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Wi-Fi faces the new wireless ecosystem: a critical review

Víctor M. G. Martínez[1] · **Moisés R. N. Ribeiro**[1] · **Vinícius F. S. Mota**[2]

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Abstract
Over the last three decades, we have become more dependent on wireless connectivity to access services and applications from nearly anywhere. The overstated emergence of the all-encompassing fifth generation (5G) of mobile systems begs the question of the future of the new generation of IEEE 802.11 (Wi-Fi) solutions. However, Wi-Fi has certain advantages compared to cellular systems in different ways: (i) a fast-paced standardization process; (ii) a diverse, agile, and highly competitive manufacturer base; and (iii) a broad base of early adopters for both office and house wireless networks. In addition, the rise of enabling technologies, such as software-defined wireless networks, may allow more robust and reliable Wi-Fi networks to bridge gaps in Wi-Fi technology to reach several vertical sectors. This review provides a technical analysis of the relationship between broadband wireless and Wi-Fi technologies. Wi-Fi has taken decisive steps with the evolution of several standards, and there is already evidence that Wi-Fi may partially (or completely) fulfill 5G's strict service requirements. Next, we discussed the Wi-Fi and 5G convergence, which allow more control over user experiences and provide better service. This review concludes with an analysis of open challenges in the convergence of 5G and Wi-Fi systems. We conclude that Wi-Fi technology has and will continue to have a decisive role as an access technology in the new ecosystem of wireless networks.

Keywords Wi-Fi · 5 G networks · New wireless generation · Coexistence · Integration · Convergence

1 Introduction

The emergence of new communication and information technologies in the twentieth and twenty-first centuries is marked by competition. Global vendors and service providers participate in collaborative and competitive games with the goals of dominating markets and imposing certain solutions and products. There are currently different schools of thought regarding addressing communication problems (e.g., telecom- and datacom-oriented solutions), and these approaches diverge substantially. For example, the telecom community typically praises reliable and centralized architectures, while datacom solutions are often only locally optimal and based on distributed architectures. As a result, such solutions' cost, performance, and dependability vary widely. The future wireless service requirements will impose a winning approach or pick and choose solutions to match these approaches' particular needs.

Initially, exploiting different application contexts, wireless local area networks (WLANs) led by Wi-Fi and 5G networks seem to be on a collision course over wireless access. Some argue that the success of 5G systems may mean the end of Wi-Fi networks, while others in the past pointed out that new inexpensive and ubiquitous Wi-Fi-based solutions would delay 5G adoption [1]. In this review, we place Wi-Fi within the radio technology arena, comparing it to the fourth and fifth generation of cellular technology, respectively, long-term evolution (LTE) and 5G new radio (5G NR) solutions. We contrast Wi-Fi against the primary capabilities of the cellular ecosystem. Such capabilities may be important when integrated into Wi-Fi to provide 5G-like services.

Due to its ubiquitous use, Wi-Fi is the first choice among wireless technologies in indoor scenarios. Mobile data offloading in recent years [2] has already highlighted

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Víctor M. G. Martínez, Moisés R. N. Ribeiro, and Vinícius F. S. Mota contributed equally to this work.

✉ Víctor M. G. Martínez
victor.martinez@edu.ufes.br

Moisés R. N. Ribeiro
moises@ele.ufes.br

Vinícius F. S. Mota
vinicius.mota@inf.ufes.br

[1] Department of Electrical Engineering, Federal University of Espírito Santo (UFES), Vitória, Brazil

[2] Department of Informatics, Federal University of Espírito Santo (UFES), Vitória, Brazil

pathways forward. However, Wi-Fi is evolving with new standards to surpass the traditional role played alongside mobile broadband networks. We answer the primary question that motivates us to perform this review by demonstrating (i) how the new Wi-Fi standards are ready to face the same scenarios as 5G systems and (ii) how several gaps in Wi-Fi solutions are being addressed with software-defined wireless network solutions.

As shown in Fig. 1, the goal of this review is to find sweet spots to fit Wi-Fi in the big 5G puzzle and discuss the integration and convergence of Wi-Fi in the new wireless ecosystem. Therefore, we analyze high-throughput Wi-Fi standards, as in [3, 4], and the new generation of Wi-Fi standards that place Wi-Fi in a privileged position to achieve key performance indicators similar to 5G systems and meet the demands of different verticals. Thus, this review goes beyond [5], highlighting the coexistence and cooperative work between Wi-Fi and the new 5G wireless systems and justifying the importance of this integration to achieve convergence of access networks.

Table 1 summarizes the acronyms used in this review. The remainder of this review and reading sequence is as follows. First, the new ecosystem of wireless networks is contextualized in Sect. 2. Then, Sect. 3 analyzes the coexistence of Wi-Fi and cellular networks and the evolutionary process to achieve convergence between these systems. Open challenges are addressed in Sect. 4, and final remarks are presented in Sect. 5.

2 New ecosystem of wireless networks

The first digital mobile technology from the early 1990s, which is referred to as the global system for mobile communications (GSM), was trapped in the telecom industry circuit-switching paradigm. By the end of the first decade of the twenty-first century, the first standard of third-generation networks (3G) was introduced, incorporating packet switching alongside circuit switching. Because of the introduction of LTE, packet switching has become the dominant paradigm. This new feature markedly contributed to improving the efficient use of network resources, increasing user access to a variety of new services well beyond a voice channel provided by the telecom world.

Popularized in the late 1990s, the IEEE 802.11 standard came in 1997 as a packet-switching native technology, specifying the physical layer (PHY) and data link layer operation for WLAN [6]. The standard began to be commercialized as Wi-Fi by the Wireless Alliance. A new branding strategy was also used, as shown in Fig. 2 with Wi-Fi 4 to 7, for the different IEEE 802.11 generations described below. Since then, most Wi-Fi evolutions have focused on increasing transmission rates. With the introduction of the 802.11n standard (up to 600 Mbps), 4G and Wi-Fi achieved similar throughputs, indicating that both WLAN and broadband technologies may compete for a market share beyond their original contexts.

The continuous development of new high-demand services, such as ultrahigh-definition video, virtual reality, critical applications of Industry 4.0, and Internet of Things (IoT) solutions [7], continued to boost the development of wireless networks toward a new level. Advanced radio heads are now required to support such a transmission level and the flexible and agile networks behind them. This new stage proposes a network paradigm capable of integrating new and legacy technologies, offering high-performance network services capable of going along with the new business models. In this context, the concept of future wireless systems arises.

Broadband wireless technologies and Wi-Fi standards timeline are shown in Fig. 2. This historical context is essential to provide a time frame for the new generation of Wi-Fi

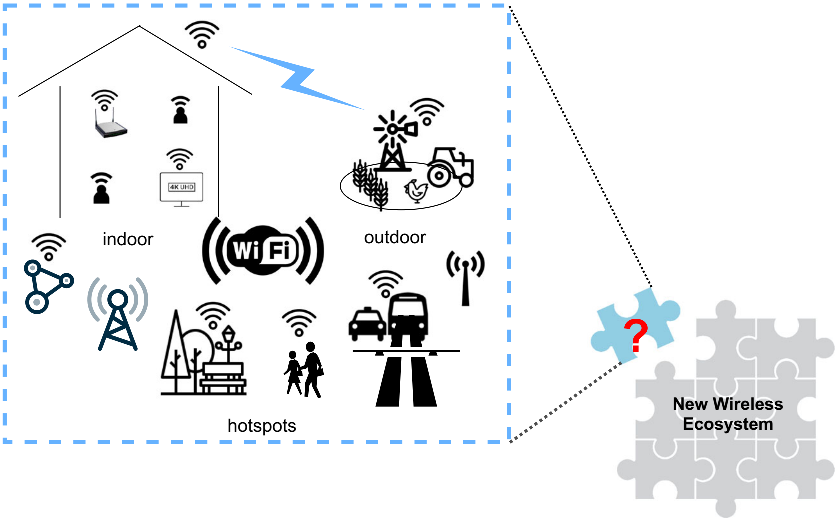

Fig. 1 New ecosystem of wireless networks

Table 1 Summary of acronyms used in this review

Acronym	Full name
3GPP	3rd Generation Partnership Project
5G NR	5G new radio standard
AP	Wi-Fi access point
ATSSS	Access traffic steering, switching, and splitting
BSS	Basic Service Set
CDMA2000	Family of 3G mobile technology standards
EDGE	Enhanced data rates for GSM evolution
eMBB	Enhanced Mobile Broadband
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HSPA	High-speed packet access
HSPA+	HSPA evolution
IMT	International Mobile Telecommunications
IoT	Internet of Things
ITU	International Telecommunication Union
KPI	Key performance indicator
LAA	Licensed-assisted access
LTE	Long-term evolution
LTE-A	LTE advance
LWA	LTE-WLAN Aggregation
LWIP	LTE-WLAN Radio Level Integration with IPSec Tunnel
MAC	Medium access control layer
MIMO	Multiple-input multiple-output
mMTC	Massive machine type communication
mmWave	Millimeter wave spectrum
MPTCP	Multi-path TCP
MU-MIMO	Multiple user MIMO
NFV	Network function virtualization
OFDMA	Orthogonal frequency division multiple access
PHY	Physical layer
QAM	Quadrature amplitude modulation
QoE	Quality of experience
QoS	Quality of services
RAN	Radio access technology
RAT	Radio access technology
SDN	Software-defined networks
SD-Wi-Fi	Software-defined Wi-Fi
STA	Wi-Fi station
TSN	Time-sensitive network
UMTS	Universal Mobile Telecommunications System
URLLC	Ultra-Reliable Low-Latency Communication
V2X	Vehicle-to-everything
V2V	Vehicle-to-vehicle
WiMAX	Fixed worldwide interoperability for microwave access
WLAN	Wireless local area networks

standards and the primary characteristics of 5G systems that will be presented throughout the review.

