IEEE 802.11ax can support data rates ranging from 0.4 Kbps to 9.6 Gbps, according to the applications needs and the served STAs. However, devices with up to 8 antennas can have some limitations in MIMO operations because each antenna’s signals may cause some destructive interference and affect performance.

3.4 Power Management

Power management in wireless communications is a key problem. This is accomplished by switching between two states: awake and doze. In the awake form, the STA can transmit and receive frames, while in the doze state, the radio is turned off. As the APs do not know the STA status, they store all the frames destined for the STAs in a buffer. Thus, APs include a Traffic Indication Map (TIM) responsible for indicating to the STAs the existence of this data inside the buffer. This means that the STA in state doze has to wake up, periodically, to realize these frames’ presence to receive

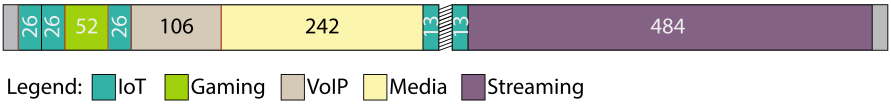

Fig. 3 80 MHz Resource Unit bandwidth allocation—Adapted from [33] through the Traffic Indication Map indicator. If there is no packets to receive, the STA returns to doze state [28]. However, scenarios with dense networks, high traffic rate, and several connected devices, make these energy management mechanisms insufficient. Consequently, the Wi-Fi 6 standard has methods that allow advanced data transmission scheduling, knowing the periods in which the STAs can transmit or receive data from the AP. This led to the emergence of TWT, which represents a scheduling function, that allows the device to negotiate and decide when to wake up or receive data. Thus, the AP can deal with the STAs the times used for medium access, allowing the STAs to enter in sleep state until their TWT comes. This allows improvements in network capacity in Wi-Fi environments [34]. These mechanisms contribute to the management of battery-powered devices. However, there are still some limitations to overcome. When the STA is active, the AP can instantly notify its decision to schedule a packet transmission. Nevertheless, being the STA in doze, this will not happen. Thus, these mechanisms should not exist whenever STAs receive critical data.

3.5 PHY Techniques Enhancements

To reduce the network overhead due to the guard intervals, which represent intervals used to ensure that different transmissions do not cause overlaps, the OFDM symbols durations was increased [35]. Long OFDM symbols are more resilient to the inter-user jitter inherent in outdoor scenarios, which is crucial for the Uplink MU transmission, allowing several users' simultaneous performance. Hence, this new standard's idea was to maintain compatibility with legacy standards, making it able to receive and send data to an STA with the previous protocol. This makes legacy equipment capable of decryption packet headers from the new standard, even if these packets' transmission does not occur wholly and successfully. It is necessary to use the re-transmission [36].

Comparing this new Wi-Fi protocol with legacy ones, we can summarize the main features in Table 4.

The IEEE 802.11ax uses a high Signal-to-Interference-plus-Noise Ratio to contribute to the QoE in indoor environments, achieving bandwidths of 9.6 Gbps. This standard also describes an optional Dual Carrier Modulation [38], increasing the robustness of the transmission by allocating the same signal in a pair of tones, which are separated in the frequency domain. Increased signal modulation means more calculations on the receiver side. The time available for the receiver to make such calculations before sending an Acknowledgment (ACK), is limited by the Short Inter-Frame Space. However, low-cost Wi-Fi devices mean low processing capacity. For this, the possibility of extending the tail of a frame was implemented, to minimize the overhead induced by the extension of the modulation and the OFDM symbols. Hence, each STA must indicate its maximum extension needed to process a frame with a given Modulation Code Scheme [39, 40].

The increase in the number of users and streaming applications leads to WLAN systems' appearance to support high data rates and reliability, called High Efficiency WLAN [28]. Hence, Long Training Field provides different ways for receivers to estimate MIMO channels on WLAN systems. With this, the evolution involves

Table 4 Feature comparison between legacy and IEEE 802.11ax—Adapted from [28, 37]

Innovation	Legacy features	IEEE 802.11ax features
Spectrum	Up to 160 MHz at 5 GHz (11ac) or up to 40 MHz at 2.4 GHz (11n)	Up to 40 MHz at 2.4 GHz or up to 160 MHz at 5 and 6 GHz
QAM modulation	256-QAM (11ac)	1024-QAM
MIMO order	4 (11n), 8 (11ac) SS	8 SS
Maximal data rate	7 Gbps	9.6 Gbps
Channel access	CSMA/CA	OFDMA on top of CSMA/CA
MU technology	MU-MIMO (11ac)	MU-MIMO, OFDMA
MU transmission direction	DL (11ac)	DL and UL
Fragmentation	Static	Flexible
Spatial reuse	Sectorization	Adaptive power and sensitivity thresholds
Power management	Many	Enhanced TWT, Microsleep

reducing the errors in estimating the best channel, and reduce the preamble overload as much as possible, especially for indoor scenarios, where several customers are competing for the communication channels [41].

IEEE 802.11ax standard was not developed exclusively for indoor scenarios, having also been thought to be used in outdoor scenarios. Therefore, this raises new challenges essentially caused by the Doppler effect that derives from the communication reflections in fast-moving objects, such as cars or trains [42]. To overcome this and improve high mobility resistance, it is proposed to insert copies of the High-Efficiency Long Training Field in the PHY packet payload midambles. As a result, the packet starts to be estimated during the packet preamble. It continues throughout the entire packet transmission, which is extremely useful in scenarios where the channels can vary quickly [28].

In the next section we will compare and contrast Wi-Fi 6 and 5G.

4 Wi-Fi 6 and 5G Comparison

The increase in the variety of technologies for accessing wireless networks leads to an urgent need to evolve 4G technology with the fifth generation's mobile communications and broadband networks. Thus, it is essential to establish a correct comparison. For example, because of the higher frequency millimeter waves, 5G networks in interior environments require massive base stations, making it difficult for the signal to penetrate walls, making 5G tough to cover in this sort of situation. Therefore, Wi-Fi technology can be an excellent ally for solving this problem, making the two technologies highly compatible, despite their differences.

Moreover, the 5G networks are highly recommended for connections in open spaces, mobile scenarios, and environments with a high density of connected devices. Usually, outdoor Wi-Fi 6 is primarily found in crowded settings, such as playgrounds. In turn, 5G represents better performance to provide coverage of a larger size, as in scenic spots. However, its base station exceeds Wi-Fi 6 in terms of coverage range and roaming. So, 5G will represent significant improvements in autonomous driving, drones, and public safety. Consequently, we can say that the evolution of these technologies must follow a mutual evolution path. Table 5 represents the comparison of the main features of Wi-Fi 6 and 5G.

From the table's analysis, we can see that there are considerable differences between the two technologies. We are starting with OFDMA technology. This technology significantly reduces delays while improving efficiency, ideal for multi-user scenarios where several small data packets are transmitted. So, we can analyze that Wi-Fi 6 only adopts this technique to increase spectrum use efficiency. However, 5G uses high air interface security, representing a derivation of the OFDM technique following a design similar to OFDMA.

Wi-Fi 6 improves the MU-MIMO technique by offering uplink support with 8 × 8 antennas. Thus, 5G uses the same principle, enhancing its capacity to 64 × 64, allowing better coverage.

Regarding the use of the spectrum, this is one of the significant differences between the two technologies. In Wi-Fi, we observed the use of unlicensed spectrum, which means that any person or company can use the frequency bands without prior registration. In 5G, this is a strategic resource that the operators of each country can only sell. Therefore, issues related to virtualization become a central problem so that the spectrum can be shared by several operators simultaneously. This problem is discussed in more detail in Sect. 6.1. Wi-Fi frequency bands are public, so we can quickly think that they are more subject to interference, making them less stable than mobile networks. However, these conflicts only happen because they are directly related to the number of users. That is, as the number of users increases, the likelihood of interference occurring increases equally. It was because of this that the OFDMA and MU-MIMO techniques were introduced.

The use of the 5G spectrum lacks permission on the part of operators. Hence, in a 5G network, traffic from all terminals must pass through the operator, representing an inefficient transmission, which requires the operator to assign a usage license whenever a new terminal tries to access the network. Moreover, Wi-Fi networks are considerably more versatile and, if a new user wants to reach the network, it merely has to create a new account. Thus, to expand this network, it is only necessary to attach more APs and customize the usage policies to ensure the proper control of resources.

