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Review

Recent Development of Emerging Indoor Wireless Networks towards 6G

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Abstract: Sixth-generation (6G) mobile technology is currently under development, and is envisioned to fulfill the requirements of a fully connected world, providing ubiquitous wireless connectivity for diverse users and emerging applications. Transformative solutions are expected to drive the surge to accommodate a rapidly growing number of intelligent devices and services. In this regard, wireless local area networks (WLANs) have a major role to play in indoor spaces, from supporting explosive growth in high-bandwidth applications to massive sensor arrays with diverse network requirements. Sixth-generation technology is expected to have a superconvergence of networks, including WLANs, to support this growth in applications in multiple dimensions. To this end, this paper comprehensively reviews the latest developments in diverse WLAN technologies, including WiFi, visible light communication, and optical wireless communication networks, as well as their technical capabilities. This paper also discusses how well these emerging WLANs align with supporting 6G requirements. The analyses presented in the paper provide insight into the research opportunities that need to be investigated to overcome the challenges in integrating WLANs in a 6G ecosystem.

Keywords: 6G; OWC; LiFi; VLC; WiFi; WLAN

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1. Introduction

With the ever-growing demand for wireless access, different generations of mobile communications have been developed, with increased performance and novel capabilities. The transition from the fourth generation (4G) to fifth generation (5G) of mobile communications has been marked by three different services defined under 5G. They are enhanced mobile broadband (eMBB), ultra-reliable low latency communications (URLLC), and massive machine-type communications (mMTC). Moving forward from 5G into the sixth generation (6G), the network requirements are defined by these services rather than by the underlying technologies [1]. The evolution into 6G has also seen increasing demand in quality of service (QoS)-aware technologies such as human-centric communications, holographic telepresence, the Internet of Everything (IoE), Industry 5.0, and space/underwater communications [2]. These novel technologies, in turn, require a complete rethink of communication networks due to their stringent latency, reliability, and capacity requirements. As such, recent developments in 6G networks are heterogeneous in nature [3], consisting of mobile networks (public and private), indoor wireless networks, and underwater and space links, as shown in Figure 1.

In view of these developments, wireless local area networks (WLANs) will play an integral role in 6G networks, as more than 80% of their traffic is generated in indoor environments [4]. Further, WLANs inherently reuse spectra, and usually offload the deployment cost to customers. WLANs have also developed over the last 20+ years with a plethora of expertise in catering indoor traffic. As such, it is essential to integrate WLANs into the 6G ecosystem to meet rising indoor access demands [5,6].

The WLAN marketplace was dominated by WiFi in the early 2000s, with data rates reaching multi-Gbps today. However, the limited bandwidth available in the sub-6 GHz range, used in the latest WiFi standard, is causing serious bottlenecks in WiFi capacity. The introduction of visible light communication (VLC) and optical wireless communication (OWC) was a notable solution for bandwidth scarcity in WLANs. The use of optical signals comes with virtually unlimited bandwidth, allowing these networks to easily scale towards multi-Gbps data rates. These kinds of data rates in indoor environments are still challenging for 5G networks. Thus, in order to meet the service requirements of 6G by 2030, it is vital to exploit the capabilities of WLANs.

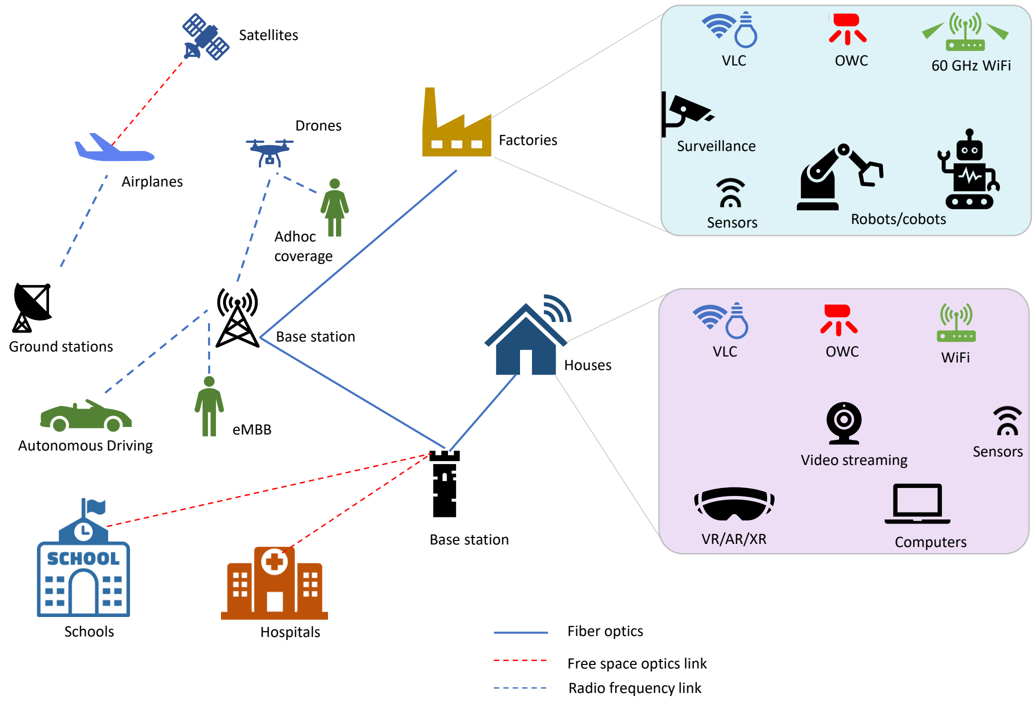

Figure 1. Components of the 6G ecosystem.

Despite the high data rates of WLANs, the latency and reliability of WLANs fall behind those of 5G/6G networks. Most of the development in WiFi in the past decade has been targeted towards increasing data rates and capacity. Naturally, the early works of VLC and OWC were also focused on improving data rates. As a result, WLANs were not considered for the 5G/6G networks in recent literature. However, the latest advancements in WLANs, such as WiFi 6/6E/7 and IEEE 802.11bb, are focused on providing latency-guaranteed, reliable WLANs. Therefore, a comprehensive study on the capabilities of the latest WLANs and their suitability for the 6G ecosystem is a timely contribution.

This paper therefore discusses how the latest advancements in WLANs place them in a viable position to support future 6G deployments. Our main contributions in the paper are as follows.

- We identify the key user applications that need critical service requirements from the 6G network;
- We employ a systematic literature review approach to provide a comprehensive review and analyses of the latest development of major WLAN technologies, including WiFi 6/6E/7, 60 GHz WiFi, VLC, and OWC, in terms of the physical layer and upper layers, and to identify research gaps;
- We also provide a discussion on their key performance metrics and how each technology is suitable for supporting 6G and emerging applications;
- Further, we also identify the research challenges and opportunities we have in using WLAN technologies to support 6G-and-beyond wireless access.

To the best of our knowledge, this is the first paper that provides a comprehensive analysis of all three major WLAN technologies and discusses the integration of WLANs in the 6G ecosystem.

The remainder of this paper is structured as follows. First, we discuss the upcoming indoor wireless applications and their requirements in Section 2. Next, the upcoming WLANs are introduced and briefly explained in Section 3. After the introduction, a detailed discussion of latest advancements in WiFi, VLC, and OWC is given in Sections 4–8. Finally, we discuss the opportunities and challenges in integrating these WLANs in the 6G ecosystem in Section 9, before concluding the paper in Section 10.

2. Emerging Applications of 6G

The massive growth of emerging technologies is one of the key drivers behind the evolution of communication networks and their capabilities [7]. For example, with the introduction of novel applications such as the Tactile Internet that require ultra-low latency and high reliability, communication networks have undergone both architectural and algorithm-based improvements. These changes include the introduction of mobile edge computing, machine-learning based resource allocation, and software-defined networking (SDN).

Emerging technologies continue to grow across diverse fields and facilitate a variety of services that benefit all kinds of end users [8,9]. The suitability of indoor wireless networks in delivering 6G applications depends on the QoS requirements of the applications. For example, e-Health applications such as telesurgery require a reliable network connection with latency in the millisecond range, while applications such as augmented reality/virtual reality (AR/VR) require high bandwidths. As such, before we dive into the specifics of indoor wireless networks, it is important to understand the requirements of some of the key emerging applications to analyse how suitable these indoor wireless networks are in catering to future 6G applications. Therefore, in the following subsections, we discuss and comparatively analyse the requirements of some of the most popular emerging applications.

2.1. Digital Health

In recent years, healthcare applications have transitioned into e-Health platforms due to advancements in the Internet of Things (IoT) and Tactile Internet (TI) [10,11]. In addition to simple services such as teleconsultations, more advanced services such as remote surgery and remote rehabilitation are also made possible thanks to advancements in TI and IoT. These e-Health applications have the ability to reduce the geographical barriers in receiving health care across regional communities. The use of IoT in healthcare has not only progressed real-time patient care, but has also improved offline administrative aspects such as hospital management systems, data gathering and analysing mechanisms, patient and drug monitoring systems, and handling data environments, which are hazardous and unreachable for humans, including high-radiation environments and underwater systems [12].