2.1 New 5G networks

With the emergence of new business models and critical applications in different branches, the International Telecommunication Union (ITU) proposed a new generation of mobile broadband networks. The new 5G networks are characterized by a rapid response to allow multiple applications to provide several services simultaneously. The ITU-R IMT-2020 recommendation introduced the different service scenarios that the new mobile networks must address. Three primary services were defined and became the primary objectives to be achieved by the 5G networks: (i) enhanced mobile broadband (eMBB) for human-centric use cases with high peak data rates for all users, (ii) ultra-reliable low-latency communication (URLLC) to address critical applications that present strict reliability and latency requirements, and (iii) massive machine type communication (mMTC) to support solutions with a huge number of connected devices. Due to the importance of vehicle communications in recent years, specifically for autonomous vehicle communications, 3GPP already recognizes vehicles-to-everything communications (V2X) as one primary service case for 5G networks. The primary key performance indicators (KPI) for these networks are shown in Table 2 [8].

The 5G architecture is network-agnostic. The network core will be shared for all radio access technologies (RATs), the existing radio interfaces, and the 5G NR interface introduced for 5G networks. This feature makes implementing rigorous control mechanisms that allow uncoupling the network core from access technologies necessary. Concurrently, other mechanisms should be implemented to orchestrate the interworking of these RATs, 5G NR access networks, mobile access networks such as LTE-A, WLAN, and fixed networks.

With network resource virtualization, multiple network slices with different characteristics can be implemented to address different service cases, maximizing the network performance, QoS, and quality of experience (QoE) [9]. Network slicing allows network operators to implement virtual logical networks and network functions for different services over the same physical infrastructure. Virtualization also offers the possibility of having a network architecture with distributed functions that actively contribute to reducing core and backhaul traffic by placing many services on edge networks closer to users.

Therefore, the orchestration and management of network services should allow maximum performance during the implementation of distributed functions, network slicing, and resource allocation. With different network domains working

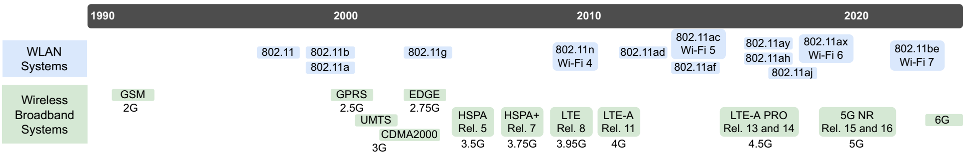

Fig. 2 Timeline of WLAN and wireless broadband technologies

under the range of 5G access technologies [10], unified network management is one of the biggest challenges in these architectures to ensure compatibility and flexibility among all technologies. The management must provide optimization and capacity planning for a slice, granting the necessary resources according to the service type requested. Other vital functions that must be fulfilled are managing the slice fault, interslice orchestration, managing slice security and monitoring, and analyzing slice resources. All these functionalities are possible using SDN and NFV as critical enabling technologies for 5G networks [11].

2.2 New generation of Wi-Fi standards

Currently, as a fundamental part of the evolution and standardization of Wi-Fi, development is being focused nearly entirely on technology that can satisfy communication requirements, such as reliability, latency, and throughput, which are similar to what 5G networks aim to achieve. These similarities are primarily due to the Wi-Fi community[1] strongly believing that the evolution of 5G proceeds hand-in-hand with Wi-Fi as a key element in integrating wireless access technologies and unlicensed spectrum bands [1]. Therefore, the sector has begun to discuss the new generation of Wi-Fi standards, which must comply in one way or another with the KPIs of 5G networks.

2.2.1 High throughput Wi-Fi

The evolution in terms of the data rate of the new Wi-Fi standards is shown in Fig. 3. The Wi-Fi 5 (802.11ac standard) [12] arises as a direct evolution of Wi-Fi 4 (802.11n standard) and is the first standard operating below 6 GHz to exceed the Gbps data rate. Later, Wi-Fi 6 (802.11ax standard), a high-efficiency standard for Wi-Fi networks, increased data rates to nearly 9.6 Gbps [13]. The Wi-Fi community strongly believes that Wi-Fi 6 will be a technology with a strong presence in the unlicensed spectrum alongside 5G NR, indicating the need to integrate this new standard and 5G network technologies. The standard aims to achieve high spectral efficiency and high throughput per area in high-density device scenarios, reducing the overlap areas to avoid collisions in the transmissions of the stations. Wi-Fi 6 directs its efforts to the search for high transmission rates. However, the standard implements better spatial reuse to combat and reduce interference through an efficient user access scheme.

Wi-Fi 6 maintains the pattern of adaptive modulations used by 802.11 and explores new modulation and coding schemes (MCS), introducing 1024-QAM modulation to improve the spectral efficiency of the transmissions. This new modulation enables a 20% increase in data that can be transmitted per cycle, enabling 40% faster speeds. A scheduling function for multiuser access was implemented to increase spectral efficiency through OFDM access (OFDMA) for uplink and downlink in the frequency domain and MU-MIMO in the spatial domain [14]. This feature allows routers to efficiently manage network traffic using smaller channel slices; thus, more devices can share the same airtime, reducing latency by up to 75%. An update of the 802.11 ax standard was announced as Wi-Fi 6E, the first Wi-Fi solution to operate in the 6 GHz band [3]. The 6 GHz operation is free of legacy traffic, providing an open frequency band for new applications and services. Access to highly reliable wider channels will begin to meet the demand that already exists for more bandwidth. The operation in this band also demands attention to the coexistence of Wi-Fi and NR 5G technologies again.

The future Wi-Fi 7, the new standard in development under the 802.11be amendment, was recently announced in recent years [15]. This project has been motivated by developing Wi-Fi networks to support real-time applications and introducing Wi-Fi time-sensitive networking (TSN) as part of the research activities for the new 802.11 standards. Wi-Fi 7 is being built on 802.11ax and will surpass the PHY layer of previous standards by doubling its bandwidth to 320 MHz channels. Combined with 4K-QAM modulation, this bandwidth enables each signal to embed more data. With these new features, incredible data rates can be obtained, reaching approximately 30 Gbps of maximum nominal throughput. The OFDMA challenges in terms of flexibility and latency are improved to meet the real-time requirements. Another new feature is the support for multi-link operations, which incorporates synchronization between links. With multilink operation, Wi-Fi 7 devices can simultaneously connect on two bands, enabling faster speeds through aggregation, or both bands can be used concurrently to share redundant data for improved reliability with ultralow and precise latencies. This standard increases the efficiency of using

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[1] In the context of this review, the authors define the Wi-Fi community as the set of societies, companies, and individuals who promote the development and adoption of Wi-Fi technologies, such as the Wi-Fi Alliance and Wireless Broadband Alliance.

Table 2 Parameters considered key capabilities of IMT-2020 [8]

KPI	Description	Value
Peak data rate	Maximum achievable data rate under ideal conditions per user/device	20 $Gbps$
User-experienced data rate	Achievable data rate that is available ubiquitously across the coverage area to a mobile user/device	100 $Mbps$
Latency	The contribution by the radio network to the time from when the source sends a packet to when the destination receives it	1 ms
Mobility	Maximum speed at which a defined quality of services (QoS) and seamless transfer between radio nodes which may belong to different layers and/or radio access technologies can be achieved	500 km/h
Connection density	Total number of connected and/or accessible devices per unit area	10^6 $devices/km^2$
Energy efficiency	Energy efficiency refers to the number of information bits transmitted to/received from users per unit of energy consumption of the radio access network	100x $bit/Joule$
Spectrum efficiency	Average data throughput per unit of spectrum resource and per cell	3x $bit/s/Hz$
Area traffic capacity	Total traffic throughput served per geographic area	10 $Mbps/m^2$

wireless channel resources, mitigating interference in high-density scenarios. Multi-AP cooperation is another important innovation of the 802.11be standard. Thus, the standard will achieve coordinated scheduling, beamforming, and distributed MIMO systems between nearby APs, similar to how the Coordinated Multi-Point (CoMP) scheme does in cellular networks. Wi-Fi 7 is ongoing, and many of its features are being debated.

2.2.2 mmWave Wi-Fi

The most popular Wi-Fi standard operating in the mmWave band is the 802.11ad standard [16], also known as *WiGig*, which resulted from collaborating with the Wireless Gigabit Alliance. WiGig is the first Wi-Fi standard to operate in the mmWave bands and the first to exceed the Gbps maximum data rate. The standard is designed to operate at 60 GHz, with broader bandwidths available for transmissions. The 802.11ay standard was published as a direct evolution of the 802.11ad and is expected to be the future of Wi-Fi communications in the mmWave band, reaching 20 Gbps through multiple independent data flows and greater channel bandwidth [17]. Additionally, as part of mmWave communications, China millimeter-wave multiple gigabit wireless systems were developed and standardized as IEEE 802.11aj

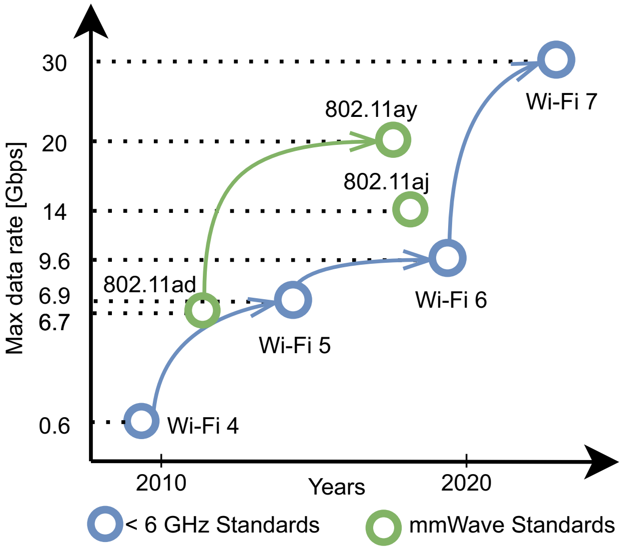


Fig. 3 Wi-Fi data rate evolution

[18]. This system is available in some regions of the world, operating in the 45 GHz frequency band and reaching up to 15 Gbps. The selection of the 45 GHz band is more attractive than the 60 GHz band, and it is expected to be more efficient for high transmission rate communications due to the lower attenuation for signal propagation.

The use of these Wi-Fi standards in the mmWave band could eliminate shortly wired Ethernet for indoor communications because the bandwidth at these frequencies is sufficient to meet such scenarios. However, they are not limited to this, and some studies suggest using mmWave Wi-Fi as backhauling technology in 5G systems [19]. Even solutions for long distances, such as access to rural areas, could be developed in multihop schemes with these standards.