For all these reasons, according to Huawei [43], one of the advantages of Wi-Fi technology is related to its uniform use, given that it is the most convenient technology due to its easy implementation and low costs. However, this technology reveals some limitations in large external coverage scenarios, failing to meet low latency requirements (<10 ms). 5G technology has the great advantage of providing low latencies and good external coverage. Nevertheless, this represents a higher cost than Wi-Fi, especially for indoor deployments and low terminal compatibility.

Therefore, the combination of Wi-Fi and 5G technology is an inevitable trend for network construction due to their complementary. Thus, the fifth generation

Table 5 Main feature comparison between Wi-Fi 6 and 5G—Adapted from [37, 43]

Innovation	IEEE 802.11ax	5G
QAM modulation	1024-QAM	256-QAM
MIMO order	8 streams	Outdoor: 16 streams; Indoor: 4 streams
Frequency bandwidth	Household: 160 MHz; Campus: 80 streams	100 MHz
Latency	Average: 20 ms	eMBB: 4ms; URLLC: 0.5ms
Mobility	50 ms	20 ms
Interference	Unlicensed—interference may occur	Licensed—no interference
Per-bit cost	Low—enterprise LAN coverage, about 1/30 5G	High—enterprise LAN coverage low—WAN coverage
Deployment period	Small and medium enterprises: within one month depending on the specific size; Large-sized enterprise: 2–3 months	LAN: 4–5 months; WAN: 1–1.5 years
Security	Guaranteed security using latest protocols	High air interface security, traffic forwarded through carriers' networks
Key technologies	OFDMA, MU-MIMO, 1024-QAM, TWT	NOMA, millimeter wave, large scale of MIMO, cognitive radio technology, ultra-wideband spectrum, multi-technology carrier aggregation
Application	AR, VR, IoT, remote control, smart manufacturing, smart home, education, shop, home, public transportation connection, etc.	AR, VR, IoT, car networking, remote control, smart manufacturing, smart home, etc.

of mobile communications adopted some Wi-Fi technologies related to flexibility mechanisms, making this technology more viable for end-to-end architectures.

In the next section we will explain the Wi-Fi 6 successor, since it promises to significantly boost the speed and stability of wireless connections.

5 Wi-Fi 7—IEEE 802.11be

With the emergence of beyond 5G mobile networks, indoor Wi-Fi traffic is changing, as radio waves suffer losses when overcoming obstacles such as buildings walls. Thus, Wi-Fi 7 is expected to provide services that allow the majority of beyond 5G traffic to be redirected to the Wi-Fi system, enabling mobile service providers to save costs. Wi-Fi 7 will have up to 4.8 times higher nominal data bandwidth compared to 9.6 Gbps Wi-Fi 6. Thus, it is expected that the overall nominal throughput of Wi-Fi 7 could be 46 Gbps. An improvement in the PHY protocol would arise due to the previous PHY headers' generalization and the introduction of a forward-compatible frame format. Wi-Fi 7 pretends to reach bandwidths over 40 Gbps employing strategies that make it easy to take advantage of twice the bandwidth and improved SS.

Despite this, it is possible to analyze some of the innovative techniques that the IEEE 802.11 Working Group will introduce.

Wi-Fi 7 is expected to provide native support for Multi-Link Operations, to improve data bandwidths in the 5 and 6 GHz bands. Wi-Fi 6 already manages to use multiple links simultaneously. As a general rule, they are independent links, and Multi-Link Operations seeks to change this to get more efficient channel resources to use. Following improvements in the spectrum, the HARQ technique will be upgraded, which allows a receiver to combine different pieces of resulting information from each transmission attempt until it can fully decode the packet, without having to wait for the sender to carry out the complete transmission.

In short, we can say that the Wi-Fi 7 evolution is based on the following premises [16, 44]:

- 320 MHz bandwidth and more efficient utilization of non-contiguous spectrum;
- Multi-band/multi-channel aggregation and operation;
- 16 SS and MIMO protocols enhancements;
- Multi-AP Coordination (e.g. coordinated and joint transmission);
- Enhanced link adaptation and re-transmission protocol (e.g. HARQ);
- Adaptation to regulatory rules specific to 6 GHz spectrum;
- Refinements of IEEE 802.11ax features.

Thus, Wi-Fi 7 is being designed to improve performance and increase spectral efficiency while reducing implementation costs. This development was anticipated by the expected revolution with the introduction of beyond 5G networks, trying to create a wireless Extremely High Throughput (EHT) network. Comparing this new Wi-Fi protocol with previous one, we can summarize the main features in Table 6.

5.1 PHY Techniques Enhancements

In addition to throughput improvements, IEEE 802.11be would exploit the IEEE 802.11ax allowed trigger-based scheduled service to provide efficient and more predictable medium access. IEEE 802.11be is planned to provide updates to reduce overhead and allow the more effective operation of managed network installations. Thus we can assume that the new technologies implemented in PHY can be summarized as follows [16]:

- More expansive bandwidth modes, including 320 MHz, 160 + 160 MHz, 240 MHz and 160 + 80 MHz. This doubles the 160 MHz used by Wi-Fi 6;
- Multi-Resource Unit item assigned to each client and compatible with increasing spectral efficiency;
- EHT led to the development of new modulation strategies, more precisely in the order of 4096-QAM, to increase the peak rate compared to the 1024-QAM adopted in the previous standard.

By doubling the channel bandwidth of Wi-Fi, approximately twice as much data may be transferred in a single transmission. The IEEE 802.11be standard calls for operation in the 6 GHz range, with a current channel design supporting up to six overlapping 320 MHz channels. Because of the 1200 MHz continuous spectrum availability in the 6 GHz band, the channel bandwidth has been quadrupled from 160 MHz (the greatest bandwidth in IEEE 802.11ax) to 320 MHz channels, double the maximum throughput. The availability of the 6 GHz band, on the other hand, is subject to regulatory approval, and not all worldwide locations may enjoy the same quantity of spectrum. Because the 5 GHz and 2.4 GHz bands cannot handle 320 MHz channels, this Wi-Fi 7 capabilities will be limited to a subset of users.

Spatial streams boost system throughput by concurrently broadcasting separate data streams via several antennas. As a result, an 8-stream system's maximum throughput is eight times that of a single-antenna system. The IEEE 802.11ax standard has MIMO capability for up to 8 spatial streams. The IEEE 802.11be generation might support up to 16 × 16, which would be twice the maximum speed above IEEE 802.11ax. While the theoretical maximum speed can only be achieved amongst

Table 6 Feature comparison between IEEE 802.11ax and IEEE 802.11be—Adapted from [16, 44, 45]

Innovations	IEEE 802.11ax features	IEEE 802.11be features
Maximal data rate	9.6 Gbps	46 Gbps
Bands	2.4 and 5 GHz in Wi-Fi 6 & 6 GHz in Wi-Fi 6E	1–7.25 GHz including 2.4, 5 and 6 GHz
Channel size	160 MHz	320 MHz
QAM modulation	1024-QAM	4096-QAM
MIMO order	8 SS	16 SS
Access point	1	Multiple
Release date	2019 (released)	2024 (expected)

devices that use the same antennas, the number of MIMO streams available to Client Stations is frequently limited to two or three. The high number of spatial streams is a crucial component for higher spectrum efficiency with the implementation of MU-MIMO, another feature provided by the IEEE 802.11be standard.

So, new PHY and MAC modes have been designed to support a transfer rate of at least 40 Gbps through various PHY enhancement technologies. However, it is essential to note that the IEEE 802.11be standard production process is still at an early stage. Several works need to be performed, such as coding and interleaving schemes for multiple Resource Units assigned to a single client, tone mapping for combination schemes, and multi-Resource Unit signaling projects.

5.2 Multi-link Operation

Multi-AP collaboration is one of the key new features of the IEEE 802.11be candidate, which depends on direct AP communication to meet the required network output objectives. It will have advantages in terms of throughput and capacity and has the potential to solve some of the problems that have the most significant effect on latency and reliability. Multi-AP collaboration is required to solve the conflict caused by Overlapping Basic Service Sets, one of the critical causes of random latency variations.