Although some of the e-Health applications such as teleconsultations may have comparatively fewer QoS requirements, real-time e-Health applications such as telesurgery have stringent latency requirements, such as 1 ms [11]. Applications of this nature also require high bandwidth, as they usually require the transmission of data generated by high-resolution video cameras. Similarly, the use of exoskeletons for rehabilitation requires latency in the same range as for remote surgery.

2.2. AR/VR/XR

Augmented reality (AR), virtual reality (VR), and extended reality (XR) have become prominent technologies, specifically in areas such as education and gaming [13]. These technologies are capable of recreating virtual experiences of real-world scenarios, thereby delivering a fully immersive experience to users. AR and VR technologies can be very useful in education, as they have the capability to provide an interactive learning environment to students, which will enhance their learning outcomes [14]. This technology can be convenient in instances such as medical documents, where two-dimensional explanation is not enough; children's books, where more interaction and entertainment can be provided; and research articles and proceedings where concepts can be further illustrated. However, applications of this nature demand resources such as high bandwidth and stringent latency. The use of VR/AR/XR technologies, audio/video recordings, and holographic images are currently facing challenges, as existing wireless networks struggle to satisfy their requirements. As such, further investigations into novel technologies are required to support these applications.

2.3. Industry 4.0 and Industry 5.0

Industry 4.0 has transformed the traditional workflow of factory settings by integrating connectivity, IoT, and intelligence [15]. Within the Industry 4.0 factory setting, activities such as managing environmental conditions of the production line such as temperature and humidity using IoT technologies can tolerate comparatively higher latency and packet loss rate values, such as 50–100 ms and 10^{-3}, respectively [16]. However, activities that deal with real-time machine and robot handling will require more stringent latency, as low as 25 µ, due to precision and health and safety requirements. Moreover, the recent discussion on Industry 5.0 has taken another step towards a fully connected industrial environment, with digital twins, human-centric communication, and artificial intelligence (AI) [17]. The Industry 5.0 environments are expected to collaborate seamlessly with humans, which requires low latency and high data rate connectivity for the monitoring, and edge computing and AI on-site for data processing.

2.4. Video Streaming (4K, 8K)

The 4K and 8K technologies were introduced as means of obtaining better-quality video output. They are enhanced video streaming standards compared to existing video streaming standards such as 720p and 1080p. For example, 1080p video supports 1920 × 1080 pixels, while 4K supports a 4096 × 2160 pixels resolution and 8K supports a 4-fold higher resolution compared to 4K. Nowadays, services such as Netflix, YouTube, AR/VR, and online gaming use 4K and 8K videos, as they provide better quality of service and experience for the users. With the appropriate encoding mechanisms, 4K and 8K can ensure not only high-definition video streaming but also low-latency live streaming over the Internet [18]. However, between the two technologies, 8K videos are more realistic due to their higher resolution of 7680 × 4320 pixels, and result in lower latency compared to 4K [19], thereby facilitating more natural communication between hosts [20]. However, to achieve a high-definition streaming experience, latency levels lower than 60 ms [18] and bandwidth connections such as 10 Gbps are required [20]. Further, to achieve the scalable video streaming service with techniques such as multicast and storage closer to the user [21], a higher network bandwidth is required in the access networks.

2.5. Virtual Presence (Telepresence)

Virtual presence or telepresence is another renowned emerging technology utilized in many industries. Telepresence is similar to video conferencing, yet is more advanced considering the quality of the audio and video offered. This technology is not just used for conducting meetings and conferences remotely, but also for applications such as robotics. Researchers combine robotics together with telepresence to manipulate the reactions of robots deployed with human-oriented environments. With the aid of telepresence, the user responses are further analysed, and robots respond much accurately [22]. The same concept is applied in the healthcare industry, where robots are used to perform surgeries [23]. Virtual presence in conjunction with virtual reality is also used in military training, online gaming, and medical simulation operations [24]. In order to facilitate the abovementioned requirements, communication channels need to transmit higher amounts of information within a limited timeframe. Hence, high-speed connections and wider bandwidth channels are essential needs. Furthermore, concepts such as performing surgeries with telepresence demand low latency, low jitter, and noise-free communication.

2.6. Smart Homes

Another well-known IoT-based system we use on daily-basis is smart home systems. IoT technology facilitates day-to-day household appliances to be connected to the Internet, thereby controlling them remotely and automatically. Examples of smart home systems range from turning on a light to managing the entire security of a premises. A well designed smart home system has the ability to reduce power consumption, and thereby the overall operational cost of the house, by turning off unused lights and appliances, manipulating the temperature levels accordingly, and adjusting the intensity of lights. To facilitate such needs, widely available and device-compatible communication technologies are required. Moreover, IoT can also add enhanced functionalities, such as implementing cameras and sensors to monitor and detect intruders [25]. A smart home can also consist of an indoor greenhouse, where humidity, temperature, watering levels, and fertilizing can be managed and automated with IoT. Furthermore, plant vitals, monitoring, and growth predictions can also be conducted with IoT systems. To enable these smart home applications, low latency and more reliable communication standards that ensure prompt alerting and accurate notifications are required.

A few other indoor applications that benefit from IoT-based smart home systems are remote education, indoor navigation systems, assisted technologies for people with disabilities, and financial systems [26]. However, most existing IoT systems still operate using legacy technologies such as 3G and 4G. Besides being mature and predictable technologies, they do not have the ability to address the resource requirements of emerging IoT technologies. For this purpose, new technologies and standards need to be explored to support emerging smart home applications [9,27] .

2.7. Machine Learning and Artificial Intelligence (AI)

Artificial intelligence and machine learning have gained their prominence in various industries, such as financial, healthcare, security, agriculture, education, and retail, due to their inherent ability to analyse current data, determine patterns, and make future predictions. For example, in the healthcare sector, these attributes can help clinicians to predict hereditary diseases and take precautions to overcome such diseases. To perform such activities, it is vital that the communication standards support high data rates and high-speed data processing. Especially when it comes to AI technology employed in industries such as healthcare and security, low latency and the reliable transmission of data are extremely paramount, as the predictions made by the AI systems depend on the network performances.

2.8. Smart Cities and Intelligent Transportation Systems

The concept of smart cities exploits the data generated by a multitude of IoT devices to improve the quality of life of people. These collected data are used to automate transportation, healthcare, factories, and many other parts of an urban area [28]. Intelligent transportation systems (ITS) are an impotent part of smart cities, where IoT applications are used to improve the transportation system of a city. Such applications can range from optimally managing traffic congestions within city limits to the safety of vehicles and pedestrians, and managing logistics associated with goods and services transportation [29]. As defined by the European Telecommunications Standards Institute (ETSI), the application layer of ITS mainly focuses on three types of services: road safety, traffic efficiency, and other applications [30]. Road safety applications, such as informing a hard brake to fellow motorists or identifying the failure of a critical function such as steering, requires latency in the range of 50–100 ms, while traffic efficiency applications such as emergency vehicle warnings should adhere to delay constraints of 100–500 ms. In addition to latency requirements, with recent trends towards using big data and different data analytic techniques and algorithms, the capacity of supporting networks should also improve in parallel [31,32].

The QoS requirements of emerging applications discussed in this section are summarised and listed in Table 1. In the next section, we provide a brief overview of the latest WLANs that can cater for latency, reliability, throughput, and other QoS requirements of these emerging technologies.

Table 1. Quality of Service requirements of upcoming applications.

Application	Data Rate	Latency	Reliability	Remarks
Healthcare (Remote Surgery)	∼2 Gbps	<1 ms	Very High	High data rate Strict latency and reliability
4k Streaming 8k Streaming	25 Mbps 100 Mbps	6–11 ms 10–20 ms	Medium	High data rate Delay tolerable to a certain limit
AR	2–20 Mbps (UL) 20–60 Mbps (DL)	5–50 ms	High	Medium data rate Strict latency and reliability
VR	<2 Mbps (UL) 30–100 Mbps (DL)	5–20 ms	High	High data rate Strict latency and reliability
XR	300 kbps (UL) 8–30 Mbps (DL)	10–30 ms	High	Medium data rate Strict latency and reliability
Industry 4.0/5.0	Tens of Mbps	25 µs	Very High	Medium data rate Strict latency and reliability
Smart Homes	<10 Mbps	<100 ms	Medium	Massive number of devices

3. Latest Developments in WLANs

There is a strong drive to build better WLANs that can support 6G applications in indoor environments. Based on the QoS requirement analyses carried out in Section 2, there are several emerging WLAN candidates that can be considered for 6G integration. Particularly, the following technologies are demonstrated to be the most viable developments that can support 6G applications in the near future.

- WiFi 6/6E, WiFi 7;
- 60 GHz WiFi;
- Visible light communication (VLC) and LiFi;
- Optical Wireless Communication (OWC);
- Terahertz communication.