2.2.3 IoT Wi-Fi

The evolution of Wi-Fi standards has also sought to satisfy the requirements for IoT solutions. An essential feature of IoT networks is the extensive deployment of sensors in wide areas; thus, wireless communications technologies that support these networks must provide coverage for long-range extensions. The two 802.11 standards designed to meet these objectives operate in the sub 1 GHz spectrum area, allowing communications with acceptable transfer rates for long distances and low power consumption for outdoor communications, as shown in Fig. 4, similar to other 5G emerging wireless technologies such as LoRaWAN, Sigfox, or NB-IoT [20]. Also, these standards are used for wireless backhauling solutions in places of difficult access for mobile operators.

The 802.11af standard defines the functionalities for using Wi-Fi wireless systems in the television white space [21]. Television white space is a spectrum resource not used at specific times and spaces, allowing it to be shared between white space devices (television users) and 802.11af devices. The 802.11af operates according to the specific spectrum regulations for each country. The band occupied by the standard is adjusted in the very high frequency (VHF) and ultra-high frequency bands. Thus, the white space database is the primary element that integrates the 802.11af architectures, which stores the available frequencies and transmission requirements for a specific geographic location [22].

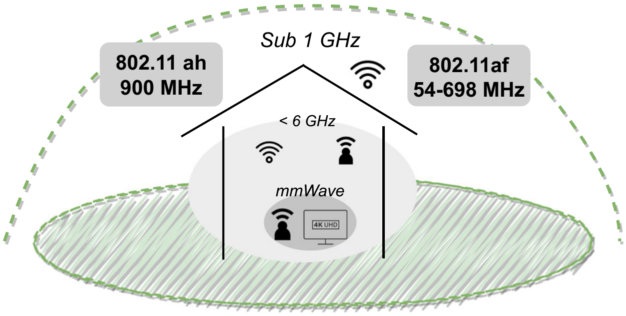


Fig. 4 Long range Wi-Fi standards

The other standard based on the sub 1 GHz frequency bands is IEEE 802.11ah [23]. The standard, also known as Wi-Fi *HaLow*, is more focused on IoT scenarios and machine-to-machine communications to support long-range wireless networks with a high density of wireless stations. 802.11ah operates in the 900 MHz band, thus building long-range and low-power wireless sensor networks and other massive multinode wireless networks [24]. The standard can implement transmission modes in short bursts of data packets with low power, offering short operating times for remote sensors with bandwidth and battery restrictions. The 802.11ba standard is used with low-power wireless systems that have active stations with a power consumption of less than 1 mW in IoT environments [25]. A summary of the primary operating frequencies of the new generation of Wi-Fi standards is shown in Fig. 5.

2.2.4 Wi-Fi for vehicle networks

Wi-Fi has been part of the planning in the automotive industry for some time. Wireless access in vehicular environments (WAVE) is defined in the amendment IEEE 802.11p to support intelligent transportation system (ITS) applications [26]. For several years, the 802.11p standard has been the primary standard for dedicated short-range communications in vehicular environments to address communications in vehicular ad hoc networks [27]. The 802.11p can serve communications for mobile elements that travel at relatively high speeds, such as vehicle-to-vehicle (V2V) communications. Additionally, the standard introduces an interesting modification to eliminate the need for association and authentication for data exchange in V2V communications and the communications between vehicles and roadside stations (V2I). However, the adoption of Wi-Fi for vehicle communication solutions has been limited due to the poor scalability of the 802.11p standard in high-mobility environments.

To meet these challenges, in recent years, work has begun on the new 802.11bd standard as an 802.11p evolution for the new generation of V2X communications [28]. Along with 5G NR V2X, 802.11bd is expected to support more advanced V2X applications with stricter QoS requirements [29]. The standard aims to attend communications with mobile nodes at speeds up to 500 km/h, achieves twice the communication range of 802.11p, and provides vehicle positioning with a location accuracy of up to 1 m. The PHY 802.11bd design is based on the 802.11ac standard and also reduces subcarrier spacing to operate on 10 MHz channels. This 2x down-clock technique was improved by incorporating midambles, a scheme that is similar to preambles but placed between the OFDM data symbols to support the decoding of the frame [30]. To increase reliability, 802.11bd proposes an adaptive

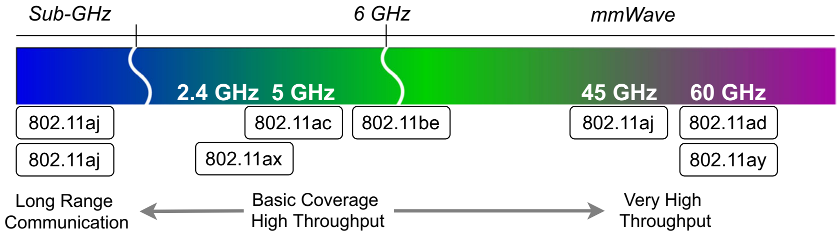


Fig. 5 Wi-Fi operating frequency spectrum

retransmission scheme, where decisions to retransmit a frame are based on the congestion level, similar to schemes used in V2X cellular communications. Another important feature is using dual carrier modulation to transmit the same symbols twice over sufficiently far-apart subcarriers, improving the block error rate performance and the communication range that can be reached. Also, efforts are being made to bring the operation of the 802.11bd standard to the mmWave band [28].

2.3 Software-defined Wi-Fi

Although efforts to maintain Wi-Fi standards as a competitive technology have been evident, some gaps remain in several areas. For example, seamless handover, fast fault recovery processes, and better mobility management are some areas that have received the highest attention from the academic community in recent years. The SDN and NFV technologies have gone beyond supporting new wireless broadband solutions such as 5G and became a determining factor in the new Wi-Fi systems [31]. In this context, software-defined Wi-Fi (SD-Wi-Fi) is a real alternative for creating new solutions and efficiently managing wireless network resources across several networks.

New scenarios with critical applications and strict requirements are being addressed by SD-Wi-Fi solutions [32]. To manage user mobility, several solutions base their operation on virtual AP entities [33, 34]. Such entities instantiated in the user plane allow more agile migration of AP functions between physical elements to obtain reliable communications. More daring SDN/NFV solutions have tried to manage mobility and create a reliable communication scheme across several domains: cloud, core network, and Wi-Fi access network [35]. The software-defined orchestration introduces the possibility of creating slicing mechanisms for Wi-Fi networks so that the requirements of different applications in more complex 5G contexts can be met [36, 37]. Various services with different data traffic profiles can support SDN-enabled heterogeneous wireless networks [38], integrating Wi-Fi, light fidelity (LiFi), and LTE technologies.

The convergence of Wi-Fi with other wireless technologies is presented as a central point of the RANs diversity proposed by the 5G networks. A representation of the new Wi-Fi standards is shown in Fig. 6. Wi-Fi coexists with current mobile radio standards and the new 5G radio as wireless access technologies, acting in indoor and outdoor scenarios such as backhauling, hotspots, and long-range communication. In parallel with the improvements in the PHY and MAC layers introduced in the new standards, a new cross-control and management layer has emerged that enhances the performance of Wi-Fi networks through SDWN solutions. In higher layers, the combined use of SDN and NFV allows the implementation of resource virtualization and network slicing to serve the different applications, where sophisticated orchestrators manage all controllers.

3 Wi-Fi in the current 4G and 5G ecosystems

From the perspective of this review, 5G networks are understood as a network paradigm rather than a specific isolated technology. For the success of this new technological commitment and its primary pillars, it is necessary to develop a new radio interface that solves all the 5G challenges globally and integrates the various existing wireless technologies with consolidated acceptance in the market. Within these technologies, Wi-Fi networks stand out as one of the leading players that 5G networks integrate.

Figure 7 shows a spider chart comparing the primary communication capabilities between 5G and Wi-Fi systems, where the new generation of Wi-Fi standards outperforms or equals the 5G systems. With the standards of high throughput, which is currently led by Wi-Fi 6, Wi-Fi technology improves compared to 5G in traffic capacity requirements, reaching up to 400 Mbps/m^2 and in the latency of the radio interface with the ability to decrease to 1 ms (theoretically near 120 μs) [39]. Recently, with the announcement of the future Wi-Fi 7, Wi-Fi will be able to break the barrier of 20 Gbps of peak data rate, reaching a theoretically reaching 30 Gbps as previously mentioned. Wi-Fi communications also continue to improve network efficiency and mobility, with mobility being a priority issue to be improved in the 802.11 standards for vehicle use cases at speeds higher than those supported by the 5G systems. The emergence of the 802.11bd