Through exploiting several bands/channels, IEEE 802.11be will separate time-sensitive traffic from network congestion, one of the main causes of significant latency variations. It should be possible to direct traffic to those bands/channels in a controlled network by isolating time-sensitive traffic from the others.

Multi-link operation enables link aggregation at the MAC layer, bringing many benefits in multiple dimensions. It also offers lower latency due to simultaneous connectivity to increased links, high reliability due to packet replication over multiple links, and assigns data streams to unique app-based links. In conclusion, it is beneficial to several applications, from Virtual Reality to industrial IoT devices.

Thus, we can conclude that channel assessment is designed for a single link in the current WLAN specifications, which means that Multi-link issues have to be carefully discussed in the EHT. Multi-link transmissions can be classified into fast connection switching for coexistence/load restrictions, data separation for efficient channel use, independent transmission, and simultaneous transmission.

Theoretically, when comparing the multi-link with the single-link techniques used in the previous standard, we can conclude that the multi-link transmissions can double the link's capacity with the same time resource. However, multi-link transmissions' performance gains can be hampered by legacy single-link devices in a practical context. Thus, the design of effective multi-link transmission schemes needs to be careful with the spectrum utilization. The complexity of the implementation project and the limitations of legacy devices operating on the same link(s) can cause some barriers. Besides, the simultaneous transmission and reception operation in the multi-link scheme can cause inter-link interference due to power leakage unless the links are configured with minimal separation or sufficiently far. Thus, if we use a large separation between adjacent links, we can reduce the spectrum's use, so it is necessary to explore some advanced analog/digital interference cancellation/suppression schemes for multi-link transmissions [16].

5.3 HARQ

The Hybrid automatic repeat request technique is an improvement on the Automatic Repeat Request (ARQ) technique. In conventional Automatic Repeat Request, when we have a wrong packet, the system discards that packet and requests re-transmission. For this, a feedback message is sent to the transmitter. These messages indicate whether the reception was successful ACK or not Non-Acknowledgement (NACK). So, if these re-transmissions did not happen, we would have a much faster data flow. The HARQ technique appears precisely for this purpose, to improve the data flow and minimize the re-transmissions of the same packet. Packets with errors then cease to be re-transmitted and are stored in a "buffer" together with re-transmission attempts in succession. Thus, at each transmission attempt, the receiver stores information in a buffer until it gathers the necessary information to packet decode without requiring it to be successfully transmitted in a single transmission. When the re-transmissions are identical between them, the information kept in the buffer is redundant. This effect, known as Chase Combination, reduces the gain of the HARQ technique. To overcome this, the Incremental Redundancy technique was introduced. This allows only the part that corresponds to the information not received by the sender to be re-transmitted. Thus, we forward less information, which means fewer bits, less energy, and more gain [16, 44] Fig. 4 represents the flow of a HARQ process.

Figure 4 depicts the HARQ technology operation, where it is possible to keep the buffer fulfilling until it is confirmed the message is thoroughly read and the ACK is sent to the transmitter. Hence, to guarantee that uplink users do not encounter ARQ blocking, the influence of retransmissions on the time-frequency problem segmentation is managed using a new block scheduling interval mainly intended for synchronous HARQ. Using this framework, the optimal margin adaptive allocation issue may be formulated. Based on its structure, sub-optimal techniques to decrease the required resource allocation while striving to reduce complexity can be developed. As a result, resource allocation is an essential method for controlling the effect of

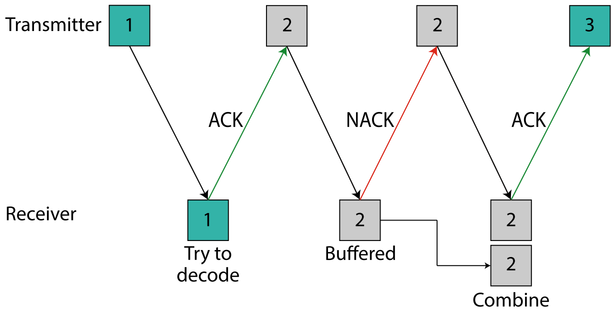

Fig. 4 Flow of a HARQ process—Adapted from [46]

re-transmissions on the time-frequency issue. Hence, in the next section, we will go through different resource allocation mechanisms that utilize techniques to increase networking facilities and opportunities.

6 Emerging Mechanisms for Wireless Networks

The next generation of wireless networks offers novel network features such as reduced latency, edge computing, and radio convergence, paving the way for a future that is always connected. In this context, and in order to provide the necessary high-quality services and connections constantly and everywhere, even in poor network circumstances, potential network failures must be controlled quickly and efficiently. Network Virtualization and Slicing techniques are the most visible feature of beyond 5G networks.

According to the 3rd Generation Partnership Project (3GPP), network slicing is a paradigm that takes advantage of virtualization techniques, in which logical networks/partitions are formed with suitable isolation, resources, and optimum topology to serve a specific purpose, service category, or individual client. Technologies such as Network Functions Virtualization (NFV), Mobile Edge Computing (MEC), and Software Defined Network (SDN) will be used to enable the physical infrastructure to provide the aforementioned functionalities. These concepts will be explored in detail throughout this section.

6.1 Network Virtualization

Wireless network virtualization issues will be fundamental in the Wi-Fi, beyond 5G, and IoT evolution. Network virtualization refers to abstracting and separating physical network infrastructure from the services and applications that operate on top of it. It generates a virtual representation of a network, allowing several virtual networks or instances to coexist and function on the same physical network infrastructure. This technology has received attention and relevance in modern networking, and it is commonly utilized in data centers, cloud computing settings, and workplace networks due to its flexibility and scalability since virtual networks may be easily constructed, adjusted, or deleted without causing any disruption to the actual infrastructure. This adaptability makes it easy to respond to changing network needs and scale resources up and down as needed.

Wireless virtualization involves abstraction and sharing physical resources of Wireless Resource Providers with different parties such as Mobile Virtual Network Operators (MVNOs) [47]. Wireless resource allocation represents an essential aspect in several fields today, such as spectrum efficiency, energy efficiency, Quality of Service (QoS), and coverage [48, 49]. In the state of the art, several approaches have been proposed to allocate resources optimally [50–53], trying to achieve a panorama where Wireless Resource Providers can sub-allocate their wireless resources to different MVNOs according to service-level agreements, and the corresponding needs [54–58]. However, the methods used have some limitations. According to [47], the use of a static pricing policy for spectrum use and monopoly in [55, 56], makes these methods unsuitable for dynamic changes in wireless environments, something unthinkable with technological densification. Moreover, according to [57], MVNOs dynamically adapt their price to use the spectrum by end-users, requesting radio frequency bands from Wireless Resource Provider according to the network demand from users to maximize their functionalities.

Over the years, issues related to virtualization have been analyzed from different perspectives. Ho et al. [59] have studied virtualization in terms of radio resource allocation. In order to dynamically assign resources for users affiliated with multiple mobile virtual network operators, the infrastructure provider must adopt efficient and flexible resource allocation mechanisms. The authors showed that the strategies both for infrastructure provider and MVNOs were optimized via a two-stage Stackelberg game in an equilibrated way. Kokku et al. [60] have analyzed the single-cell virtualization regarding the Long Term Evolution. The authors demonstrated that network virtualization could run different flow schedulers in different slices, run different slices simultaneously with different types of reservations, and perform slice-specific application optimizations for providing customized services using prototype implementation and detailed evaluation on a testbed for both downlink and uplink directions. Feng et al. [61] present a conclusion about multi-cell network virtualization Long Term Evolution. The authors introduced the cell clustering approach in the presented study, which may greatly minimize the complexity of resource slicing and make it practicable in wireless networks. Finally, the test results show that network performance has significantly improved. The efficiency of the spectrum is doubled, and the packet loss rate is reduced to 1/20.

Naveen Sapavath et al. [47] present an approach to virtualization that considers the use of three layers for dynamic power, bandwidth, and price adjustment in wireless networks. Thus, this development aims at the optimal interconnection between Wireless Resource Providers, MVNOs, and end-users. Wireless Resource Providers are competing with each other, allocating radio frequency slices and offering prices so that MVNOs can rent radio resources and meet their customers' needs, making final customers improve their QoE. All in all, the benefits of virtualization technologies have meant that MVNOs have no doubts about using this technology in their services. Thus, in addition to technical advantages, network virtualization will also reduce the cost of equipment and the entire network's management due to the abstraction in the wireless network infrastructure and radio resources. This allows creating a series of virtual resources that can be offered to different service providers [62, 63].