WiFi is a well-known WLAN technology that has been used for decades in both home and industry environments. The latest standards of WiFi, WiFi 6/6E, introduced revolutionary changes in the network layer that improve the latency, reliability, and connection density of WiFi networks. The WiFi 7 standard, which is still under development, is expected to fine-tune these features and introduce more coordinated approaches for network operation. In addition, most of the indoor devices are already equipped with WiFi connectivity. Hence, WiFi becomes a natural candidate for the indoor 6G applications. Further, 60 GHz WiFi is also currently under development as the IEEE 802.11ay standard. This millimetre-wave-range WiFi is best suited for high-data-rate applications, and there are commercial devices such as VR headsets that support this standard. While wide market penetration is yet to happen, industry adoption is promising for 60 GHz WiFi.

Another WLAN technology that is being developed to harness the massive unlicensed bandwidth of the optical range is VLC. VLC helps reduce energy consumption by reusing the lighting infrastructure of buildings for communication purposes. In recent years, most of the VLC developments have been marketed as light fidelity (LiFi) systems. LiFi systems are built using VLC as the foundation; however, they offer seamless networking and interfacing capability with existing systems such as Ethernet.

The LiFi standards support a variety of physical layer modes that can serve a wide range of services. For instance, a simple on–off keying (OOK) modulation can serve low-data-rate sensor devices, while the orthogonal frequency division multiplexing (OFDM)-based physical layer is expected to serve high-data-rate applications. Therefore, VLC, along with LiFi, is considered to be a good candidate for 6G integration.

OWC is another candidate considered for supporting 6G implementation. OWC uses infrared signals to establish indoor WLANs. Due to its inherent feature of supporting higher bandwidth, interest in optical wireless communication is also rising. Though OWC is not yet standardized, certain physical layer aspects of OWC are already included in the VLC standard. Therefore, it is safe to believe that OWC is next in line for standardization.

Moreover, terahertz communication is also gaining momentum in both indoor and outdoor communication. The terahertz range also brings hundreds of GHz of unlicensed bandwidth. The exact figure of the supported bandwidth changes from country to country due to spectrum regulations. The main challenge in terahertz communication is the implementation of transceivers. There are promising developments in research in building practical and cost-effective transceivers. However, terahertz communication needs significant developments to be a part of indoor WLANs that can serve 6G applications in the near future.

Each of the technologies discussed above uses different wavelengths (frequency bands) on the electromagnetic spectrum. Figure 2 shows where all these technologies are located on the electromagnetic spectrum. The technologies that operate at higher frequencies (lower wavelengths) provide higher data rates. However, they are vulnerable to higher signal attenuation, and hence lower coverage areas. In this paper, we discuss technologies that are only a few years away from commercialization, as the rest are still in the early stages of the development. Therefore, we extensively discuss the development of WiFi, VLC, and OWC in the following sections of this paper.

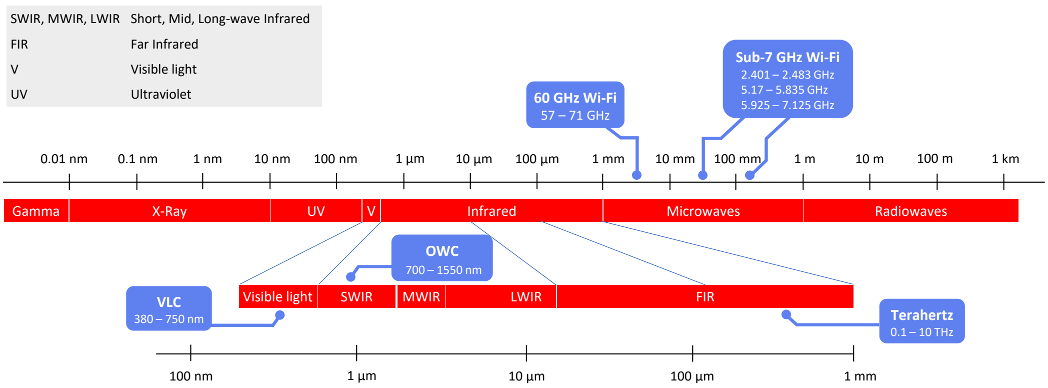

Figure 2. Positioning of the communication technologies in the electromagnetic spectrum.

4. WiFi 6/6E: IEEE 802.11ax

Since the introduction of the legacy IEEE 802.11 standard, WiFi has experienced a significant growth in data rates over the years. Starting with 2 Mbps in 1997, the IEEE 802.11 standard has come a long way, with IEEE 802.11ac (WiFi 5) reaching 6.93 Gbps in 2013. Due to higher data rates supported by the latest WiFi technologies, WiFi has also been considered for outdoor deployment in conjunction with other wireless networks [33]. The development of these WiFi standards has primarily been focused on improving data rates using higher-order modulation and coding schemes, multi-input multi-output (MIMO) techniques, and wider channel allocations [34,35]. However, as discussed earlier, 6G applications require guaranteed latency and reliability for the uninterrupted delivery of services. To support these QoS requirements of emerging applications, the latest WiFi 6/6E/7 and 60 GHz WiFi standardization have proposed a number of features [36]. In this section, we discuss these developments of WiFi 6/6E, WiFi 7, and 60 GHz WiFi, and investigate how they align with the 6G ecosystem. For this purpose, we start our discussion with WiFi 6 in this section, and continue with WiFi 7 and 60 GHz WiFi in Sections 5 and 6, respectively.

In 2019, IEEE 802.11ax was introduced to address the inherent challenges associated with legacy IEEE 802.11 wireless technologies and to enhance the network performances and connectivity. In this section, we discuss such challenges and the proposed techniques in IEEE 802.11ax in detail.

4.1. Orthogonal Frequency-Division Multiple Access (OFDMA)

The channel access of WiFi 5 and older networks is governed by the carrier-sense multiple access/collision avoidance (CSMA/CA) mechanism, which works well for lightly crowded networks. However, when the network load increases, the CSMA/CA networks become inefficient quickly. Introducing OFDMA into WiFi networks improves the efficiency of the underlying networks in many fronts. Firstly, as shown in Figure 3, OFDMA is able to allocate a single subcarrier frequency among multiple users. OFDMA also enables the transmitters to avoid frequency selective fading. However, the most important advantage in WiFi networks is attributed to the small payload generated by existing and upcoming indoor applications. As a result of these small payloads, the entire bandwidth of a single subcarrier is not required for data transmission. As OFDM allows for sharing the same subcarrier among multiple users, OFDMA improves the resource utilization, specifically for applications with smaller payloads. For instance, legacy WiFi networks would allocate all their subcarriers for every single transmission, as shown in the Figure 3a, which results in a waste of bandwidth resources for applications with small payloads. With OFDMA, as shown in Figure 3b, a transmitter can allocate portions of bandwidth depending on the requirement. Further, it allows for parallel transmissions in the time domain; hence, it achieves lower latency values compared to OFDM systems using effective resource allocation algorithms [37].

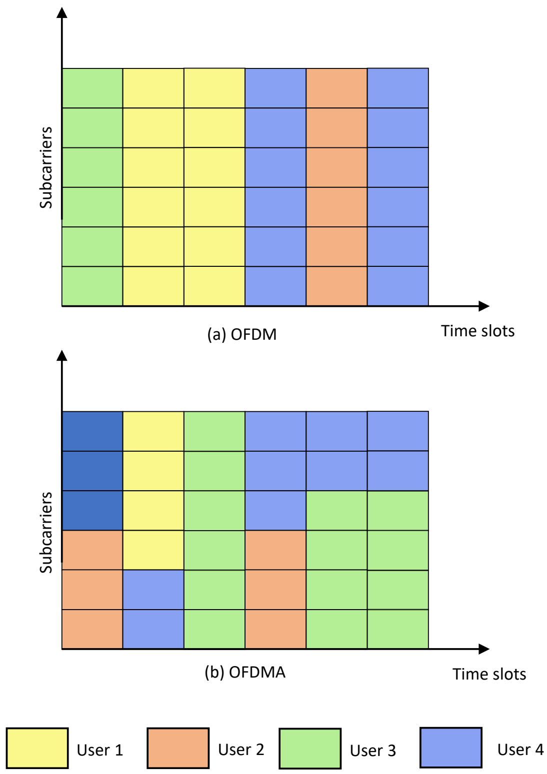

Figure 3. (**a**) OFDM systems allocate all the subcarriers to a single user; (**b**) OFDMA systems can allocate sets of subcarriers to different users.

4.2. Spatial Reuse (SR)

Access point (AP) densification is another challenge faced by WiFi networks. The number of WiFi access points in a given space is increasing at an exponential rate, causing extensive interference, which in turn results in performance degradation in the entire network. As such, improving the efficiency of dense WiFi networks was identified as a matter of paramount importance by the IEEE 802.11ax task group.

To overcome this problem, the concept of spatial reuse (SR) was introduced in dense deployments. The idea of SR is to allow access points with overlapping coverage, overlapping basic service sets (OBSS), to transmit data in parallel, thereby increasing the spectral efficiency in the networks. SR uses a combination of techniques, such as the basic service Set (BSS) colouring mechanism. The BSS colouring mechanism assigns a random ID to each AP, which is different from its neighbouring APs. Therefore, a user detecting a preamble of a packet can instantly identify whether it is coming from an interfering AP before decoding the packet [38].