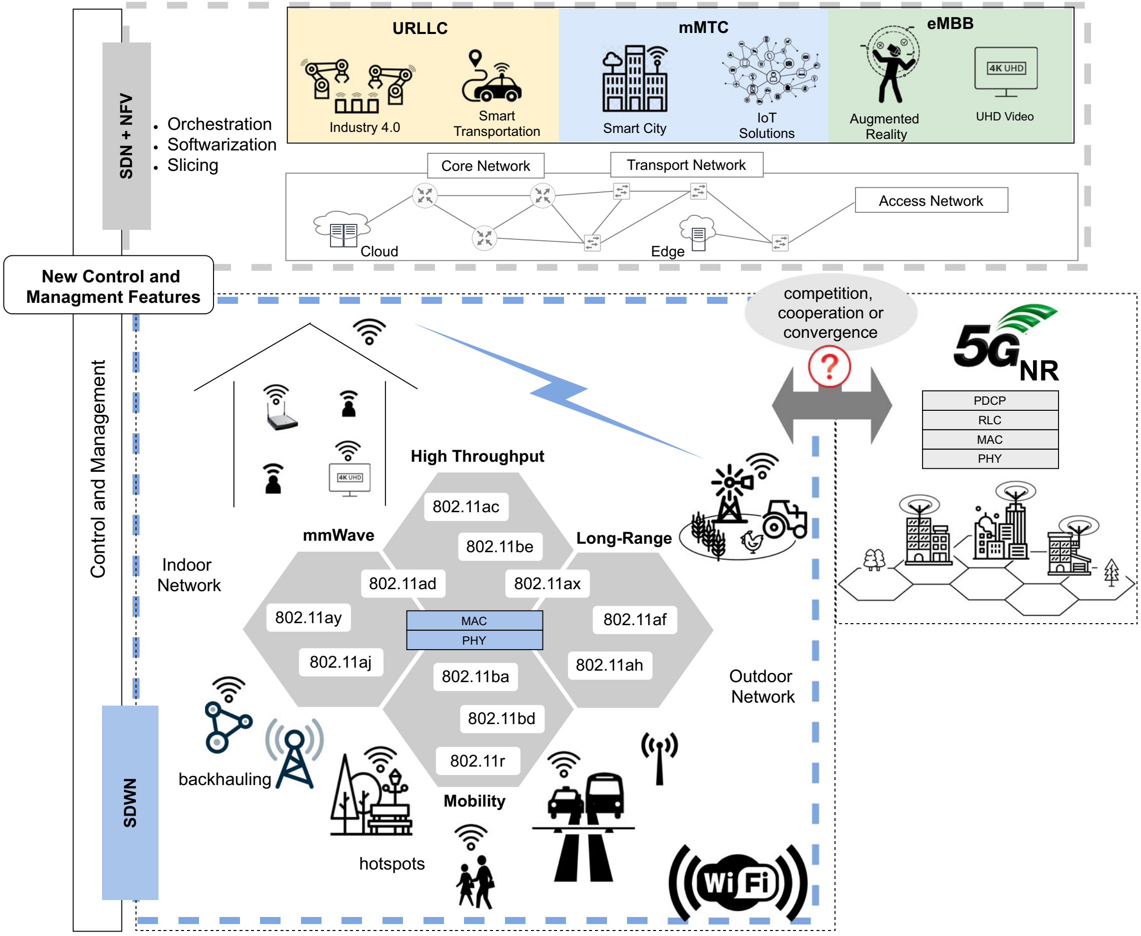


Fig. 6 New Wi-Fi ecosystem and management

standard, still under development, places Wi-Fi on par with 5G systems to serve high-speed nodes near 500 km/h.

Analysis shows that Wi-Fi can provide similar performance as 5G systems in many cases from the perspective of several KPIs. This excellent positioning that the Wi-Fi standards have reached raises a debate on how the relationship between 3GPP technologies, specifically 5G systems, and Wi-Fi systems will be in the coming years. Even though it seems that there will be severe competition, particularly for the use of the unlicensed spectrum, the opinion of experts and the actions of responsible organizations have shown an interest in a harmonious coexistence of both technologies. Therefore, these technologies will continue to cooperate, as has happened with phenomena such as the offloading of cellular network traffic. Therefore, both technologies are expected to succeed in this new ecosystem of wireless networks that is driven by their integration and convergence at different levels as the desired horizon. The rest of this section presents the actions and mechanisms developed over the last few years that justify the evolution in the cooperation, integration, and convergence of 5G and Wi-Fi.

3.1 Coexistence

According to several worldwide industry leaders, who participate in developing and implementing 5G solutions, Wi-Fi

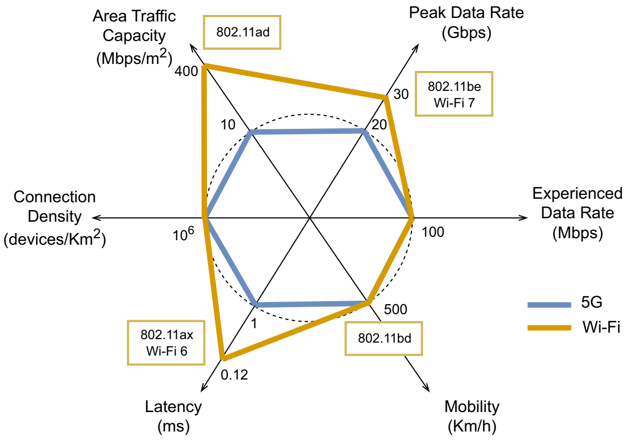


Fig. 7 Wi-Fi vs. 5G adapted from [39]

is recognized as one of the RAT systems that will be integrated with 5G, thus sharing the unlicensed spectrum. Intel recognizes and classifies Wi-Fi as a critical wireless technology for 5G networks [40], considering the joint evolution of Wi-Fi and 5G networks toward a heterogeneous access network as the primary task for developing such systems. Samsung's vision [41] recognizes Multi-RAT as one of the key enabling technologies for 5G, which will allow the integration of licensed and unlicensed spectrum bands to achieve better performance. According to them, this integration will enable better energy efficiency of the network, greater density of connections, mobility, and data rates, with Wi-Fi being one of these wireless technologies to be integrated due to its low deployment cost and the natural preference for mobile users. For Huawei [42], 5G has among its critical missions to guarantee the best delivery of any service to any user; thus, using any spectrum band or RAT is fundamental to achieving this goal.

Even though these and other manufacturers include Wi-Fi networks as a critical RAT of the 5G network environment, many see 5G networks as the end for IEEE 802.11 networks. However, the Wi-Fi community defends the idea that 5G does not represent a risk to the survival of the technology. In addition, as presented earlier, Wi-Fi development workgroups have worked intensively in recent years to achieve an evolution of IEEE 802.11 networks. This result has been demonstrated in the emergence of new standards to continue guaranteeing a competitive technology in tandem with the demands that users and new services impose on wireless networks.

In this debate, it is essential to understand that the evolution and development of Wi-Fi is a phenomenon independent of the evolution of cellular networks. Although the development of both technologies can be said to have occurred in parallel, the fact that different organisms govern these technologies ratifies the independence of each development. The new 5G paradigm is a complex system for mobile networks, developing a new radio access standard and network slicing mechanisms throughout all physical topology, led by ITU-IMT-2020 and the 3GPP project. The IEEE 802.11 standards marketed as Wi-Fi technology were created and developed by the IEEE 802.11 working group. The Wi-Fi Alliance certifies the technology, which also tries to integrate the industry and the manufacturers, which is why Wi-Fi is not an explicit part of the 5G networks but will surely be one of the primary competitors as part of radio access technologies.

Wi-Fi development has been evident for wireless technology specialists, highlighted in its strong acceptance by its users and cellular operators. The global Wi-Fi market is projected to grow from 9.4 billion dollars in 2020 to 25.2 billion dollars by 2026, and Wi-Fi traffic, in general, will represent more than 50% of the total IP traffic [44]. The growth of Wi-Fi estimated for the coming years according to a Cisco Internet Report [43] is shown in Fig. 8, with expected growth from 2018 to 2023 of nearly four times the number of hotspots. The evolution of unlicensed spectrum technologies such as Wi-Fi can be identified as accompanied by new business stages [45]. The Wi-Fi networks started from a stage of simple access, where all types of internet use were supported with tremendous effort. Then, Wi-Fi went through stages of intelligent access, integrating with other mobile technologies to better understand users' needs, and reached an access stage at the operator level to support various critical applications with high QoS requirements. Finally, Wi-Fi reached a stage where access is massive and connects all types of devices and "things," fitting into the IoT paradigm, to which 5G networks will also have to provide support in mMTC [46].

Despite those who push from one side to another to survive or impose one technology over the other [4], most specialists believe in collaboration between the two technologies, seeing both technologies as complementary [47, 48]. Wi-Fi will remain the technology implemented for indoor environments, while cellular technologies will prevail more for outdoor environments. Both technologies will undeniably continue to coexist, and the best way to coexist is to collaborate for a better user experience. Studies [1] have shown that Wi-Fi offloads 4G data for approximately 25 billion dollars. These data are estimated to triple for 5G networks, which shows that 5G will need Wi-Fi even more than 4G does today.

3.2 Cooperation: mobile data offload

Mobile data offloading has become a technique that turns Wi-Fi into a necessary technology in the face of different cellular wireless technologies [49]. The constant and rapid growth that mobile data traffic has experienced has caused cellular operators to look for solutions to the saturation of radio links and the low penetration capacity in indoor environments presented by cellular signals. A solution to these problems are the well-known cellular traffic offloading techniques, a stack of architectures and protocols that have allowed mobile

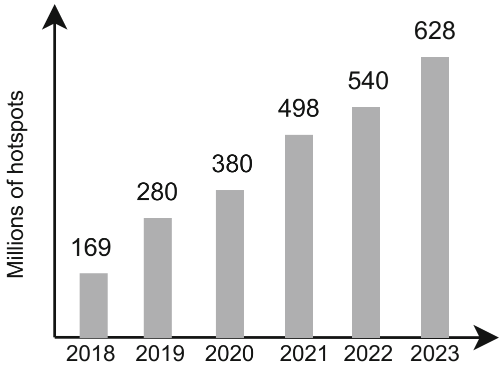


Fig. 8 Global public Wi-Fi hotspot growth adapted from [43]

operators to establish and control alternative routes for the cellular network traffic. Offload solutions quickly became the primary option for operators because the increase in the number of base stations to solve these cellular network problems would mean prohibitive costs that would make these networks inefficient and unproductive. This result is why Wi-Fi began to increase in capacity, improving its performance and the QoS and QoE of the users through alternative RANs, which could offer the capacity increases that cellular operators need.

Wi-Fi networks are one of the most popular options for offloading and perhaps the most used in cellular networks worldwide. Several reasons make Wi-Fi technology an excellent candidate as a solution for offloading cellular traffic [50]. Wi-Fi networks are currently the most widely deployed RAN technology, with meager costs, and most users' mobile devices have Wi-Fi interfaces. Conversely, similar to small cell networks and femtocells, Wi-Fi can provide indoor service with high data rates, offering greater network capacities and bandwidths. These features make Wi-Fi the option operators choose to address capacity limitations, spectrum limitations, and poor indoor penetration that RAN technologies present in cellular networks. Even with all these advantages, Wi-Fi has the strong limitation of not interacting directly with cellular networks standardized by 3GPP. This limitation introduces problems related to the authentication of users, mobility management, and control of the offload process, all directly influencing the QoS of the services provided in broadband wireless networks [51]. For its interest, 3GPP addressed these problems with a new architecture for integrating 3GPP systems and WLAN called interworking WLAN [52]. However, this solution was deficient in treating user mobility between the different access networks (3GPP and IEEE). Thus, an update was published in Release 8 [53], which improved the accessibility and continuity of users in the network, and in Release 12 [54], LTE-WLAN radio level interworking was defined.