Due to the introduction of virtualization techniques, the Internet Service Provider function has been divided into two parts: infrastructure provider and service provider. The first is responsible for implementing and maintaining the physical infrastructure, while the second is responsible for providing a variety of services for users. Thus, there is an urgent need to achieve good resource allocation due to the advances of virtualization techniques [64]. As a result, resource allocation is considered one of the biggest challenges to wireless virtualization issues. Resource allocation decides the best way to dynamically allocate resources to MVNOs, to match registered users' demand, energy efficiency, spectrum management, and to fulfil

QoS requirements. Tai Ho et al. [64] propose a dynamic resource distribution system that can be extended to the reseller and service provider MVNOs, who depend almost exclusively on Internet Service Providers facilities to support MVNOs customers. As a result, the authors provide a multiple time-scale framework to tackle the infrastructure provider's optimization problem, which decomposes the price decision, base station assignment, and resource allocation into separate time-scale algorithms to meet the design objectives. Finally, they suggest a branch and bound method for optimally solving the pricing decision problem. The simulation findings indicate the trade-off between energy efficiency, income for infrastructure providers, and isolation provided.

However, virtualization issues do not stop. One of the most common features in modern APs is the support for several Virtual Access Points (VAPs). This means that a single physical device can create multiple independent Basic Service Sets (BSSs) (a set of wireless clients connected with an AP), reaching up to 32 VAPs in some cases. We can take advantage of this when, for example, it is needed to separate a guest Wi-Fi network from an internal network without installing an additional AP. One of the shortcomings of existing VAPs is that service information for all VAPs can be the same but transmitted separately by each one. Thus, it is necessary to reduce this information redundancy. To reduce overhead, the IEEE 802.11ax amendment introduces multiple Basic Service Set Identifier (BSSID) support, which allows identifying information to be sent to all BSSs simultaneously, for example, through a common beacon. All BSSs in the multiple BSSID use the same Basic Service Set (BSS) color, and the frames of the BSSs of a multiple BSSID set are considered intra-BSS frames [65, 66]. Many conventional techniques need more adaptability to address changing demands. As a result, virtualization support is critical in orchestrating applications and services, enabling effective resource management and utilization from the core to the edge operations.

With the introduction of new social needs, such as autonomous driving, virtualization has grown in capacity and is now being applied to the RAN via resource allocation. This change emphasizes the importance of a well-designed, robust resource allocation approach that is both energy and cost-efficient. The successful implementation of such a resource allocation mechanism is crucial in ensuring high-quality services are delivered. Given the radio and power resources scarcity, good RAN scheduling becomes critical for achieving peak performance. The QoS of multiple services may be assured by carefully controlling and distributing resources fulfilling the varying demands of consumers. Network slicing also plays a significant part in this, as described in the next paragraph.

6.2 Network Slicing

Network slicing is a network architecture innovation in 5G that is also expected to be inherited in the next generation [2, 67]. Network slicing allows numerous isolated and independent virtual (logical) networks, or slices, to coexist on the same physical network infrastructure. Each network slice is designed to support certain use cases or applications, each with its own set of requirements and features. The benefits of network slicing are multiple. First, network slicing enables multi-tenancy by virtual multiplexing networks, allowing many virtual network operators to share the same physical network infrastructure [68]. This lowers the capital cost of network implementation and operation. Second, network slicing enables customized slices for distinct service types with differing QoS requirements, allowing service differentiation as well as the guarantee of service level agreements for each service type. Third, because slices may be produced on-demand and updated or canceled as required, network slicing improves network management flexibility and adaptability [69, 70]. Moreover, network slicing enables end-to-end management of the whole network, from the core to the edge. This guarantees that the needed level of service is maintained consistently across the network.

An SDN controller is a centralized entity that abstractly represents multiple resources and control logic, allowing for the smooth generation and maintenance of network slices. In this perspective, a network slice may be viewed as a client of the SDN architecture, exploiting the SDN controller's capabilities and operations. Network operators and service providers can build pre-defined blueprints for network slices, outlining each slice's intended attributes and needs, using the SDN controller as a mediator. This allows for the fast and on-demand creation of network slices adapted to individual service requirements. By referring to a slice as an SDN client, we accept that it communicates with the SDN controller to share its needs and expectations. In turn, the SDN controller orchestrates the resources and implements the appropriate control logic to fulfill these needs, resulting in a customized slice instance. SDN and network function virtualization are technologies that enable the implementation of NFV. SDN uses the cloud computing model in network administration, with a centralized controller to dynamically steer and regulate traffic flow and choreograph network resource allocation for performance improvement [71].

NFV implements network operations such as firewalls, load balancing, and address translation as software instances known as virtual network functions that operate on virtual machines on top of conventional servers (referred to as NFV nodes) without the need for specific hardware [72]. Thus, in NFV, a network service is a component of a network slice, and a network slice comprises one or more virtual network functions. NFV complements SDN in network slicing implementation because SDN builds control plane activities that enable slicing, whereas NFV provisions services, controls the life cycle of network slices, and orchestrates slice resources by realizing virtual network functions [73]

Many sectors will benefit from the virtualization features provided by NFV in order to allow such logical network slices and support numerous 5G use cases (e.g., mission-critical applications, media personalization, and mobile broadband). Virtual Network Functions' quick deployment and simple management, as well as their dynamicity and high availability, efficiently enable the provisioning of smart segmentation, customization, and programmability of the network to match the demands of each service. Indeed, the progression to 5G and beyond entails managing highly dynamic network slices made up of several virtual nodes. They can be generated or deleted in response to service demands or other goals set by mobile carriers, such as cost reduction and energy usage. The need for network slices, which will enable operators to provide networks "as a service," demonstrates itself to be a key concept for future use cases, such as putting both bandwidth and latency demands on the network, defining optimal personalized verticals to respond to the requirements of users, specific applications, and services dynamically and flexibly. The authors of [74] feel that network slicing is one of the essential technologies in 5G mobile networks. The slicing technique enables virtual networks to offer individualized services on demand. Slices can be manipulated through software-based solutions in [75]. Approaches using SDN were employed to enable software-enabled virtualization, allowing for the creating of several virtual or logic networks. These slices will be enabled on a single network, divided into different logical networks. This method is used in [76] since VPN is an example of a slice on conventional networks. However, slices will be mutually autonomous, and each slice's control and administration system will be independent. In [77], the authors conducted a thorough analysis of network slicing with enabling technologies, standardization initiatives, industry programs that expedite network-slicing utilization, and future research objectives. In [78], the author discuss the current status of 3GPP standardization, strategies to lessen the complexity created by network slicing, and future research prospects. The next section will explain how we can integrate slicing concepts in RAN.

7 Radio Access Network

A RAN is a significant component of a wireless telecommunications system that uses a radio connection to connect individual devices to other network portions. RANs are critical connection points for telecom network operators, representing major network expenditures, performing heavy and complicated processing, and currently facing fast-growing demand as more edge and 5G use cases arise for telco customers.

Virtualization and Slicing may be used in RAN to help telcos update their networks. This is especially essential given that the industry's future is focused on the transition to 5G. In fact, the ongoing 5G network transformation frequently relies on RAN virtualization and increasingly assumes that it is container-based and cloud-native.

This section goes throughout RAN Slicing, its research challenges, and the importance of virtualization concepts on RAN.

7.1 RAN Slicing

It has been established in 3GPP that 5G RAN should be slice-aware in order to process slice-specific traffic in accordance with customer needs.