IEEE 802.11ax also introduced two network allocation vectors (NAVs) to support SR. NAVs are countdown timers that are set at the beginning of the transmission. When the NAV is zero, the transmission is considered to be over and the channel is available. Although a NAV typically keeps track of its own AP's transmissions, there can be neighbouring APs that influence the NAV. Hence, in IEEE 802.11ax, another NAV is introduced to keep track of neighbouring AP transmissions, such that the user can distinguish the status of its own channel and the neighbouring channels [38].

Another SR mechanism that is being deployed by 802.11ax is the overlapping basic service set-packet detection (OBSS-PD) mechanism. It manipulates the transmission power level to sustain a flexible trade-off between interference and spatial reuse capability [38].

4.3. Multiuser MIMO (MU-MIMO)

MIMO is typically used to increase the data rate between an AP and a user device by adding multiple spatial streams. However, most of the devices found in WLANs have only one or two spatial streams, making MIMO not very effective. On the other hand, MU-MIMO allows for the transmission of multiple spatial streams between AP and multiple users. MU-MIMO was first introduced in WiFi 5 to enable simultaneous downlink transmissions. However, WiFi 6 features both uplink and downlink MU-MIMO for up to eight users. As such, MU-MIMO capability is quite useful in serving upcoming 6G applications where an AP has to serve multiple high-data-rate application simultaneously.

4.4. Higher-Order Modulation Schemes

The WiFi 6 standard supports 1024 quadrature amplitude modulation (QAM) with a 5/6 coding rate. With this modulation scheme, 1.2 Gbps of data rate per spatial stream can be achieved. Hence, WiFi 6 is capable of providing Gbps data rates without MIMO if the channel conditions are favourable. In addition, with multiple spatial streams, it is possible to reach beyond 10 Gbps. As a result of incorporating 1024-QAM in WiFi 6, a 25% improvement in throughput is achieved in comparison to 802.11ac [39].

4.5. The 6 GHz Range

The wireless bandwidth available in the 2.4 GHz and 5 GHz ranges is around 60 MHz and 500 MHz, respectively, and therefore requires other techniques, such as modulation, to increase the data rates. However, with the release of the 6 GHz band for unlicensed use, WiFi receives around 1200 MHz of fresh bandwidth. The 6 GHz networks are called WiFi 6E, and experience less interference from existing networks. The channelization of the WiFi in different bands is shown in Figure 4 for comparison.

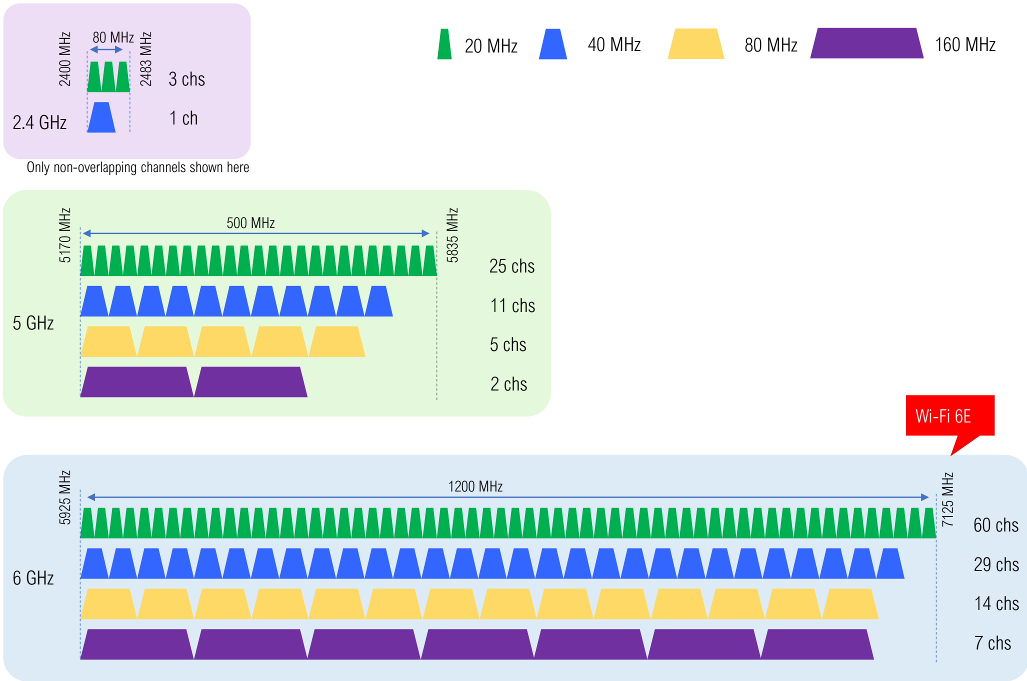

Figure 4. Channelization of sub-7 GHz WiFi standards.

4.6. Target Wakeup Time (TWT)

Target wakeup time (TWT) was a technique adopted from the 802.11ah standard, and was introduced to conserve the power of energy-constrained IoT devices/sensors deployed at smart homes. With TWT, devices can negotiate wake up and transmission times and stay in sleep mode for the remainder of the time. Since TWT also helps minimize channel contention, WiFi 6 can support a massive number of indoor IoT devices without affecting general users.

With the aforementioned design changes, WiFi 6 was able to support high data rates, low latency, and highly reliable connectivity to cater for 6G applications in indoor environments. Many network equipment vendors such as Cisco, tp-link, and Netgear are already shipping WiFi 6 routers and other equipment [40–42]. On the other hand, consumer device manufacturers such as HP, Dell, Samsung, and Apple have integrated the WiFi 6 support in their latest devices [43,44]. Furthermore, the adoption rate of WiFi 6E is also increasing around the globe [45]. Most countries have adopted the 5925–6425 MHz range while considering extending it to adjust bands as well.

5. WiFi 7: IEEE 802.11be

While WiFi 6 standardization activities were ongoing, the IEEE 802.11be task force was formed to work on extremely high-throughput (EHT) WLAN, which will eventually become WiFi 7 (IEEE 802.11be) [46,47]. IEEE 802.11be introduces across-the-board improvements to WiFi, including both physical and medium access control (MAC) layer improvements to optimize coordination among multiple APs and frequency bands [48]. Figure 5 illustrates an overview of the WiFi 7 features. In the coming subsections, we discuss these changes introduced in WiFi7 and the resulting improvements in more detail.

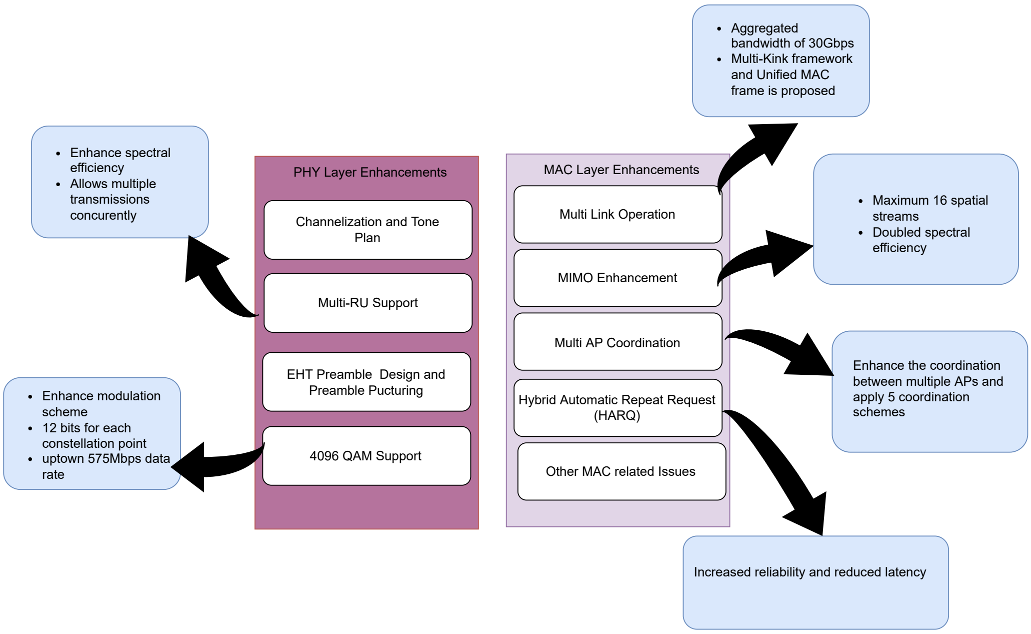

Figure 5. Overview of WiFi 7 features.

5.1. Bandwidth Enhancement

WiFi 7 increases the maximum wireless bandwidth from 160 MHz to 320 MHz [46]. This enhancement facilitates higher throughput, low latency, and improved jitter. Furthermore, bandwidth modes, including 240 MHz, noncontiguous 160+80 MHz, contiguous 320 MHz, and noncontiguous 160+160 MHz, were also proposed for WiFi 7 [49]. As a result, sensitive applications, such as high-quality (4K/8K) video streaming, VR, and AR, can be efficiently supported [47] in WiFi 7.