The primary beneficiaries of Wi-Fi offloading are the mobile network operators and the users of the service because it reduces network congestion while offering a better QoS for the customers. Additionally, Wi-Fi maximizes the revenue potential and allows lower operational costs for wireless broadband operators. Also, Wi-Fi offloading and other forms of cooperation, such as the simultaneous use of 3GPP and non-3GPP links for more reliable communications or higher throughput communications, are possible due to the efforts to integrate both technologies developed to date. As a result, cellular and Wi-Fi technologies have converged to use and develop similar features at the radio access and core network levels, reaching a more efficient design and supporting operation in large bandwidth.

3.3 Integration and convergence

The capacity of Wi-Fi networks to provide offloading and upload of data from cellular networks is one of the keys to integrating technologies. Some years ago, unlicensed spectrum technologies became of primary interest to broadband operators. Thus, the broadband network industry understood that the coexistence and convergence of heterogeneous networks operating in both types of the spectrum are essential for developing new wireless technologies such as 5G networks [55]. Those who promote the 5G project are not oblivious to this issue but have placed the convergence of networks and spectra in a privileged spot and understand that 5G networks will not achieve the expected economic and practical benefits without it. The Wi-Fi community was also aware of this phenomenon when the chairman of the Wireless Broadband Alliance stated that it was evident that the limits between licensed and unlicensed spectrum technologies were disappearing, leaving their borders nearly imperceptible [46].

As has already been explained, cellular operators using Wi-Fi technology have multiplied considerably, even with the limitations of coverage, spectral efficiency, and reliability that Wi-Fi faces. For the spectrum integration proposed by 5G, solutions have already been developed to coexist with the current cellular networks and Wi-Fi. The 3GPP defined and standardized new technologies allowing cellular networks and Wi-Fi integration. These technologies dynamically share the spectrum and allow operators to benefit from the additional capacity networks of unlicensed bands such as Wi-Fi. In Release 13 [56], the licensed-assisted access (LAA) feature was introduced, adapting LTE to operate in the unlicensed spectrum [57]. To achieve this goal, access is made through a secondary carrier component cell assisted by a primary carrier component operating in the licensed spectrum and using the LTE carrier aggregation feature. The solution explicitly allows the operation of LTE in the 5 GHz unlicensed band, providing an interesting Wi-Fi protection feature. LAA has been designed with a mechanism that selects a clean channel to dynamically avoid interference with Wi-Fi operating in this band. Improvements were intruded in later releases with enhanced LAA (eLAA), until it arose in Release 15 [58], further enhanced LAA (FeLAA), becoming the first 5G standard that adapted LAA and eLAA [59].

3.3.1 Lessons from Wi-Fi and 4G integration

Several solutions for integrating Wi-Fi access exist in current 4G (LTE) systems. Two solutions have been defined for RAN-level integration for different Wi-Fi deployments. First, to provide cellular operators with greater control in the deployment and use of WLAN, the aggregation of radio level traffic over LTE-WLAN, formally called LTE-WLAN aggregation (LWA), was also introduced in 3GPP Release 13 [60]. LTE systems can divide the traffic toward Wi-Fi infrastructures through a function in the base stations. At the user equipment level, the traffic of individual systems can be aggregated and sent to both the base stations and the WLAN access networks. In these systems, connection control is maintained on the part of LTE systems because Wi-Fi systems lack efficient management and control solutions. The WLAN functionality is integrated with the radio station in collocated network deployment, which is more suited for small cell deployments. For noncollocated deployment, the radio station and WLAN access are connected through a logical node called WLAN termination integrated with the Wi-Fi access controller.

Another technique that is closely related to LAA, also introduced in Release 13, is the integration at the LTE-WLAN radio level with IPSec tunnel (LWIP) [61], where traffic between the LTE system and the user equipment is transported in a WLAN through a tunnel transparently. LWIP provides more efficient load balancing between LTE and Wi-Fi to benefit from the increased capacity of Wi-Fi. The primary difference between LWA and LWIP is the layer where LTE and Wi-Fi traffic aggregation is performed. LWA performs this aggregation function at the packet data convergence level, while LWIP performs it at the IP layer. An LWIP node is anchored to a radio station operating as a macro node, and the traffic over the Wi-Fi access is forwarded through the LWIP node. Unlike LAA, which uses a modified LTE waveform in the unlicensed spectrum, LWA and LWIP use a proprietary Wi-Fi waveform, providing deeper integration with the unlicensed spectrum. Later, enhanced LWA and enhanced LWIP were introduced to support the integration of LTE and Wi-Fi radio links that use Wi-Fi to access the unlicensed spectrum in the 60 GHz band [62].

3.3.2 Outlook on Wi-Fi and 5G convergence

For the integration of Wi-Fi access in 5G systems, all previous experience with mechanisms implemented in 4G networks is considered. With the new 5G architecture, access is done neutrally, and the user devices can connect to 5G services seamlessly across any access. In addition, the access network has a functional and no structural design, which facilitates its implementation and operation management. These characteristics allow for improving the deployment of Wi-Fi integration, solving problems such as the difference in Wi-Fi architectures for integration with 4G and the differences in requirements for its implementation in user devices.

Release 15 [58] proposes a solution for integrating untrusted Wi-Fi access with 5G systems. The integration is done through the non-3GPP interworking function, which transmits signalization and data between both systems. These two types of traffic are transported with IPSec tunneling once the users have completed their authentication and registration for 5G services over Wi-Fi access. Access selection is provided by the access network and selection policy entity, and the user equipment route selection policy is in charge of traffic selection control across the access networks.

Several aspects to enable Wi-Fi access in 5G systems for different deployments are addressed in Release 16 [63]. First, the case of users accessing 5G services through trusted Wi-Fi access is considered. In this scenario, the connection with the 5G core is managed by the trusted non-3GPP gateway function that can be collocated with the WLAN controller. The second scenario discussed is for cable modem and wireline-based accesses. In this case, Wi-Fi-based devices can access 5G services through a residential gateway through the fixed access gateway function. Finally, Wi-Fi-only devices with no subscriber identity credentials can be served through Wi-Fi trusted access to connect to the 5G services. In this case, the trusted WLAN interworking function (TWIF) is used to perform signaling with the user devices and authentication and registration with encryption.

A control plane is responsible for providing QoS for users with Wi-Fi access. With the trusted non-3GPP gateway function being used as the decision entity, QoS treatment can be established for each flow. Also, the access traffic steering, switching, and splitting (ATSSS) functionality was incorporated to route traffic across multiple accesses. With this functionality, the multiaccess protocol data unit concept is defined, capable of establishing protocol data unit sessions where traffic can be served by 3GPP access, trusted non-3GPP access, and untrusted non-3GPP access. At the user plane, there are two routing functionalities for multiple access: (i) the multipath TCP (MPTCP) functionality, where ATSSS operates as an MP-TCP proxy between user devices and the network, and (ii) the ATSSS low-layer functionality, which performs switching, splitting, and steering at the traffic level in IP flows [65].

The ATSSS conception represents perhaps the complete result in efforts to converge between 3GPP and non-3GPP access technologies. Its primary capabilities support various access technologies while evidencing an evolution from coexistence toward convergence in network access, making Wi-Fi and broadband networks (4G/5G) work as one. Thus, the path toward the convergence of access technologies has markedly improved end users' experience through various access options, as shown in Fig. 9. The incorporation of MPTCP in the user plane as one of the ATSSS functionalities plays an essential role in the management of core convergence, with evident improvements in data rates, link utilization, and session setup latency compared to hybrid access [66].

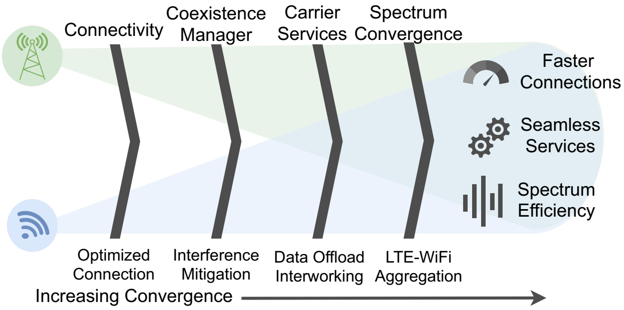


Fig. 9 Technology convergence adapted from [64]

Combining both technologies provides much better results, offering more uniform coverage with better QoS and QoE. Figure 10 shows the spectrum convergence as the final step of the more complex integration and convergence process of technologies. Convergence begins with optimizing the connections to select the best network and managing coexistence to mitigate interference between the licensed and unlicensed spectrum. This integration becomes stronger through carrier services with the data offload and interworking processes discussed above to finally reach spectrum convergence. By bridging the gap between licensed and unlicensed technologies, Wi-Fi technology has a decisive role in playing alongside other small cell technologies to enhance and accelerate the deployment of 5G use cases. As a result, faster communications, greater spectrum efficiency, and seamless services are obtained. Also, there is no competition between both technologies, and a common interest between both technologies is to reach a point of convergence where both offer better communication performance with a better user experience. However, some challenges remain despite all the integration and convergence efforts between Wi-Fi and 5G.

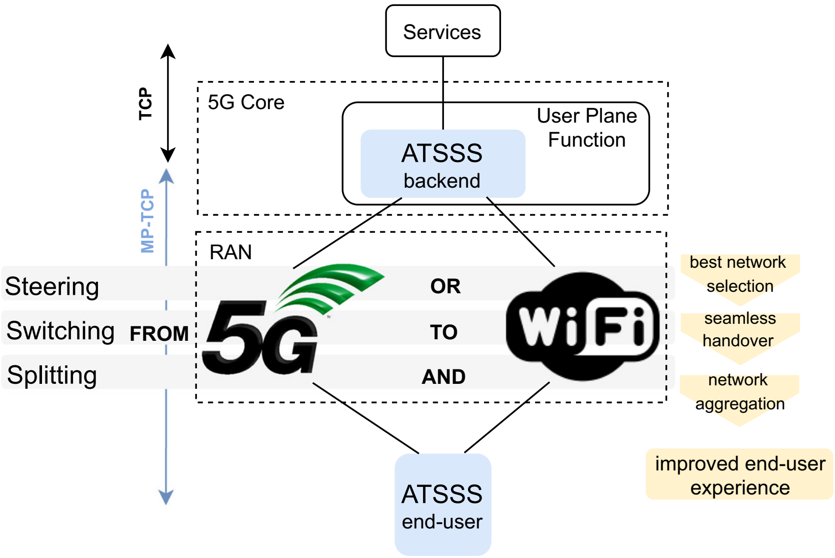
4 Challenges for Wi-Fi and 5G convergence

The challenges of enabling tight integration with 5G systems are still complex within the heterogeneous environments of enterprise, residential, and public Wi-Fi. Attempting to define a strict convergence approach at the RAN level to support carrier-centric use cases with a high degree of homogeneity between architectures is one of the premises of success for service providers. However, using this approach for highly controlled environments escapes somewhat when integrating Wi-Fi as an access technology. In these scenarios, the integration must be much more flexible. Therefore, efforts of the 3GPP have been focused on defining architectures and exchanging messages for the 5G control plane and data plane over non-3GPP access via gateway functions. In addition, new proposals were introduced to improve the Wi-Fi-5G convergence in Release 17 [67], which was recently published, that use the resources of both networks more effectively and provide a better user experience.