RAN slicing is the most promising technology in 5G networks and beyond since it provides a flexible and scalable network architecture to accommodate a wide range of services with varying QoS demands. Given to this, it is possible to create distinct logical networks on a same physical network infrastructure. This means that the network may be separated into several virtual slices, each with its own set of features and service needs. Each network slice may be optimized to fit the demands of various applications and services. One slice, for example, may be devoted to IoT services, while another could be tailored to serve virtual reality or online gaming services. RAN slicing allows for optimal resource allocation by ensuring that each slice has the capacity to provide appropriate performance for certain services. This technology is especially important beyond 5G since the network is designed to accommodate a variety of use cases with varying needs. RAN slicing may dynamically and elastically assign network resources to deliver customized services for isolated logical networks by slicing shared physical wireless networks into many remote logical networks. This advantage drive the research on RAN slicing for Next-Generation Wireless Networks. Extensive industry efforts have gone into ratifying the RAN slicing framework. The 3GPP has undertaken substantial research on the slicing-based architecture for 5G networks [79]. Several proofs-of-concept RAN slicing systems have been created and assessed using real-world network traffic data [80, 81]. The next section will discuss the research challenges associated with RAN slicing.

7.2 RAN Slicing Research Challenges

While the radio characteristics discussed above make slicing implementation easier, there are still several issues regarding resource allocation and management. The coexistence of a high number of slices creates several issues in terms of resource allocation to slices and flows, taking into account not just radio resources but also processing resources (for MEC and virtual radio functions). Adapting current resource allocation systems, developing new ones, and integrating them into the new context of slicing in the RAN is one open research topic. These schemes must work together to maintain QoS for individual slices, equity among slices, and overall resource efficiency [82]. A number of studies offer an overview of fairness in the distribution of multiple resources. While many of these approaches may be relevant in the context of slicing, there are several related open questions according to [70]:

- Resource interplay—because a service might use numerous network resources, there is an inherent tradeoff between network resources. For example, in computer offloading services, service latency is considered to be the amount of time it takes to task transmission and processing. If a user connects to a remote MEC server with plenty of computing capabilities for job processing, task transmission latency will be considerable. On the other hand, if a user connects to a nearby MEC server with insufficient computing capacity, task processing takes longer. In computing offloading services, the allocation of computing and communication resources is connected. Similarly, numerous network resources are interconnected, which complicates RAN slicing.
- Strict QoS requirements—5G networks and beyond have demanding QoS standards, including greater throughput and lower latency, than typical 4G networks. The usual Ultra-Reliable and Low Latency Communications (URLLC) service in 5G, in particular, needs ultra-high dependability (e.g., 99.999%), which is substantially tighter than that of other services. Furthermore, data packet payloads in

URLLC services are often minimal, such as 32 bytes [83]. Because of the high transmission overhead, the standard Shannon theory, which is designed for long-length packet transmission, cannot assess the transmission performance of short-length packets. The finite block length channel coding theory should be used to quantify the feasible rate for short-length packets.

- User mobility—because of the high network density, users may often migrate beyond the scope of their associated network infrastructure, resulting in a dynamic network topology. High-mobility vehicle users, for example, can often prompt handover. The dynamic network topology alters the distribution of service traffic, making previously ideal slice allocation poor over time, decreasing network performance, and potentially violating customers' QoS requirements. When network performance falls below a certain threshold, modifying current slices or establishing new slices is triggered, incurring slice reconfiguration expense.

7.3 vRAN

Initially, mobile network deployment was based on a monolithic method, with baseband processing units and radio modules located close to an antenna. These two major components make up what is often known as RAN, which is a key component of mobile networks together with the core network, terminals, and transport.

RAN was identified as one area that will help operators take advantage of virtualization through independent combinations of hardware and software, allowing more competition in ecosystems and the ability to choose the best solutions for each user or service. RAN comprises three fundamental components:

1. Antennas are devices that transform electrical impulses into radio waves.
2. Radios convert digital data into wireless signals and guarantee that transmissions occur in the frequency ranges and at the appropriate power levels.
3. Baseband units perform a variety of signal processing operations that enable wireless communication. Traditional baseband enables wireless communication by combining specialized hardware with many lines of code using licensed radiofrequency. Baseband Unit processing identifies mistakes, protects wireless signals, and guarantees that wireless resources are used efficiently.

These needs arose with the current trends in network automation, virtualization, and orchestration. Due to the RAN functionalities, it is possible to distinguish between real-time and non-real-time processing functions, which helps prioritize critical services. Following the evolution of the RAN techniques, Virtualized Radio Access Network (vRAN) architectures represent a promising solution for the densification needs of beyond 5G networks, as they decouple base stations functions from Radio Unit (RU), allowing processing power to be pooled at cost-effective Centralized Unit (CU). Compared to state-of-the-art RAN systems, vRAN provides flexible function relocation (split selection) and permits split with less stringent network requirements. This functional slitting is presented in Fig. 5, where the base station is split into three logical nodes: CU, the Distributed Unit (DU) and the RU, each capable of hosting different functions of the vRAN.

Since the processing and time requirements for specific tasks in the lower sections of the RAN are high, RAN virtualization presents many important challenges. These functions are essential because they determine several elements of RAN capacity and coverage. Nonetheless, the potential benefits of virtualization might be considerable:

1. A vRAN provides substantial harmonization benefits, such as a single consistent hardware platform throughout the core network, RAN, and Edge. This might simplify network administration while lowering operational and maintenance expenses.
2. Network operations will be isolated from the processing hardware in a complete vRAN. This means that RAN network services from various manufacturers might run on the same hardware, improving the service provider's flexibility. In certain situations, hardware may even be shared among service providers.
3. vRAN provides a chance to adopt proven solutions for non-RAN-specific functions already accessible in today's public Cloud technologies. By agreeing to utilize industry-standard components for everyday activities, the need for costly vendor-specific modifications would be eliminated. If this is accomplished, the RAN ecosystem will be able to concentrate on mission-critical components.
4. vRAN promises greater flexibility since functionality and capacity may be more simply installed where and when needed. This sort of adaptability might be facilitated by Cloud technology.
5. A widely used open platform might decrease barriers to cross-domain innovation, allowing for new use cases and services.

These initiatives build on current SDN/NFV softwarization and cloudification of RAN. This allows operators to choose the amount of centralization (functional split) of the so-called vRAN services for each RU while considering available network resources and user demand.

The challenge of vRAN design is exacerbated by the introduction of MEC [85], a business model in which operators lease computer and network capabilities to vertical industries such as autonomous driving. MEC services are designed for ultra-low

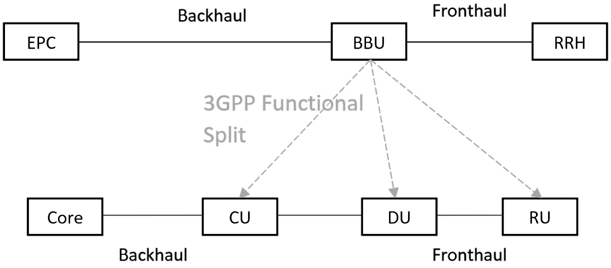

Fig. 5 Functional split—Adapted from [84]

latency and high-bandwidth applications. Thus they are often placed close to consumers, implying a full-stack distributed implementation [86]. As a result, there is an inherent conflict between MEC and vRAN, due to their different architectural approaches and objectives, which strives for the greatest feasible centralization of RAN operations. Given the importance of MEC services (a new income stream for operators), it is critical to build them in collaboration with vRAN to alleviate stress and guarantee that their performance meets beyond 5G expectations. MEC is a business concept that attempts to provide vertical sectors with low-latency and high-bandwidth services by bringing computer and network resources closer to the end-users. This suggests a distributed approach with MEC servers deployed at the network edge. The objective is to increase QoS in applications that demand real-time processing and high-speed data transport, such as autonomous driving or augmented reality. vRAN, conversely, is a virtualized solution to the Radio Access Network that entails centralizing RAN functions in a cloud-based architecture. Baseband processing operations are abstracted from physical base stations and relocated to a centralized data center with vRAN. This centralization enables more effective resource allocation and administration and greater network scalability and flexibility. The conflict between MEC and vRAN stems from their opposing architectural concepts. MEC seeks to deploy computing resources closer to the edge to achieve reduced latency, whereas vRAN seeks centralization to accomplish effective resource management. Placing MEC servers near customers suggests a dispersed deployment, whereas vRAN necessitates a centralized design.

vRAN increased the openness and intelligence of interfaces, allowing for multi-vendor RAN implementation. Therefore, it this worth noting that the vRAN intends to expand the SDN idea of divorcing the control plane from the user plane and augment conventional Radio Resource Management functionalities with embedded intelligence through RAN Intelligent Controller near-RT.