5.2. Multi-RU (Resource Unit)

Supporting multi-RU assignment to a single user (SU) is another feature introduced in WiFi 7. In IEEE 802.11ax, only a single RU is assigned to a user transmit, and receives frames at a given time, which limits the spectrum resource scheduling. As a solution to the above issue and to improve the spectral efficiency, the multiple resource unit (multi-RU) concept was introduced with IEEE 802.11be [46,49].

5.3. MU-MIMO

The IEEE 802.11be standard doubles the MU-MIMO streams to 16 in order to further increase the network's ability to serve multiple users simultaneously. However, there are challenges in increasing the MU-MIMO streams further, as there is an overhead associated with channel state information. The overhead tends to hamper the MU-MIMO gain [50]. Hence, in order to enable the full capacity of MU-MIMO, further investigations are required [47].

5.4. 4096-QAM

Another key highlight of WiFi 7 is the introduction of 4096-QAM for peak data rate improvements. With 4096-QAM, the modulator assigns 12 bits for each constellation point. As a result of the enhanced modulation scheme, WiFi 7 can optimize its gain by up to 20% compared to IEEE 802.11ax [47]. As per the experiments conducted by [51–53], with the application of 4096-QAM in emerging technologies, users can experience about a 50% increase in data throughput and optimized performance. However, increased modulation orders require a very high signal-to-noise ratio (SNR) at the receiver. Hence, 4096-QAM will be reserved for special scenarios where the required SNR is achievable.

5.5. Coordination Schemes

In legacy WiFi, multiple APs cannot be completely optimized and utilized effectively as a result of a lack of coordination between them. Moreover, such multi-AP situations heighten the negative effects of interference [46]. In order to overcome these multi-AP-related issues, IEEE 802.11be introduces multitude coordination schemes, as follows:

- Coordinated spatial reuse (Co-SR);
- Coordinated OFDMA (Co-OFDMA);
- Coordinated beamforming (Co-BF);
- Joint transmission (JT).

Using these schemes, the emerging technologies discussed earlier can experience better coordinated communication with reduced interference.

5.6. Multilink Operation

The IEEE 802.11be standard operates in 2.4, 5, and 6 GHz bands. Due to frequency selectivity and noncontiguous channels, it is not possible to operate in a wide contiguous bandwidth all the time. Hence, the use of multiple links (multilinks) from different frequency bands is proposed as a solution in IEEE 802.11be. The multilink operation allows APs or devices to communicate using multiple links, which is beneficial for high-data-rate and/or delay-sensitive applications.

5.7. Time-Sensitive Networking (TSN)

The IEEE 802.1 standard was developed to support time-sensitive traffic in Ethernet networks by assigning them dedicated time slots. There is increasing interest in including this standard in WiFi 7 to achieve a deterministic delay for mission-critical applications [54]. In particular, how time-sensitive networking functionalities can be implemented in WiFi 7 physical and MAC layers has become an ongoing research focus in this area [55].

5.8. Enhanced Link Reliability

Hybrid automatic repeat request (HARQ) is a common technique used in mobile networks, which is also used in IEEE 802.11be [56]. In case of a retransmission, if HARQ is available, the retransmission frame will only contain part of the information bits of the failed frame and coded bits, with or without the modulation coding scheme (MCS). HARQ, along with the proposed mechanism, therefore results in increased reliability and reduced latency [47]. Maintaining a reliable connection is beneficial, especially for life-critical emerging technologies that rely on remote connections such as remote surgery.

The development of WiFi 7 is still underway, and commercial products are yet to be developed.

6. 60 GHz WiFi: IEEE 802.11ay

The 60 GHz WiFi is also a great candidate to support high-data-rate applications of future 6G networks. IEEE released its first millimetre-wave WiFi standard, IEEE 802.11ad, in 2012, and at the time, it was the only multi-Gbps WiFi standard available. The standard operates with 2.16 GHz of bandwidth in the 57–71 GHz range and supports maximum data rates of 6.7 Gbps [57]. However, it was soon realized that the applications of 60 GHz WiFi such as uncompressed video streaming, snap wireless file synchronization, and wireless virtual and augmented reality demand much higher data rates and reliability.

To improve IEEE 802.11ad to support such emerging applications, the IEEE 802.11ay task group was formed in 2015 [58]. The following subsections will discuss the basic building blocks of the 60 GHz WiFi standards, with a primary focus on the IEEE 802.11ay standard.

6.1. Modulation and Coding Schemes (MCS)

Following its predecessor, IEEE 802.11ay includes three different physical layer modes, as follows:

- Control mode;
- Single-carrier mode;
- OFDM mode.

The control mode is based on DBPSK (differential binary phase shift keying), with a coding rate of 1/2. Therefore, the data rate is around 27.5 Mbps, which is low compared to other modes [59]. However, because the control mode is used for control signalling such as beacon transmission, beamform training, sweep messages, and other management messages, it is important to use a lower-order modulation scheme to ensure easier detection of control and management messages, even under low-SNR conditions.

The single-carrier (SC) mode offers the advantage of simpler transceiver design and low energy consumption. However, the data rates in this mode can reach as high as 34 Gbps due to higher-order modulation schemes and low coding rates. Similarly, the OFDM mode also reaches close to 40 Gbps of the maximum bandwidth [60]. However, the OFDM transceivers are complex and power-hungry compared to SC transceivers. A complete list of MCS of these modes is given in Table 2.

It is worth noting that the data rates discussed here are for a single spatial stream. Depending on the number of additional spatial streams used, the data rate will multiply.

Table 2. Modulation and coding rates of IEEE 802.11ay.

MCS	Modulation	Coding Rates	PHY Rate
Control mode	$\pi/2$-DBPSK	1/2	27.5 Mbps
Single-carrier mode	$\pi/2$-BPSK $\pi/2$-QPSK $\pi/2$-16QAM $\pi/2$-64QAM	1/2, 5/8, 3/4, 13/16, 7/8	330 Mbps–34.65 Gbps
OFDM mode	SQPSK, QPSK, 16QAM, 64QAM	1/2, 5/8, 3/4, 13/16, 7/8	630 Mbps–37.92 Gbps

6.2. Channel Configurations

Despite the availability of around 14 GHz of bandwidth in the 60 GHz range, the IEEE 802.11ad only uses a channel bandwidth of 2.16 GHz. On the other hand, IEEE 802.11ay introduces wider channels of 4.32 GHz, 6.48 GHz, and 8.64 GHz by using channel bonding and aggregation, as shown in Figure 6 [61]. Channel bonding is where two or more contiguous channels are merged to make a single channel. There will be no channel spacing between the merged channels, and a single waveform will use the merged channel. In contrast, channel aggregation will combine two or more contiguous or noncontiguous channels with channel spacing with different channels using different waveforms [62].

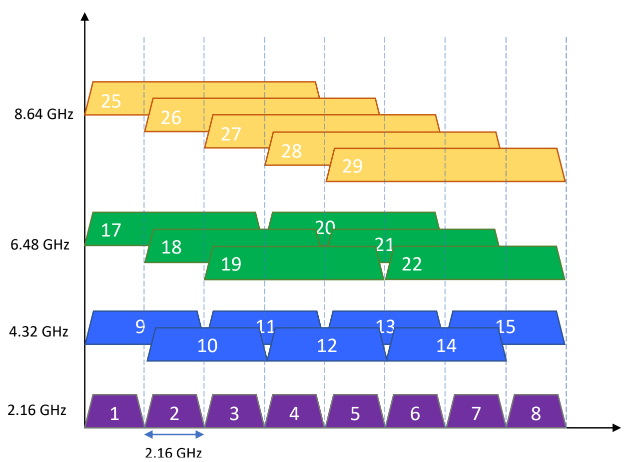

Figure 6. Channelization of IEEE 802.11ay.

6.3. MIMO Operation

As discussed under the modulation and coding schemes, having multiple spatial streams can multiply the overall throughput. Yet, the first 60 GHz WiFi standard did not support any MIMO schemes. The IEEE 802.11ay standard, however, supports MIMO in up to eight streams in both single-user mode (SU-MIMO) and multiuser mode (MU-MIMO) [58]. Using the SU-MIMO scheme, two users can establish a high-throughput link between them, while the MU-MIMO is generally used in the AP to transmit downlink information to multiple users simultaneously.

The adoption of 60 GHz WiFi has been slow compared to other WiFi standards. However, many vendors are steadily adopting the 60 GHz range into their products. For instance, the Nighthawk X10 router by Netgear supports 60 GHz operation [63]. Moreover, chip manufacturers are increasingly designing chips that support 60 GHz WiFi, which will mitigate the lack of consumer devices that support 60 GHz WiFi in the market [64].

Table 3 presents a comparison of key features and limitations of the current WiFi standards. Sections 4–6 show that WiFi networks are evolving fast towards imminent integration with 6G networks. The sub-6 GHz networks are adding more capacity and improving their latency and guaranteed access features. On the other hand, the 60 GHz version is also expanding its scope in terms of modulation schemes, channel configurations, and MIMO operation. Hence, WiFi has the potential to be the first WLAN standard to fully integrate with the 6G ecosystem and provide seamless connectivity to users while meeting the 6G QoS requirements.