4.1 Convergence management

Other issues related to access visibility and network manageability should be addressed. For example, the current Wi-Fi and cellular access systems manage radio resources independently of each other [68]. Thus, some Wi-Fi functionalities that manage network resources assume homogeneous radio environments, making transitions to non-Wi-Fi access points impossible. Thus, 3GPP has taken a step forward and already has mechanisms to share some characteristics of Wi-Fi implementation through cellular systems. However, to achieve more technical and commercial success in integrating Wi-Fi and 5G networks, it is necessary to create an interface that allows complete network management and

Fig. 10 Access traffic steering, switching, and splitting



control policies between both technologies. With such a solution, enterprise and residential Wi-Fi networks could request access to 5G services provided by an operator for certain Wi-Fi users.

The ability of customers to route traffic through one or several access networks is one of the premises of convergence between Wi-Fi and 5G. This routing task across multiple accesses cannot fail to guarantee the efficient use of available resources and connectivity to seamlessly switch traffic flows between the access networks. Although 3GPP defines this similarly to ATSSS, further study is required to achieve a fast reaction time to changes in connection quality for traffic routing. Aspects such as session continuity [69], traffic routing under policy control [35], and fast reaction to changes in connection quality [70] are still being investigated by the academic community in partnership with the industry.

4.2 Access network selection

Through the WLAN selection policy function, 3GPP defines policies to select when to route data flows over Wi-Fi access. However, the rules that govern the selection criteria are limited only to the load analysis on the access and backhaul network, ignoring other interesting QoS metrics such as the estimated throughput per band, the maximum number of connected clients, or the supported frequency bands. This limited analysis conspires with an optimal access network selection, sometimes affecting customer communication quality requirements.

To improve the selection of WLAN access, the Wireless Broadband Alliance proposes to incorporate the aforementioned missing parameters into the WLAN selection policy rules. In addition, it is necessary to make the native Wi-Fi QoS metrics available through measurements at both the AP and STA levels to be used in access selection tasks at the user equipment. Concurrently, having IP service level metrics via measurements in the transport and core networks would also improve the access selection at the user level.

4.3 RAN measurements in ATSSS

In the context of ATSSS, load balancing and priority modes are supported, lacking mechanisms that evaluate access, considering the conditions of the radio channel. To take full advantage of 3GPP and non-3GPP access convergence, RAN-level measurements should be incorporated into the ATSSS functionalities. Radio-level measurements of access nodes (5G NR and WLAN AP) can provide beneficial information on the conditions and quality of radio links, including radio link latency statistics.

Thus, 5G systems will perform an optimal distribution of traffic through various types of access and would improve the user experience with more efficient use of radio resources. The information collected would also improve the operation of the architecture in general because the 5G core could compare the information of different accesses to proactively adjust the distribution of the traffic across 5G and Wi-Fi. These measurements would support the MPTCP solution in deciding when to add or remove specific subflows and estimate path characteristics that evaluate and control congestion.

4.4 Multipath proxy deployment

For the implementation of the ATSSS MPTCP, an application proxy called the transport converter [71] is defined. The primary function of this application is to assist in deploying MPTCP as an extension of TCP. The proxy assumes that all network attachments are managed by the same administrative entity, implying that transit through third-party networks is prohibited. This condition imposes new challenges because, as we have already discussed, it can be supported by third-party WLAN access networks within the conception of the MPTCP proxy for ATSSS.

Improving the architectures and protocols is necessary to implement these proxies more flexibly. Thus, use cases can be expanded to apply ATSSS for multiple routes. In this context, software-defined wide area network (SD-WAN) implementations that integrate multipath solutions could benefit and allow multiple proxies to be operated by third parties, independent of the administrative domain in the 5G core.

4.5 Wi-Fi slicing

As in 5G network solutions, Wi-Fi slicing is a service that must work automatically and autonomously, interacting with the network to guarantee the operation of an application. Because the 5G core network is agnostic to access technologies, integrating Wi-Fi slicing in a 5G system is possible and can be used in the entire network [72]. Slicing can enable 5G network users to receive seamless access to 5G services over Wi-Fi segments allocated for 5G services and applications.

The ability to associate a Wi-Fi device with a network slice, move a Wi-Fi device from one network slice to another, isolate traffic between different network slices in the same network, and define resources for a network slice are some essential capabilities that enable the Wi-Fi access network to be sliced [73]. The management and orchestration of sliced Wi-Fi networks is another critical issue. The ability of Wi-Fi systems to report key performance indicators based on the combination of the selected WLAN and the allocated VLAN (slice) will allow more efficient system management per slice basis. In addition, it is expected that for Wi-Fi networks, cross-domain orchestration supported by SDN techniques will enable network slicing across access, transport, and core domains similar to 5G systems [74].

4.6 End-to-end QoS

To satisfy the QoS requirements for 5G applications and services, the 5G QoS parameters should be mapped to their Wi-Fi QoS counterparts. Therefore, the 5G QoS flows transported across WLAN accesses can be differentiated in this way. To solve this challenge and achieve this QoS differentiation of 5G flows, labeling of the 5G data packets is performed. Then, the tag is inserted into the IP header using the differentiated services code point byte as defined in the DiffServ architecture [75]. Thus, differentiated services can be mapped for different access categories using the QoS differentiation used in WLAN networks, the latter defined by the 802.11e standard [76]. Another way to perform this QoS differentiation in WLAN accesses is by identifying and prioritizing the traffic that transports 5G flows. This solution is engaging in those cases where some routers reset the differentiated services tags before the packets reach the WLAN.

The Wi-Fi community is improving the QoS capabilities of WLAN networks and thus supports new applications such as industrial IoT, TSN, and edge computing. These development lines aim to provide new tools for network-centric WLAN QoS management, where QoS policies, rules, and parameters of all flows can be integrated for end-to-end QoS management for WLAN.

4.7 Deterministic communications

In URLLC scenarios, applications generate traffic flows that require bounded low latency while sharing the communication channel with noncritical application flows. To guarantee the timing behavior of these applications, in addition to aspects related to reliability and fault recovery, the 802.1 working group has been working on standardizing time-sensitive networks [77]. TSN is effective over Ethernet networks to guarantee end-to-end worst-case latency through mechanisms to support scheduled traffic, frame preemption, and traffic filtering and policing. With Industry 4.0 and automation insight scenarios, 5G systems need perfect coupling with technologies, including TSN domains. For this purpose, 3GPP has made marked progress toward integrating the 5G system with IEEE 802.1 and introduced technical aspects.

Although Wi-Fi has made many advances in various aspects of the PHY and MAC layers, such as throughput, coverage, and spectrum use, Wi-Fi systems do not offer deterministic conditions in the network to serve critical applications. Because Wi-Fi is an 802-LAN technology that is similar to Ethernet, the TSN capabilities are expected to be mapped seamlessly from Ethernet to Wi-Fi without architecture changes or protocol translation gateways. Efforts have been made to enable the primary TSN protocols in Wi-Fi solutions [78]. The Wi-Fi 6/6E standard currently supports some basic TSN features. However, the Wi-Fi 7 standard will evolve on the way to real low latency communications [79]. Thus, Wi-Fi could present advantages over wireless broadband systems because 4G/5G systems are not native 802 technologies; thus, more efforts are required to integrate these systems. Currently, it is possible to integrate Wi-Fi and 5G networks in the field of TSN solutions using translation interfaces defined in 3GPP Rel. 16 [80].

4.8 New Wi-Fi business model

Another challenge of interest is the new Wi-Fi business model in the context of 5G systems. Unlike traditional strategic models focused on competition, the new wireless ecosystem has made new business models evolve toward an approach that focuses more strongly on customers. The explosive growth of Wi-Fi hotspots (see Fig. 8) has forced mobile, fixed-line, and integrated operators to think about a new and concrete business strategy. In this scenario, the new business model of Wi-Fi solutions does not necessarily have to offer innovative content but rather demonstrate flexibility in accessing this content when compared to traditional business models.

For mobile virtual network operators, the possibility of using Wi-Fi is presented as a reality to become a more robust competitor to traditional mobile network operators' business model approaches. For example, Wi-Fi calling or voice-over Wi-Fi is attractive for mobile operators, providing multiple benefits and boosting indoor coverage. Additionally, Wi-Fi offloading provides solid opportunities for fixed-mobile operators to reduce costs. In some cases, Wi-Fi network investment can be justified in environments with constraints in providing cellular capacity and coverage. Currently, the price of user equipment, including chip and modem costs, continues to be lower even for the latest generation of Wi-Fi solutions compared to 5G mobile network equipment [4].

Economic cost will also be an important factor that will define the behavior of users. Even as cellular solutions are moving toward unlimited data subscriptions, the prevailing monthly subscriptions on the market today put these solutions at a disadvantage over Wi-Fi, which is predominantly free with fixed broadband. However, with falling data costs and exponentially increasing traffic growth, service providers have looked into new sources of revenue. New charging models for Wi-Fi are beginning to emerge, where in most cases, direct Wi-Fi monetization [81] is challenging for service providers. Wi-Fi has long been considered a free service, and some companies have begun applying indirect monetization. This new scheme may go beyond direct monetization by attracting new Wi-Fi users and applying strategies of Wi-Fi offloading. The Wi-Fi first strategy involves cable operators onloading as much cellular traffic as possible to their Wi-Fi network, advertising strategies, and sponsored access.