Ayala-Romero et al. [87] describe a machine learning method to resource orchestration in energy-constrained vRANs to handle the challenge of estimating power consumption and software stack processing performance. The authors demonstrated that the provided methodologies are data-efficient—they converge an order of magnitude quicker than existing machine learning methods—and have demonstrable performance, which is critical for carrier-grade vRANs. They showed the benefits of their ideas in a testbed and implemented them in Open-Radio Access Network (O-RAN)'s non-real-time RAN Intelligent Controller (RIC)

Garcia-Saavedra et al. [88] suggest two heuristics for a nearly-optimal backtracking technique and a low-complex greedy approach. Their challenge is to decide whether to place the functions on the RUs or on the CU. Their objective is to maximize the number of functions placed on the CU in order to minimize the cost of the system. Part of the problem is simplified, in addition to the use of non-optimal methods, because all RUs served by the same CU use the same functional split. The authors introduced FluidRAN, a modeling technique that reduces RAN expenses by choosing splits and RUs-CU routing pathways together. They demonstrated that pure RAN is rarely a viable upgrade solution for current infrastructure. FluidRAN ignores the potential of executing all RAN functions in an RU, which is quite typical in real-world networks, particularly during the transition to beyond 5G systems.

Because there is no direct traffic between RUs and the core, just between RUs and the CU, this reduces the routing problem. As a result, the authors only considered the CU when it was co-located with the core.

According to Singh et al. [89], RAN energy consumption is one of the main sources of Operational Expenditure for telecom operators. Furthermore, beyond 5G is expected to change the paradigm in several fields, such as RAN architecture, disaggregation virtualization, and cloudification. These changes require a more exhaustive beyond 5G RAN orchestration, which requires greater energy efficiency. To respond to this need, the authors present a vRAN model aligned with the beyond 5G specifications through realistic and dynamic models for computational load and energy consumption costs. The optimization of energy consumption and its costs was modeled through a distributed integer quadratic programming model with NP-Hard nature. To evaluate the performance of the proposed solutions, the authors resorted to real data from a metropolitan area, having achieved an improvement in the energy efficiency of up to 42%, compared to traditional RAN techniques. However, the authors show that in a vRAN configuration, it is not always efficient to allocate all processing in Telco zones or central clouds. The best strategy is to process most of the information at the far Edge whenever available. Among the various far-Edge Cloud configurations presented and mid-haul capacities, the authors show that implementing a high-capacity mid-haul link along with high-capacity servers is not always the best option, as the two features serve opposite purposes.

8 Open-Radio Access Network

O-RAN is based on RAN element interoperability and standardization, including a uniform interconnection standard for many suppliers' white-box hardware and open-source software elements. O-RAN design incorporates a modular base station software stack on off-the-shelf hardware, allowing baseband and radio unit components from different vendors to work together smoothly. Through the shared features of efficiency, intelligence, and adaptability, O-RAN emphasizes simplified 5G RAN performance targets. O-RAN used at the network edge will assist 5G applications like autonomous vehicles and the Internet of Things, efficiently support network slicing use cases, and enable safe and quick over-the-air firmware upgrades.

This section will explain the O-RAN Architecture, the corresponding challenges, and the proposals and techniques that already take advantage of this new paradigm.

8.1 O-RAN Architecture and Challenges

Current RAN technology is delivered as a hardware and software-integrated platform. The number of mobile networks subscribers and the number of cells and sites is likely to increase in the future due to network densification and the introduction of additional frequency bands. In fact, it is expected that 8.8 billion mobile subscriptions will be active in 2026, including 3.5 billion subscriptions of beyond 5G [90]. Thus we require more flexible and centralized deployed networks by design.

The goal of O-RAN is to provide a multi-supplier RAN solution that allows for the separation—or disaggregation—of hardware and software through open interfaces and virtualization, hosting software that controls and maintains networks in the Cloud.

The variety of anticipated benefits include enhanced supply chain, solution flexibility, and new capabilities, which will lead to more competition and additional innovation. The O-RAN Alliance is an organization that develops radio access network specifications in line with the beyond 5G requirements. There is an urgent need to ensure that the RAN has the underlying capability to meet strict latency requirements and the ability to control multiple users simultaneously. Thus, following a similar path to beyond 5G, where NFV have started a long time ago, O-RAN also began to introduce virtualization concepts in its architecture.

The virtualization process in RAN requires the coordination of RAN, with the vRAN that coordinates the functions of base stations from a data-center using NFV and SDN technologies. The CU/DU functions are thus virtualized, enabling OPEX reduction through energy savings, IT conversion of RAN, and accessible network extension by installing new resource units and their connection with the CU/DU pools. Due to this, CAPEX savings are expected, as less investment will be needed due to polling capacity and RAN resources optimization.

As a complement to virtualization and disaggregation inside RAN, O-RAN Alliance was created to define the open and interoperable interfaces between RAN elements, which allows operators to work with different vendors flexibly.

Table 7 presents the main O-RAN challenges. From the table, it is possible to observe that even with the substantial efforts that have been made, O-RAN is still in its early stages and must handle the complexity associated with an expanded ecosystem based on infrastructure disaggregation.

The upgraded 3GPP nodes, functions, layers, and interfaces serve as the foundation for the O-RAN reference architecture [93]. Figure 6 represent the O-RAN architecture introduced by O-RAN Alliance.

From the figure, O-RAN architecture's functional modules comprise the RIC non-Real-Time layer, which performs policy administration and analytics operations. The RIC near real-time layer performs time-sensitive activities such as load balancing and handover and interference detection. Layer integration enables the RIC near the Real-Time layer to benefit from the RIC non-Real-Time layer's intelligently trained models and real-time control features.

The multi-RAT CU protocol stack, which is implemented on a virtualization platform, allows protocol processing for 4G or 5G while also creating security isolation and virtual resource allocation, among other things. The Open Radio Unit (O-RU) and Open Distributed Unit (O-DU) components are linked via an O-RAN fronthaul interface with a well-defined Lower Level Split (LLS) that enables Enhanced Common Public Radio Interface (eCPRI) and Radio over Ethernet (RoE). Further development and standardization of these interfaces will promote interoperability, competitiveness, and innovation throughout the O-RAN supply chain.

By decreasing the barrier to entry for new O-RAN 5G ecosystem members, the innovation required to satisfy ever-changing consumer expectations can be completely unlocked. Based on their particular network use case profile, operators will

Table 7 O-RAN challenges—Adapted from [91, 92]

Challenge	Description	Feature area
Depth of virtualization	To build an open and fully virtualized RAN solution, a suitable telco Cloud-based infrastructure must first be established	Deployment
Maturity on Open vRAN vendors	Open vRAN deployments are far from widespread, and they are not yet capable of managing the same volumes of traffic as traditional systems	vRAN
Performance	Traditional 5G suppliers may rely on their knowledge to give superior performance to Open vRAN, namely in terms of latency performance needs and scalability to manage large traffic volumes. Although first Open vRAN implementations demonstrated good key performance indicators results, comparable performance under more challenging traffic scenarios must be confirmed	Throughput
Capabilities	Mobile operators will need to swiftly upskill current IT/Cloud personnel while also recruiting fresh people to handle network maintenance and fault management	Deployment
Transport network	Mobile carriers will need to deploy fiber fronthaul rollout to meet the increased capacity required and to connect centralized network parts to cell sites. Latency needs will also be a significant issue to overcome	Deployment & Throughput
Interoperability	When Telcos collaborate, an Open vRAN ecosystem must give a clear picture of duties and accountability. While a collaborative approach certainly has a lot of promise, and adopting open interfaces would ease interactions, live networks will require convincing proof that a minor call drop problem will be quickly detected, examined, and repaired	Security
Handle complex integration	O-RAN enhances multi-vendor situations that necessitate the integration of multiple software and hardware solutions, therefore increasing the complexity of system integration	Deployment
Enable E2E service orchestration	Telcos have been working for years to allow End-to-End (E2E) service orchestration. The problem applies for all Telcos, but brownfields will very certainly need to deliver E2E service orchestration capabilities to both their O-RAN and legacy infrastructures, adding complexity	Deployment
Secure consistent network performance	One often raised worry pertains to the technical maturity of O-RAN solutions as compared to conventional architectures deployed massively over highly densified and demanding networks. It is critical to provide feature parity, constant network performance, and QoE	Throughput
Operations & maintenance capabilities	The increasing number of suppliers necessary to deploy a single network might initially make maintenance and network operations more complicated. Furthermore, a new technical team profile is essential as the environment shifts from hardware to software-focused and virtualized	Deployment