Table 3. Key Features and Limitations of Emerging WiFi Technologies.

WiFi Standard	IEEE 802.11ay (60 GHz)	IEEE 802.11ax (WiFi 6)	IEEE 802.11be (WiFi 7)
Key features	• Multi-Gbps data rates with single-carrier modulation • Beamforming • Fast session transfer mode to switch to sub-6 GHz channels • Less interference from existing systems	• Supports OFDMA • Spatial reuse to increase efficiency • Power saving modes of IoT devices • Higher order modulation	• Supports larger bandwidths • 4096-QAM modulation • Enhanced resource allocation granularity • Coordination schemes for multi-AP operation • Supports time-sensitive networking
Limitations	• Unfavourable propagation characteristics • High path loss • Possibility of signal blockage	• Existence of non-WiFi 6 devices can affect performance • Complexities in resource allocation • Increased collision probability due to power saving mechanisms	• Complex HARQ modes • Complex coordination mechanisms • High power consumption

These latest developments of WiFi 6, WiFi 7, and 60 GHz WiFi will play a key role in the 6G ecosystem by providing an added means of connectivity for devices that do not have embedded 6G transceivers and/or for situations where WiFi is more suitable than mobile network connections. For example, in dense urban locations where weakened 6G connectivity is available inside the buildings due the multitude of obstacles, WiFi can serve as a complementary solution to provide the high-bandwidth, low-latency, reliable connectivity required by indoor users. Further, WiFi and 6G could be simultaneously used to provide seamless connectivity and enhanced user experiences. For example, in a smart city/home/office environment, WiFi can be used to connect IoT devices with higher data rate requirements, whilst 6G wireless connections could be used for human-centric ultra-low-latency and high-bandwidth applications, including 4k video streaming and AR/XR.

7. Visible Light Communication and LiFi

Visible light communication is envisioned to play a crucial role in WLANs in the 6G era with the plethora of unlicensed bandwidth available in the visible light spectrum.

The developments in VLC can be categorized into two broad areas: (1) the standardized works that are carried out according to the available VLC standards; and (2) the ongoing research work that does not strictly follow any standardization.

Most of the research work portrays VLC as a physical layer technology for 6G, where the upper layer architecture is the native mobile communication architecture or an architecture such as backhaul links [65,66]. However, as the focus of this paper is on WLANs that can augment 6G networks, we will examine the standardized VLC WLANs in this paper. In the following subsections, we discuss different standardizations introduced by IEEE and ITU, as well as their key features, to evaluate how they can support 6G deployments.

7.1. IEEE 802.15.7 and IEEE 802.15.13

IEEE 802.15.7 was the first visible light communication standard proposed by IEEE, and has laid the foundation for the most recent light communication standards [67]. This particular standard introduced both MAC and physical layer specifications for VLC devices. The MAC layer supports multiuser communication using CSMA/CA-based MAC protocols, and includes a variety of modulation schemes, such as OOK, variable pulse position modulation (VPPM) and colour shift keying (CSK) in the physical layer. Due to the diversity of modulation schemes used, the data rates can also range from 11.67 kbps to 96 Mbps. This standard has now been superseded by IEEE 802.15.13, which offers significantly better features [68].

IEEE 802.15.13 introduced new modulation schemes as well as improvements in the MAC layer. As a result, data rates up to 10 Gbps and an operating distance of up to 200 m were achieved in IEEE 802.15.13. The newly introduced physical layers feature OFDM and pulsed modulation (PM) for high-data-rate operations. There are several physical layer modes available in this standard. The data rates, modulation techniques, and coding schemes supported in each physical layer mode are listed in Table 4. As shown in Table 4, PHY I, PHY II, and PHY III are based on OOK, PPM, and CSK. However, the latest additions are based on pulsed modulation and OFDM (LB-PHY and HB-PHY), which are capable of reaching multi-Gbps data rates [69,70]. The diverse range of modulation schemes allows VLC to support different applications in the 6G environment. For instance, energy-constrained IoT devices might choose pulse position modulation (PPM) over OFDM, whereas a VR headset can be operated using OFDM. Hence, IEEE 802.15.13 offers a great deal of versatility in modulation schemes.

IEEE 802.15.13 supports all common topologies, such as peer-to-peer, star, and broadcast, as well as a new coordinated topology, as shown in Figure 7. As illustrated in the figure, the coordinated topology allows for a primary coordinator to coordinate multiple VLC networks via backhaul. Supporting different topologies can motivate novel networking arrangements in 6G indoor applications and will lead to better use of network resources.

Table 4. Physical layer modes in IEEE 802.15.13.

Physical Layer Mode	Data Rate	Modulation	Coding Scheme
PHY I	11.67–266 kbps	OOK/PPM	Convolutional codes Reed–Solomon codes
PHY II	1.25–96 Mbps	VPPM/OOK	Run-length limit codes
PHY III	12–96 Mbps	CSK	
Pulsed Modulation PHY	100s of Mbps	2-PAM	8B10B line codes
Low-Bandwidth PHY (LB-PHY)	10s of Mbps	OFDM	Bit-interleaved codes
High-Bandwidth PHY (HB-PHY)	Multiple Gbps	OFDM	Adaptive bit loading

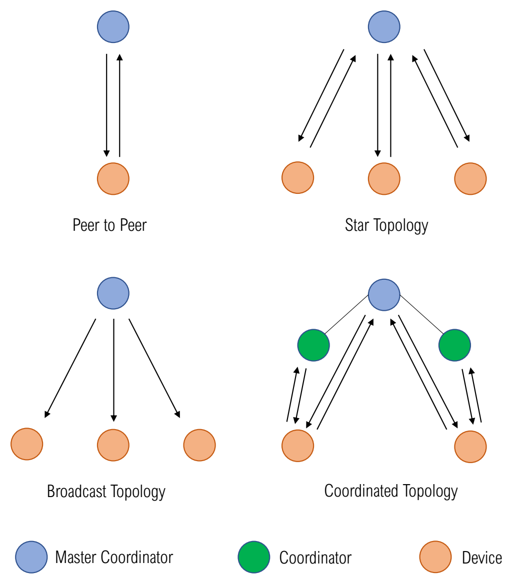

Figure 7. Network topologies supported in IEEE 802.15.13 standard.

7.2. ITU G.vlc

The International Telecommunication Union (ITU) initiated the G.9991 (G.vlc) standard as an approach to LiFi technology in 2015. As a result of this study, the standard G.9991 was introduced in 2019. This standard primarily focused on a system architecture to facilitate high-speed indoor wireless communications [71].

The G.vlc standard provides a complete architecture for an indoor optical wireless communication system that operates in visible light and infrared ranges with the operational wavelength bands, defined as (380 nm–780 nm) and (800 nm–1675 nm), respectively [71]. The architecture reference model of the G.vlc standard presents a very generic model, as shown in Figure 8. Further, it allows five network topologies, as listed below:

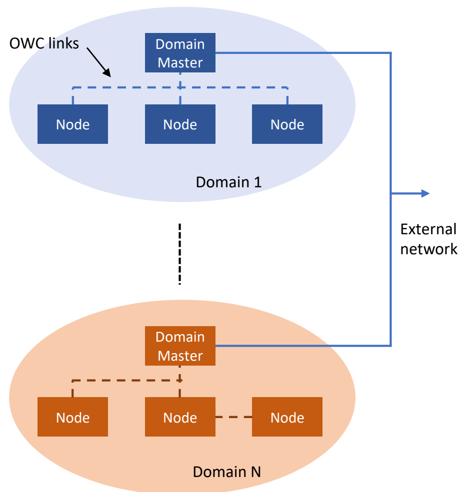

Figure 8. Network architecture reference model of G.vlc.

- Point-to-point (peer-to-peer);
- Point-to-multipoint;
- Multipoint-to-multipoint (mesh);
- Relayed mode;
- Centralized.

The networks can therefore be configured to support a variety of services for 6G applications. As shown in Figure 8, domain is a subset of the network participants and the domain master node will coordinate the resources among its members. Hence, the resource allocation happens at the domain master node, which can carefully allocate resources to meet the QoS requirements of the user applications.

Unlike the IEEE 802.15 standards, the G.vlc standard consists of only OFDM-based physical layers. Due to the non-negative nature of optical signals, asymmetrically clipped optical OFDM (ACO-OFDM) and DC-biased optical OFDM (DCO-OFDM) are used [72]. The DCO-OFDM physical layer is intended for high-data-rate links, while the ACO-OFDM physical layer is designed for less demanding use cases. The data rates could reach around 250 Mbps in the downlink and 200 Mbps in the uplink for point-to-multipoint system configuration [72,73]. The adaptive OFDM physical layer and other functionalities, such as robust line coding and bit loading, make G.vlc a very resilient standard for 6G indoor wireless deployments.