5 Conclusions

The development of wireless networks has gone through several generations, evolving to support different applications and services. The world of wireless communication technologies is immersed in implementing 5G mobile broadband networks. The 5G systems have the challenge of supporting a broad spectrum of new applications that demand high-performance requirements from the networks that support them. These applications include those that demand high transmission rates in broadband scenarios, critical applications with high reliability and low latency requirements for communication, and managing thousands of communications in scenarios with a high density of devices.

The new generation of Wi-Fi standards addresses features to satisfy the same demands as 5G systems for new applications and services, placing Wi-Fi networks in competition with new wireless technologies. Thus, using established standards supported by new technologies such as virtualization and SDN can be explored to meet the new application requirements in the existing network infrastructures. These characteristics ratify Wi-Fi networks as one of the fundamental technologies in mobile traffic offloading, currently serving a considerable part of this traffic, particularly in indoor environments. Also, Wi-Fi and 5G convergence offer improved visibility into Wi-Fi networks, allowing them more control over user experiences and providing better service. However, this long road of integration and convergence is far from over, and Wi-Fi will have to evolve over the next few years to earn a place beyond 5G (B5G) systems. It may be too soon to decide, but we believe that Wi-Fi systems will continue to have a strong presence in new generations of wireless networks that are to come.

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Data Availability The authors declare that the data supporting the findings of this study are available within the paper.

Declarations

Conflict of interest The authors declare no competing interests.

References

1. Kinney S (2018) For enterprises, Wi-Fi is here to stay, analyst says. https://www.rcrwireless.com/20180703/network-infrastructure/wi-fi/for-enterprises-wi-fi-is-here-to-stay
2. He Y, Chen M, Ge B, Guizani M (2016) On WiFi offloading in heterogeneous networks: various incentives and trade-off strategies. IEEE Commun Surv Tutor 18(4):2345–2385. https://doi.org/10.1109/COMST.2016.2558191
3. Naik G, Park J-M, Ashdown J, Lehr W (2020) Next generation Wi-Fi and 5G NR-U in the 6 GHz bands: opportunities and challenges. IEEE Access 8:153027–153056. https://doi.org/10.1109/ACCESS.2020.3016036
4. Oughton EJ, Lehr W, Katsaros K, Selinis I, Bubley D, Kusuma J (2021) Revisiting wireless internet connectivity: 5G vs Wi-Fi 6. Telecommun Policy 45(5). https://doi.org/10.1016/j.telpol.2021.102127
5. Selinis I, Katsaros K, Allayioti M, Vahid S, Tafazolli R (2018) The race to 5G era; LTE and Wi-Fi. IEEE Access 6:56598–56636. https://doi.org/10.1109/ACCESS.2018.2867729
6. Gast MS (2005) 802.11 wireless networks: the definitive guide, 2nd edn. O'Reilly Media, Inc., USA
7. Spinelli F, Mancuso V (2021) Toward enabled industrial verticals in 5G: a survey on MEC-based approaches to provisioning and flexibility. IEEE Commun Surv Tutor 23(1):596–630. https://doi.org/10.1109/COMST.2020.3037674
8. ITU-R Recommendation (2015) ITU-R M.2083 IMT Vision: framework and overall objectives of the future development of IMT for 2020 and beyond
9. Khan LU, Yaqoob I, Tran NH, Han Z, Hong CS (2020) Network slicing: recent advances, taxonomy, requirements, and open research challenges. IEEE Access 8:36009–36028. https://doi.org/10.1109/ACCESS.2020.2975072
10. Baranda J, Mangues-Bafalluy J, Pascual I, Nunez-Martinez J, l. Cruz JLD, Casellas R, Vilalta R, Salvat JX, Turyagyenda C, (2018) Orchestration of end-to-end network services in the 5G-crosshaul multi-domain multi-technology transport network. IEEE Commun Mag 56(7):184–191. https://doi.org/10.1109/MCOM.2018.1701329
11. Yousaf FZ, Bredel M, Schaller S, Schneider F (2017) NFV and SDN-key technology enablers for 5G networks. IEEE J Sel Areas Commun 35(11):2468–2478. https://doi.org/10.1109/JSAC.2017.2760418
12. Gast MS (2013) 802.11ac a survival guide. Wi-Fi at Gigabit and Beyond, 1st edn. O'Reilly Media, Inc., USA
13. Khorov E, Kiryanov A, Lyakhov A, Bianchi G (2019) A tutorial on IEEE 802.11ax high efficiency WLANs. IEEE Commun Surv Tutor 21(1):197–216. https://doi.org/10.1109/COMST.2018.2871099
14. Wang K, Psounis K (2018) Scheduling and resource allocation in 802.11ax. In: IEEE INFOCOM 2018 - IEEE conference on computer communications, pp 279–287. https://doi.org/10.1109/INFOCOM.2018.8486204
15. Khorov E, Levitsky I, Akyildiz IF (2020) Current status and directions of IEEE 802.11be, the future Wi-Fi 7. IEEE Access 8:88664–88688. https://doi.org/10.1109/ACCESS.2020.2993448
16. Nitsche T, Cordeiro C, Flores AB, Knightly EW, Perahia E, Widmer JC (2014) IEEE 802.11ad: directional 60 GHz communication for multi-gigabit-per-second Wi-Fi [invited paper]. IEEE Commun Mag 52(12):132–141. https://doi.org/10.1109/MCOM.2014.6979964
17. Ghasempour Y, da Silva CRCM, Cordeiro C, Knightly EW (2017) IEEE 802.11ay: next-generation 60 GHz communication for 100 Gb/sWi-Fi. IEEE Commun Mag 55(12):186–192. https://doi.org/10.1109/MCOM.2017.1700393
18. IEEE (2018) Enhancements for very high throughput to support Chinese millimeter wave frequency bands (60 GHz and 45 GHz). IEEE Std 802.11aj-2018, pp 1–306. https://doi.org/10.1109/IEEESTD.2018.8345727
19. Feng W, Li Y, Jin D, Su L, Chen S (2016) Millimetre-wave backhaul for 5G networks: challenges and solutions. Sensors 16(6). https://doi.org/10.3390/s16060892
20. Khalifeh A, Aldahdouh KA, Darabkh KA, Al-Sit W (2019) A survey of 5G emerging wireless technologies featuring

LoRaWAN, Sigfox, NB-IoT and LTE-M. In: 2019 International conference on wireless communications signal processing and networking (WiSPNET), pp 561–566. https://doi.org/10.1109/WiSPNET45539.2019.9032817