Table 7 (continued)

Challenge	Description	Feature area
Network lifecycle management	Because O-RAN networks are intended to be multi-vendor environments, updates should be carefully planned and coordinated across network providers to avoid the possibility of interoperability difficulties	Deployment

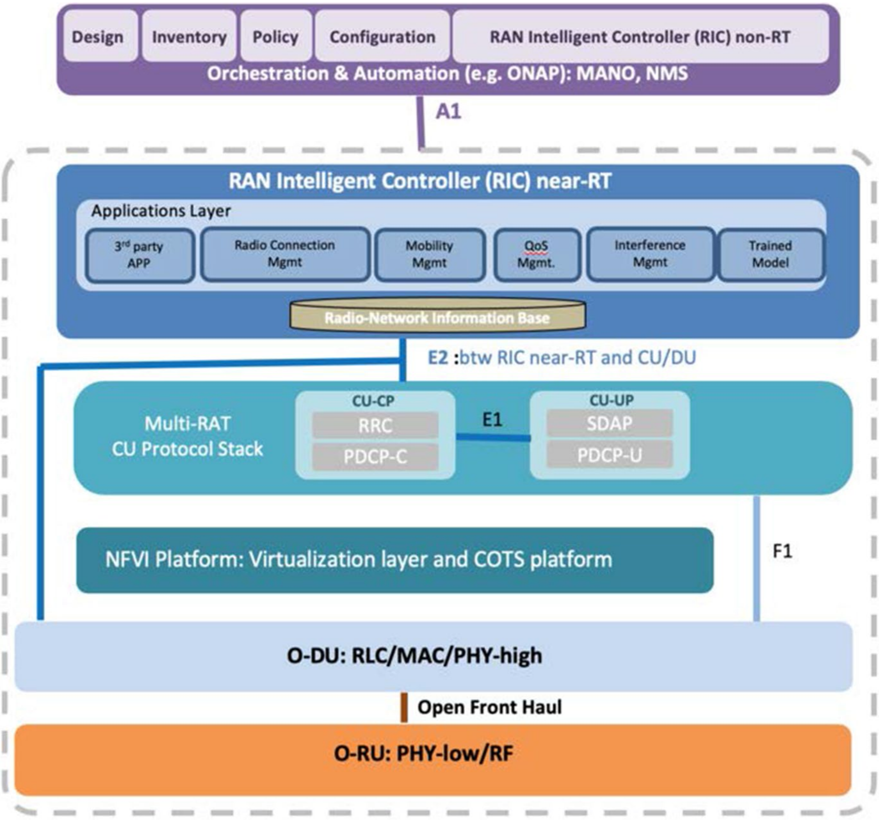

Fig. 6 O-RAN architecture—*Source* [94]

be able to use best-of-breed components. This opens up the potential to shorten development cycles by developing different network sections individually while jointly leveraging additional innovative horsepower.

The open radio access network architecture for cloudified RAN is interoperable and standard. It is projected to be a crucial technology in 5G networks, significantly improving RAN performance.

O-RAN, associated with vRAN techniques, virtualizes radio access network elements and defines suitable open interfaces for connecting these elements. One of the essential characteristics of O-RAN is its open interface, which allows mobile network operators to create their services. O-RAN enables distinct RAN levels to be separated and deployed as virtual functions, which can openly communicate with each other for service provisioning [95]. Thus, we can combine the advantages of both. vRAN provides the ability to deploy various industry-leading vRAN functions at the best locations to serve their functional purposes, creating beyond 5G networks with a much more flexible design than the traditional RAN. This increases performance without linearly scaling the entire RAN. Furthermore, vRAN outperforms traditional parameter-based and reactive security techniques regarding threat prevention. vRAN also protects assets by allowing communication services providers to execute vRAN functions now and transition to O-RAN on the same infrastructure when O-RAN standards and technology mature. This enables dynamic reactions to variable demand and prevents wasteful usage of capacity. The multivendor ecosystem fosters competition and innovation with solutions from many RAN suppliers. The separation of the management and control planes from the vRAN functions enables the O-RAN intelligence to be managed and controlled centrally by a new entity created in the O-RAN specifications, known as the RAN Intelligent Controller, allowing the RAN to be programable.

Disaggregation is critical for 5G deployment and evolution because it allows mobile operators to expose the RAN network and use multi-vendor solutions. O-RAN opens up new opportunities for RAN customization and flexibility consistent with the diversity of 5G use cases and needs.

8.2 O-RAN Disaggregation Proposals

The O-RAN Alliance has evaluated the different RU/DU split options proposed by the 3GPP, with specific interest in alternatives for physical layer split across the RU and the DU [96].

Processor-based platforms that implement an open interface between components RU/CU/DU using hardware- and software-defined functions bring Cloud-scale economics and agility to the radio access part of the network through modular softwarization for capacity management, increasing reliability and availability. The use of O-RAN in the network results in the acceptance of new services and applications, the realization of network slicing, and the DevOps concept. Compared to traditional RAN, which had combined Remote Radio Unit and Baseband Unit with a high-cost transport network, O-RAN deployment and administration are flexible due to its agnostics front-haul [97].

Kazemifard et al. [97] model the containerized network function placement, and resource allocation of an O-RAN enabled 5G network while attempting to minimize the data plane's End-to-End delay by offering flexibility and increasing the chance of selecting appropriate resources. Various layers of 5G RAN can run as Virtual Network Functions on different data centers in other locations in O-RAN. A chain of these Virtual Network Functions provides the basic telecom connectivity for a 5G network.

Yang et al. [98] proposed architecture for software-defined RAN via virtualization for O-RAN. Vertically, it achieves total virtualization and programmability. Hence, horizontally helps heterogeneous network convergence by delivering open, programmable, adaptable, and reconfigurable wireless networks. Perveen et al. [99] proposed a dynamic traffic forecasting technique in federated O-RAN to estimate future traffic demand. They present a completely reconfigurable admission control framework based on user demand and network capacity. Thus, they conducted an extensive study on multiple metrics compared to benchmarks from other studies.

Furthermore, they have demonstrated that the proposed architecture can support a high number of devices linked in the federated O-RAN simultaneously.

Kumar et al. [100] suggest an approach based on automated neighbor relations for avoiding changeover failures in an O-RAN with open interfaces to reduce the issues associated with network densification, which grows as the number of cells increases. The created strategy manages neighbor cell connections, optimizes the Neighbour Cell Relation Table, and enhances handover timing, call drop rates, and the total number of successful handovers. Ibrahim Tamim et al. [101], propose a network outage-oriented paradigm of virtualized O-RAN nodes in an O-cloud deployment. They offer an optimal deployment approach for the virtualized O-RAN units in the cloud to reduce network outages while meeting performance and operational requirements. The objective is to autonomously solve the O-RAN performance and availability concerns while preserving service quality.

O-RAN is a technology that the industry has touted as a solution that benefits both the operator and end-user viewpoints. It is a RAN-specific architecture that improves commercially-proofed 3GPP solutions by providing new interfaces and nodes from the ground up. Finally, an O-RAN design combined with a broad radio access network decomposition may provide several benefits, which will be assessed after commercial deployment.

Overall, O-RAN is associated with disaggregation, which may be specified in at least four dimensions: (1) separation of control and user planes, which has already been done in 5G/new radio systems; (2) horizontal disaggregation related to opening interfaces; (3) vertical disaggregation related to decoupling hardware and software; and (4) disaggregation of software and data pipe, through the introduction of AI/ML techniques and connectivity to external contextual data sinks, which can play an essential role in Radio Resource Management optimization and performance.