7.3. LiFi: IEEE 802.11bb

LiFi is another VLC technology developed in the recent years, and is the first standard to work on LiFi products. With the cooperation between IEEE 802.15.13 and ITU G.9991 standards, the IEEE 802.11bb standard was established to facilitate a standardized LiFi mass market [74–76]. The 802.11bb standard specifies the following enhancements in the physical layer and the MAC layer to support emerging indoor technologies [74,76].

- 380 nm to 5000 nm band for uplink and downlink transmissions;
- All modes of operation achieve minimum single-link throughput of 10 Mbps;
- At least one mode of operation that achieves single-link throughput of at least 5 Gbps;
- Capability of working on different modulation bandwidths among solid light sources;
- Channel access via hybrid coordination function (HCF);
- Coexistence and detection with overlapping basic service set (OBSS);
- Power management modes.

The IEEE 802.11bb standard is still under development. As stated earlier, the IEEE 802.11bb standard supports a wide range of physical layer data rates, and includes advanced MAC layer features [77]. The physical layer of IEEE 802.11bb was expected to be derived from both the IEEE 802.11 standard and the G.vlc standard. The IEEE 802.11 chipsets operate between 20–160 MHz of bandwidth and will require minimum changes to be converted to light communication frequencies. On the other hand, G.vlc includes many optimizations, such as adaptive bit loading, that result in good performance under frequency-selective channels. However, recently, the task group has abandoned the G.vlc physical layer and started working exclusively on IEEE 802.11-based physical layers.

The MAC layer and channel characteristics are still emerging for this particular standard [76,78]. However, it is safe to believe that the MAC layer would be similar to that of IEEE 802.11, with specific modifications for the optical physical layer. Therefore, the IEEE 802.11bb products will have familiar underlying technology and will fast-track the deployment of LiFi.

There are a few companies that already provide LiFi solutions for domestic and industrial uses. For instance, pureLiFi is a pioneer in LiFi products that supports a range of consumer devices and adheres to common communication standards [79]. Oledcomm is also a LiFi vendor, which is known for its range of products and its data rate. The latest LiFi modules of Oledcomm can reach the Gbps range [80]. Another key player in the LiFi space is Velmenni, which provides both indoor and outdoor solutions. However, the outdoor solutions are point-to-point links, which are similar to free space optics solutions [81].

Due to the abovementioned advancements in the physical layer supporting higher data rates and easy adaptation of the matured upper layer protocols, VLC technology is a good candidate to be considered for integrating into the 6G ecosystem to support emerging indoor applications. VLC can be used to complement 6G wireless connectivity by providing connectivity for devices that are not equipped for RF communication and/or in environments where RF signals may cause electromagnetic interference with other devices, such as in hospitals and factories. Further, VLC can complement the 6G ecosystem where a high data rate and low-latency connectivity is required, with direct line-of-sight connections such as vehicle-to-vehicle communication supporting the implementation of fully autonomous vehicles.

8. Optical Wireless Communication (OWC)

The term 'optical wireless communication' (OWC) is sometimes used as a blanket term for multiple technologies, such as VLC and infrared wireless communication. However, in this paper, we explicitly use it to represent infrared wireless communication. Optical wireless communication has a long history, dating back to the 1970s [82]. The Infrared Data Association (IrDA) first standardized OWC for point-to-point links, and later extended it to WLANs. Interestingly, the first IEEE 802.11 standard also included an infrared physical layer [83]. However, it was not developed afterwards due to the convenience of using radio frequency signals in WLANs. With the recent developments in the physical layer that can exceed 10 Gbps data rates [84], OWC has attracted attention from both academia and industry again.

As discussed earlier, OWC operates in the infrared region of the optical spectrum, and utilizes mature laser diodes and photodiodes to generate and detect signals [85]. The infrared region is a vast range that expands from 700 nm to 1 mm wavelengths. The OWC systems typically operate in the 780 nm to 950 nm, 1310 nm or 1550 nm ranges, which creates roughly 180 THz of bandwidth [86–88]. In comparison, recent Wi-Fi 6/7 systems operate with a maximum of 1.2 GHz of bandwidth, while 60 GHz Wi-Fi systems have access to around 8 GHz of bandwidth.

Due to its significantly large bandwidth, OWC can establish point-to-point wireless links in the order of hundreds of gigabits per second [89,90]. However, there are practical challenges in implementing WLANs with point-to-point OWC links. For instance, WLANs prefer wide beams that can cover multiple users, as the WLAN users tend to be mobile. Therefore, more practical OWC links operate in the range of a few gigabits per second to tens of gigabits per second [85,91]. Emanating from the fibre optics background, OWC links are inclined to use simple modulation schemes such as OOK as opposed to multicarrier modulation techniques. It is worth noting that due to the close proximity in the electromagnetic spectrum, VLC and OWC share similarities in their channel models and propagation characteristics. However, OWC has the advantage of invisible beams, which greatly helps in beamsteering and wavelength division multiplexing (WDM) operations. The relative positions of OWC, VLC, and microwave techniques in the electromagnetic spectrum are shown in Figure 2 [92].

OWC is still in the research and development stage, pending the standardization and commercialization of products. However, parts of the OWC physical layer have already been included in VLC standards. Hence, it is safe to believe that the standardization of OWC will happen in the near future. In this section, we will discuss the recent developments of OWC and how it can serve 6G applications in the form of WLANs [93,94].

OWC systems are typically operated as intensity modulation/direct detection (IM/DD) systems, where the transmit signal is modulated to the instantaneous optical intensity. The frequency and phase information is not used in these modes. Therefore, most of the systems employ OOK or VPPM for lower to multigigabit data rates [90,95]. The IEEE 802.11-1997 specifically uses 16-PPM and 4-PPM schemes [83]. IM/DD systems have the advantage of simplicity in the signal processing domain compared to radio frequency systems such as Wi-Fi.

On the other hand, coherent modulation schemes such as OFDM have also been trialled for OWC [96]. The main advantage of OFDM systems is its resilience to multipath effects. Although IM/DD systems work well for LOS links, under non-LOS (NLOS) scenarios, multipath effects come into play causing intersymbol interference (ISI) [97]. OFDM OWC systems are fairly robust against multipath effects and are superior in spectrum utilization compared to IM/DD systems. Nonetheless, OFDM OWC systems require complex signal processing and unipolar OFDM implementations due to non-negative nature of the optical signals.

Recent OWC developments have an optical fibre heritage, as opposed to earlier systems [98–100], and are biased towards using laser diode transmitters rather than LED transmitters. Although LEDs provide good diffusion of the signal, the modulation bandwidth is far too limited to implement anything near the gigabit range. Therefore, laser diodes, with their well-established fibre optic techniques, have taken the place of transmitters. The receivers are built using photodiodes that are suitable for the operating wavelength, while optical concentrators and filters are used at the receivers to enhance the quality of the incident signal at the photodiode.

One of the physical layer aspects of OWC that is of particular interest is the beamsteering operation. Since OWC links are very narrow beams, it is necessary to steer them towards the users to have a useful SNR value. Further, using narrow beam widths and precision beamsteering, it is possible to operate multiple overlapping channels in the same coverage area without causing interference [98,100].

Based on the developments in the physical layer, novel upper layer (data link and network layers) approaches are required to efficiently use the recent OWC physical systems [101]. As mentioned earlier, IrDA and IEEE included OWC in their older standards. IrDA introduced the advanced infrared (AIr) standard to establish indoor WLANs with nondirected wide-angle transceivers ($\pm 60^\circ$). This particular standard was able to achieve data rates in the range of 250 kbps to 4 Mbps using 4PPM with variable repetition encoding. Variable rate encoding is supported to improve the SNR when the link quality degrades. Doubling the repetition rate improves the SNR by 3 dB [102]. The MAC protocol proposed for this standard is called the AIr-MAC, which is based on the CSMA/CA mechanism. This MAC protocol supports both reliable and unreliable modes of transmissions [103]. Similarly, the IEEE 802.11 standard also facilitates optical wireless communication at speeds of 1 Mbps and 2 Mbps using 16PPM and 4PPM, respectively. The MAC protocol and remaining upper layer protocols were the same as for the RF physical layer.

These upper layer protocols, however, are not suitable for recent physical layer developments of OWC, due to their complex operation and user requirements. In a study on OWC upper layers under the OMEGA-Home Gigabit Access Project [104], a technology-independent MAC layer, shown in Figure 9, was introduced, which can be transparently used for any multi-gigabit WLAN technology. This MAC layer is called Inter-MAC, and it paves the way to heterogeneous WLANs with radio frequency and optical technologies. The Inter-MAC architecture has a split plane architecture, where the data plane is directly interfacing the transmission technologies, while the control and management planes are transparent to the underlying physical layer characteristics. A practical demonstration involving the Inter-MAC and OWC techniques is shown in [105], with high-data-rate VR headsets.

A more comprehensive split-plane architecture for OWC was presented in [106–108]. As shown in Figure 10, the presented architecture has a wide control beam that covers the whole coverage area. On the other hand, the data beams are narrow and cover a specific set of users. Each of these data beams has separate processing threads in the central office, such that they operate independently of each other. Furthermore, the fibre links attached to the access points ensure that there will not be any capacity bottlenecks with the increasing traffic load. Hence, an AP in this architecture can easily support the high data rates expected in 6G networks.