21. IEEE (2014) Television white spaces (TVWS) operation. IEEE Std 802.11af-2013, pp 1–198. https://doi.org/10.1109/IEEESTD.2014.6744566
22. Flores AB, Guerra RE, Knightly EW, Ecclesine P, Pandey S (2013) IEEE 802.11af: a standard for TV white space spectrum sharing. IEEE Commun Mag 51(10):92–100. https://doi.org/10.1109/MCOM.2013.6619571
23. Khorov E, Lyakhov A, Krotov A, Guschin A (2015) A survey on IEEE 802.11ah: an enabling networking technology for smart cities. Compu Commun 58:53–69. https://doi.org/10.1016/j.comcom.2014.08.008
24. Akeela R, Elziq Y (2017) Design and verification of IEEE 802.11ah for IoT and M2M applications. In: 2017 IEEE International conference on pervasive computing and communications workshops (PerCom Workshops), pp 491–496. https://doi.org/10.1109/PERCOMW.2017.7917612
25. Deng D-J, Lien S-Y, Lin C-C, Gan M, Chen H-C (2020) IEEE 802.11ba wake-up radio: performance evaluation and practical designs. IEEE Access 8:141547–141557. https://doi.org/10.1109/ACCESS.2020.3013023
26. IEEE (2010) Wireless access in vehicular environments. IEEE Std 802.11p-2010, pp 1–51. https://doi.org/10.1109/IEEESTD.2010.5514475
27. Eze EC, Zhang S, Liu E (2014) Vehicular ad hoc networks (VANETs): current state, challenges, potentials and way forward. In: 2014 20th International conference on automation and computing, pp 176–181. https://doi.org/10.1109/IConAC.2014.6935482
28. Naik G, Choudhury B, Park J-M (2019) IEEE 802.11bd 5G NR V2X: evolution of radio access technologies for V2X communications. IEEE Access 7:70169–70184. https://doi.org/10.1109/ACCESS.2019.2919489
29. Anwar W, Traßl A, Franchi N, Fettweis G (2019) On the reliability of NR-V2X and IEEE 802.11bd. In: 2019 IEEE 30th annual international symposium on personal, indoor and mobile radio communications (PIMRC), pp 1–7. https://doi.org/10.1109/PIMRC.2019.8904104
30. Ma X, Ding S, Busse CR, Esley IS (2021) Multi-layer QoS analysis of IEEE 802.11bd based VANET for safety applications. In: 2021 IEEE 18th Annual consumer communications networking conference (CCNC), pp 1–6. https://doi.org/10.1109/CCNC49032.2021.9369544
31. Dezfouli B, Esmaeelzadeh V, Sheth J, Radi M (2019) A review of software-defined WLANs: architectures and central control mechanisms. IEEE Commun Surv Tutor 21(1):431–463. https://doi.org/10.1109/COMST.2018.2868692
32. Martínez VMG, Mello RC, Hasse P, Ribeiro MRN, Martinello M, Guimarães RS, Frascolla V (2018) Ultra reliable communication for robot mobility enabled by SDN splitting of WiFi functions. In: 2018 IEEE Symposium on Computers and Communications (ISCC), pp 00527–00530. https://doi.org/10.1109/ISCC.2018.8538603
33. Gilani SMM, Hong T, Jin W, Zhao G, Heang HM, Xu C (2017) Mobility management in IEEE 802.11 WLAN using SDN/NFV technologies. EURASIP J Wirel Commun Netw 2017(1):67. https://doi.org/10.1186/s13638-017-0856-9
34. Moura H, Alves AR, Borges JRA, Macedo DF, Vieira MAM (2019) Ethanol: a software-defined wireless networking architecture for IEEE 802.11 networks. Comput Commun 149:176–188. https://doi.org/10.1016/j.comcom.2019.10.010
35. Guimaraes RS, et al (2020) An SDN-NFV orchestration for reliable and low latency mobility in off-the-shelf WiFi. In: ICC 2020 - 2020 IEEE International conference on communications (ICC), pp 1–6. https://doi.org/10.1109/ICC40277.2020.9148900
36. Isolani PH, Cardona N, Donato C, Marquez-Barja J, Granville LZ, Latré S (2019) SDN-based slice orchestration and MAC management for QoS delivery in IEEE 802.11 networks. In: 2019 Sixth international conference on software defined systems (SDS), pp 260–265. https://doi.org/10.1109/SDS.2019.8768642
37. Isolani PH, Haxhibeqiri J, Moerman I, Hoebeke J, Marquez-Barja JM, Granville LZ, Latré S (2020) An SDN-based framework for slice orchestration using in-band network telemetry in IEEE 802.11. In: 2020 6th IEEE Conference on network softwarization (NetSoft), pp 344–346. https://doi.org/10.1109/NetSoft48620.2020.9165358
38. Alshaer H, Haas H (2020) Software-defined networking-enabled heterogeneous wireless networks and applications convergence. IEEE Access 8:66672–66692. https://doi.org/10.1109/ACCESS.2020.2986132
39. Workgroup G (2017) The role of Wi-Fi and unlicensed technologies. Wireless Broadband Alliance, pp 1–57
40. Intel (2016) Intel 5G. Network, cloud and client. Technical report, Intel Corporation
41. Samsung (2015) 5G vision. Technical report, Samsung Electronics
42. Huawei (2016) 5G network architecture. A high-level perspective, Technical report, Huawei Technologies
43. (2020) Cisco annual internet report (2018-2023). Technical report
44. MarketsandMarkets (2021) Wi-Fi market by component, density, location type, organization size, vertical, and region - global forecast to 2026. Technical Report
45. Sun W, Lee O, Shin Y, Kim S, Yang C, Kim H, Choi S (2014) Wi-Fi could be much more. IEEE Communic Mag 52(11):22–29. https://doi.org/10.1109/MCOM.2014.6957139
46. Gabriel C, Adlane Fellah M-R (2016) WBA Industry Report 2016. The unlicensed road to 5G. Wireless Broadband Alliance, pp 1–35
47. Kinney S (2018) The parallel development of 5G and Wi-Fi. https://www.rcrwireless.com/20180705/network-infrastructure/wi-fi/parallel-development-5g-wi-fi-tag17-tag99
48. Kinney S (2018) Convergence marks 5G, Wi-Fi future, Boingo CTO says. https://www.rcrwireless.com/20180710/network-infrastructure/wi-fi/convergence-5g-wi-fi-tag17
49. Mehmeti F, Spyropoulos T (2017) Performance analysis of mobile data offloading in heterogeneous networks. IEEE Trans Mob Comput 16(2):482–497. https://doi.org/10.1109/TMC.2016.2557799
50. Suh D, Ko H, Pack S (2016) Efficiency analysis of WiFi offloading techniques. IEEE Transactions on Vehicular Technology 65(5):3813–3817. https://doi.org/10.1109/TVT.2015.2437325
51. Fortetsanakis G, Papadopouli M (2016) How beneficial is the WiFi offloading? A detailed game-theoretical analysis in wireless oligopolies. In: 2016 IEEE 17th international symposium on a world of wireless, mobile and multimedia networks (WoWMoM), pp 1–10. https://doi.org/10.1109/WoWMoM.2016.7523504
52. Institute ETS (2006) Requirements on 3GPP system to wireless local area network (WLAN) interworking (TS 22.234 Release 6). Technical report, 3GPP
53. Rajavelsamy R, Choudhary M, Das D (2015) A review on evolution of 3GPP systems interworking with WLAN. J ICT Stand 3(2):133–156. https://doi.org/10.13052/jicts2245-800X.322
54. 3GPP Technical Group (2014) Mobility between 3GPP wireless local area network (WLAN) interworking (I-WLAN) and 3GPP systems; general packet radio system (GPRS) and 3GPP I-WLAN aspects; stage 3. Technical Report TS 24.327, 3GPP
55. Bayhan S, Gür G, Zubow A (2018) The future is unlicensed: coexistence in the unlicensed spectrum for 5G arXiv:1801.04964 [cs.NI]
56. 3GPP Technical Group (2015) Study on licensed-assisted access to unlicensed spectrum. Technical Report 36.889, 3GPP

57. Markova E, Moltchanov D, Gudkova I, Samouylov K, Koucharyavy Y (2019) Performance assessment of QoS-aware LTE sessions offloading onto LAA/WiFi systems. IEEE Access 7:36300–36311. https://doi.org/10.1109/ACCESS.2019.2905035
58. 3GPP Technical Group (2018) System architecture for the 5G system (5GS). Technical Report TS 23.501, 3GPP
59. Baena E, Fortes S, Barco R (2020)KQI performance evaluation of 3GPP LBT priorities for indoor unlicensed coexistence scenarios. Electronics 9(10). https://doi.org/10.3390/electronics9101701
60. Määttanen H, Masini G, Bergström M, Ratilainen A, Dudda T (2017) LTE-WLAN aggregation (LWA) in 3GPP Release 13 & Release 14. In: 2017 IEEE Conference on standards for communications and networking (CSCN), pp 220–226. https://doi.org/10.1109/CSCN.2017.8088625
61. Laselva D, Lopez-Perez D, Rinne M, Henttonen T (2018) 3G PP LTE-WLAN aggregation technologies: functionalities and performance comparison. IEEE Commun Mag 56(3):195–203. https://doi.org/10.1109/MCOM.2018.1700449
62. Lagen S, Patriciello N, Giupponi L (2020) Cellular and Wi-Fi in unlicensed spectrum: competition leading to convergence. In: 2020 2nd 6G Wireless Summit (6G SUMMIT), pp 1–5. https://doi.org/10.1109/6GSUMMIT49458.2020.9083786
63. 3GPP Technical Group (2018) Study on the wireless and wireline convergence for the 5G system architecture. Technical Report 23.716, 3GPP
64. Karter N (2015) When worlds converge. https://www.qualcomm.com/news/onq/2015/02/23/when-worlds-converge
65. Kang Y, Kim C (2019) A multi-access session management for ATSSS support in 5G network. In: 2019 25th Asia-pacific conference on communications (APCC), pp 409–412. https://doi.org/10.1109/APCC47188.2019.9026504
66. Mahmoodi T, Johnson SH, Condoluci M, Ayadurai V, Cuevas MA, Dohler M (2019) Managing 5G converged core with access traffic steering, switching, and splitting. In: Paving the way for 5G through the convergence of wireless systems, pp 209–226. IGI Global, USA. https://doi.org/10.4018/978-1-5225-7570-2.ch008
67. 3GPP Technical Group (2021) Study on access traffic steering, switch and splitting support in the 5G system (5GS) architecture; phase 2. Technical Report 23.700-93, 3GPP
68. WBA, NGMN (2019) RAN convergence paper. Wireless Broadband Alliance, pp 1–28
69. Fondo-Ferreiro P, Gil-Castiñeira F, González-Castaño FJ, Candal-Ventureira D (2020 A software-defined networking solution for transparent session and service continuity in dynamic multi-access edge computing. IEEE Trans Netw Serv Manag, pp 1–1. https://doi.org/10.1109/TNSM.2020.3033071
70. Rahate GR, Chopade NB (2019) Vertical handoff solution on software defined radios for next generation wireless networks. In: 2019 International conference on innovative trends and advances in engineering and technology (ICITAET), pp 233–238. https://doi.org/10.1109/ICITAET47105.2019.9170145
71. Bonaventure (Ed.) O, et al (2020) 0-RTT TCP convert protocol. RFC Editor
72. Members W (2018) Network slicing. Understanding WiFi Capabilities. Wireless Broadband Alliance, pp 1–15
73. Qin Q, Choi N, Rahman MR, Thottan M, Tassiulas L (2020) Network slicing in heterogeneous software-defined RANs. In: IEEE INFOCOM 2020 - IEEE conference on computer communications, pp 2371–2380. https://doi.org/10.1109/INFOCOM41043.2020.9155532
74. Kovacevic I, Shafigh AS, Glisic S, Lorenzo B, Hossain E (2020) Multi-domain network slicing with latency equalization. IEEE Trans Netw Serv Manag 17(4):2182–2196. https://doi.org/10.1109/TNSM.2020.3008005
75. Nichols K, Blake S, Baker F, Black D (1998) Definition of the differentiated services field (DS Field) in the IPv4 and IPv6 Headers. RFC Editor
76. Liu Y, Meng M (2009) Survey of admission control algorithms in IEEE 802.11e wireless LANs. In: Proceedings of the 2009 ETP international conference on future computer and communication. FCC '09, pp 230–233. IEEE Computer Society, USA . https://doi.org/10.1109/FCC.2009.47
77. Lo Bello L, Steiner W (2019) A perspective on IEEE time-sensitive networking for industrial communication and automation systems. Proc IEEE 107(6):1094–1120. https://doi.org/10.1109/JPROC.2019.2905334
78. Cavalcanti D, Cordeiro C, Smith M, Regev A (2022) WiFi TSN: enabling deterministic wireless connectivity over 802.11. IEEE Commun Stand Mag 6(4):22–29. https://doi.org/10.1109/MCOMSTD.0002.2200039
79. Adame T, Carrascosa-Zamacois M, Bellalta B (2021) Time-sensitive networking in IEEE 802.11be: on the way to low-latency WiFi 7. Sensors 21(15). https://doi.org/10.3390/s21154954
80. Atiq MK, Muzaffar R, Seijo O, In Val, Bernhard H-P (2022) When IEEE 802.11 and 5G meet time-sensitive networking. IEEE Open J Ind Electron Soc 3:14–36. https://doi.org/10.1109/OJIES.2021.3135524
81. Yu H, Cheung M, Gao L, Huang J (2017) Public Wi-Fi monetization via advertising. IEEE/ACM Trans Networking 25(4):2110–2121. https://doi.org/10.1109/TNET.2017.2675944