9 Future Opportunities

Despite the efforts made, wireless communications still require further investigation to confirm its promising status and help in society's development. Therefore, it is essential to ensure that evolution will never stand still, continuously improving wireless technology in various fields such as performance, spectral efficiency, and implementation costs. Thus, according to [16] it is expected to debate the problems around 6 GHz coexistence, QoS with artificial intelligence integration, and energy management. Despite the efforts made, trying to raise the quality of Wi-Fi 7 when Wi-Fi 6 is still in a preliminary phase of implementation involves many technical issues that require further investigation, confirming Wi-Fi 7 promising status. Therefore, it is expected to debate the problems around 6 GHz coexistence, integration of low and high-frequency bands, integration with artificial intelligence, and energy management. With beyond 5G powering it all, efforts to operate responsibly, ethically, and sustainably will be required, ensuring that our decisions promote equality, put people first, protect and increase digital data trust, and assure sustainability [102].

9.1 Coexistence in the 6 GHz

Wi-Fi 7 intends to explore the spectrum from 1.2 to 6 GHz. However, to make this happen effectively, IEEE 802.11be standard must coexist with different technologies, which operate on the same spectrum frequencies, such as IEEE 802.11ax and beyond 5G communications. Thus, wireless communications' coexistence is a constant challenge since the rules of access to spectrum vary between networks, which can make it challenging to share the spectrum resources fairly, so it will be necessary to evaluate two coexistence scenarios [103]. First, the networks would establish coexistence arrangements independently, without any coordination with the adjacent networks. In the second one, networks must interact to organize their coexistence and determine the laws together. In the latter scenario, a network management plan between heterogeneous technologies will be needed. Thus, artificial intelligence mechanisms are fundamental to achieve coexistence objectives, providing the necessary intelligence for adaptation mechanisms. Given the possibility for new activities that these frequencies will enable, the recent modification in spectrum regulation for the 6 GHz frequency range has become a possible game-changer in terms of the future of beyond 5G.

9.2 Low and High Frequency

The mobile traffic on wireless networks growth means that sub-6 GHz frequencies start to raise doubts about its long-term future. Thus, it is necessary to develop a system that allows controlling the entire spectrum's existence of frequencies. Hence, one possible solution will be to provide a trading channel between the different frequency bands through Fast Session Transfer and on-channel tunneling for multi-band operations [104]. Also, given that there are already some solutions for managing network data migration to integrate the microwave spectrum [105–107], it is essential to explore integrated low and high-frequency bands, which will raise new problems, from the hardware to the dimension of the system. Another analysis direction is the study of cooperation between the different spectrum in use. Beyond 5G technologies will entail a variety of heterogeneous communication systems, including various frequency bands, communication topologies, and service delivery mechanisms. Furthermore, the hardware configurations of access points and mobile terminals will differ significantly. A more complicated architecture will be necessary to upgrade large beyond 5G MIMO. Hence, communication protocols and algorithms will get more complex, and AI and machine learning will also be integrated.

9.3 Slicing

A network operator can utilize dynamic network slicing to enable dedicated virtual networks to facilitate the efficient delivery of any service to a diverse set of customers, cars, equipment, and industries. When numerous users are linked to a large number of heterogeneous networks in 5G and beyond communication systems, it is one of the necessary factors for manage. Software-defined networking and network function virtualization are key enabling approaches for achieving dynamic network slicing. These impact the cloud computing paradigm in network administration, such that the network has a centralized controller to steer dynamically and regulate traffic flow, as well as choreograph network resource allocation for performance improvement [70, 108]. As a result, the network slicing approach should examine how to grant partial access to each slice in order to configure and manage it without generating security concerns. Furthermore, network slice management must be automated in order to eliminate manual efforts and mistakes.

Static partition sharing or elastically dynamic sharing can be used to implement resource sharing. Because of the changing nature of network load, dynamic resource sharing across slice tenants improves network resource consumption. There are several special difficulties that must be addressed in resource sharing. Radio resources, for example, can be shared among RAN slices. A suitable radio scheduling method is necessary to allocate radio resources among these slices. Furthermore, computational resource sharing and other resource sharing must be considered. While resource sharing benefits infrastructure providers, it challenges other concerns like slice isolation [76].

9.4 Guaranteed QoS

Management of wireless network resources will become increasingly important. Intelligently and appropriately recognizing the various QoS and QoE requirements for different types of users is an essential topic in the wireless evolution, which leads to the introduction of Artificial Intelligence and Machine Learning in some control systems. The emergence of home services like 4k/8k videos has created new challenges in the QoS requirements for different users, such as throughput and loss rate. Therefore, according to [16], this requires that the network operates in a manner adapted to the user's requirement, allocating the necessary wireless resources to improve QoS.

Enhanced Distributed Channel Access techniques will contribute to the statistics and forecast of network usage. However, they may be unable to improve the worst use case because they have some limitations, such as the inability to distinguish different types of traffic only according to QoS fields and to understand sensitive applications' latency requirements.

Thus, Machine Learning mechanisms that are aware of each usage situation and application requirements can be methods to satisfy users' QoS requirements through a set of observations that reflect the state of the network and the user's expectations. For example, in a multi-link communication, an Machine Learning mechanism can consider the history of a particular link (busy/idle) and predict the state that the link will be in the future. In an optimized way, this allows switching between links quickly, avoiding interference, and guaranteeing communications quality. Machine Learning is also necessary to develop PHY/MAC protocols by optimizing parameters such as selecting the best protocol to use in each case, multi-link aggregation, channel modeling, estimation of channel variation over time, allocation of Resource

Units, coordination of APs, among others. This is especially important in highly latency-sensitive use-cases like autonomous driving, where a campus-based automated vehicle network may rely on roadside sensors and edge computing to perform effectively and safely. The URLLC slicing capabilities of beyond 5G are a critical component of this service proposal.

9.5 Power Management

Improving battery designs is as fundamental as improving the power mechanisms of wireless networks. With new Wi-Fi 7 requirements and features being introduced, such as multi-link operation or the HARQ technique, the level of battery consumption can increase substantially. This can be a problem for small devices, which cannot have a high-capacity battery attached. Thus, new mechanisms for effective battery management should be studied, such as tunning on/off links flexibly, based on the current network conditions or based on the predictions made by Machine Learning mechanisms. These mechanisms can also be useful at this point, helping to achieve intelligent energy efficiency, taking into account the used network and hardware characteristics [109, 110]. For example, in a Multi-AP network, APs participating in transmissions can intelligently increase or decrease transmission power based on the predicted motion path, considering the user's QoS requirements and channel conditions. New energy-efficient designs, algorithms, and hardware will enable wireless networks to be fueled by small batteries, energy harvesting, or over-the-air power transmission.

10 Conclusion

With historical advances and emerging standards, many mechanisms have been proposed to increase the efficiency of wireless communications to address the growing needs of people's everyday lives. Therefore, the wireless standards continue to be modified to suit the society needs like gaming, streaming, or IoT. It is necessary to evaluate the technologies considering the densification of wireless deployments and analyzing the increase in QoS/QoE requirements. In this survey, many aspects of the wireless history and the main mechanisms that were innovative at the time of its launches are presented to the readers, such as the CSMA/CA, OFDM, or MIMO techniques. The evolution continues with Wi-Fi 7 and beyond 5G, which are in an early stage of their development process and continue to have some open issues.

A critical problem to address is the formulation of strategies, particularly those relating to QoS in a network with different services. Virtualization is critical for driving uptake and harvesting mobile network operators' full beyond 5G potential and innovative edge applications. Network slicing significantly alters the overall networking perspective by abstracting, isolating, coordinating, and separating logical network components from underlying physical network resources. O-RAN develops a unified architecture through numerous improvements and delivers several benefits by disaggregating hardware and software, such as low latency and network slicing.

This survey presented a critical view on the interconnection of Wi-Fi with beyond 5G. This joint evolution may provide society with the best choice of these wireless technologies according to their needs, never detracting from the fast bandwidth and low latency's. So, while Wi-Fi 6 can, for example, help with machine-to-machine communications in the industry, beyond 5G can help expand the industry with communication between multiple buildings. Moreover, we presented the possible applications and the technologies to be deployed for wireless next-generation communication. We also described the possible challenges and research directions to reach the desired goals.

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Declarations

Conflict of interest All co-authors have seen and agree with the contents of the manuscript. We certify that the submission is original work and is not under review at any other publication.

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