Furthermore, the MAC protocol in operation has a significant impact on the performance of the network. While WLANs typically prefer contention-based MAC protocols, WiFi is moving into more contention-free mechanisms with recent standards. Hence, both contention-based and contention-free MAC protocols have been investigated for OWC. A contention-based MAC protocol for OWC was presented in [109,110]. This MAC protocol can adjust itself to suit the network congestion. These kinds of MAC protocols are useful for networks with frequently changing users and moderate network requirements. For instance, shopping malls have mobile users who will not stay connected to the same AP for a long period of time. On the other hand, contention-free MAC protocols are useful for scenarios where the users have stringent requirements on the data rate and latency. For example, a VR gaming room has a consistent set of users who require high data rates and low latency. A contention-free MAC protocol for OWC with dynamic reconfigurability was presented in [111]. This study presents a contention-free MAC protocol that can change the service intervals and other parameters to suit the traffic requirements.

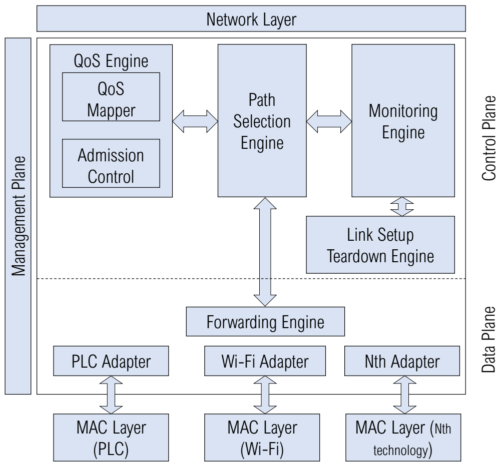

Figure 9. Inter-MAC architecture.

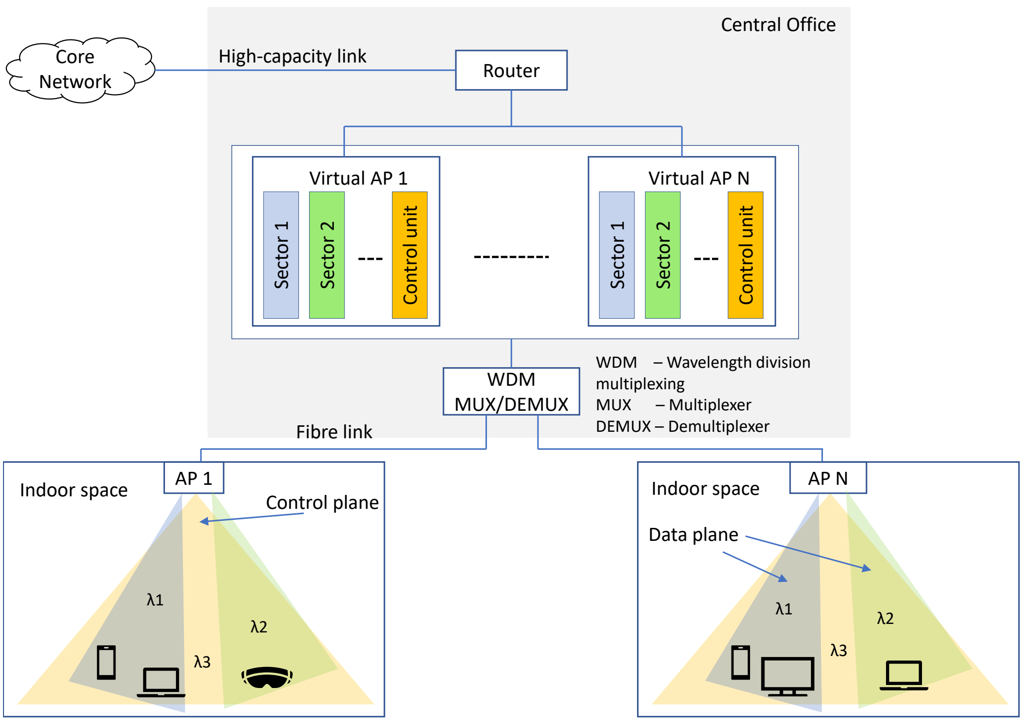

Figure 10. Split-plane architecture for OWC.

From the developments happening in the physical and upper layers of OWC, it is clear that OWC is progressing as a viable WLAN in 6G that can address most of the pressing issues that 5G and other WLANs face today. For instance, the high-density deployments, increasing interference, and spectrum crunch in the low frequencies are easily addressable using OWC WLANs. Though the commercial products are yet to be developed, OWC will be an integral part of the 6G ecosystem with its lucrative features. The use cases of OWC in the 6G ecosystem will be similar to that of VLC. However, due to its ability to provide ultra-high data rates and low latency, OWC can complement 6G in environments such as smart cities where reliable high-data-rate communication becomes a must. For example, OWC could be used to transmit data between vehicle to vehicle and vehicle to infrastructure, including streetlights and traffic lights, enabling real-time communication and control of traffic flow of autonomous vehicles without using RF signals [112].

9. WLAN Integration with 6G: Challenges and Opportunities

In the previous sections, we have presented a comprehensive analysis of the state-of-the-art indoor WLANs. In this section, we investigate the feasibility and challenges of the integration of these technologies in the 6G ecosystem.

Integration of different networks to support diverse use cases, applications, and services have been studied extensively. These network technologies include WiFi, 4G, 5G, and optical [113–116]. The integration of WLANs with cellular networks has also been considered since 4G systems to a great extent [117–119]. These efforts were mainly focused on integrating WiFi with mobile networks due to the wide availability of WiFi. However, with the development of VLC networks, which coincided with the 5G era, a significant amount of work was carried out on the integration of VLC and WiFi with 5G networks [120,121]. All of these efforts involved integrating WLANs with the mobile network. Due to the challenging nature of this approach, practical deployments need further investigations. In particular, factors such as security, deployment cost, protocol mismatch, guaranteed QoS, energy-efficiency, and equipment limitations need to be addressed in achieving such fully converged networks when one or more networks are integrated with each other [122–124].

Further, compared to previous wireless technologies, 6G is defined by the applications and services and not by the underlying technology [125]. Hence, the 6G ecosystem is expected to be built of heterogeneous networks of different natures [126]. Therefore, in this paper, we propose to use the WLANs in the 6G ecosystem to satisfy the requirements of 6G indoor applications. This kind of convergence in networks is called 'superconvergence' [6]. We identified the following research opportunities to overcome the challenges to realize superconvergence between WLAN and 6G to support emerging mobile and IoT applications.

9.1. Enhanced Security

Security in 6G networks is identified as a matter of paramount importance due to a multitude of reasons, such as mission-critical applications, privacy of data, and heterogeneity of the architecture. The security vulnerabilities of 6G networks typically arise from the underlying communication technologies, novel network architecture, and user application [127].

Underlying communication technologies such as mobile cellular communication, WiFi, VLC, and OWC also have existing security vulnerabilities [128,129]. In addition to that, the emergence of AI/ML-based attacks, intelligent network management and orchestration, intelligent transceivers, and the development of quantum computing pose greater threats on these technologies [130,131]. While most of the communication technologies are yet to develop defenses against these threats, VLC has seen a significant improvement in security, using physical layer security (PLS) techniques [127,132]. PLS techniques add another layer of security at the physical layer to enhance the overall security of the transmission. Further, OWC also uses PLS, time-slot coding, and chaotic phase techniques to improve the security of the links [133–135].

On the other hand, upcoming WiFi networks support WiFi Protected Access 3 (WPA3), which provides greater security at the upper layers with the use of cryptography. However, none of the current communication technologies are equipped with mechanisms to face

AI/ML-based or quantum computing-based attacks. Hence, crucial developments are required in 6G communication technologies to face future security threats.

The 6G networks are expected to have unconventional network architectures depending on the deployment scenarios and technologies involved. For instance, spectrum sharing between cellular and WLAN networks, heterogeneous networks with different security protocols, and zero-touch deployments can give rise to new security vulnerabilities in 6G networks [123,130]. Furthermore, with the advent of the network as a service (NaaS) concept, network function virtualization (NFV), SDN, cloudification, and deep slicing will become more and more common in 6G networks [136]. These will also bring vulnerabilities such as external attacks into the networks. While there are proposed solutions in the literature, such as encrypting signalling data and network isolation, further explorations of anomaly detection mechanism in the network and security measures are warranted to protect 6G networks from attacks on the vulnerabilities of network architectures [128].

Finally, the novel user applications of 6G can also bring security vulnerabilities to the networks [127]. The addition of massive number of sensor nodes, as well as industrial equipment such as collaborative robots, will open doors for attackers to find more vulnerable points to enter the network. Therefore, the user applications should use security at multiple levels and support different security protocols due to the diversity of the 6G networks.

9.2. High-Bandwidth Backhaul for WLAN

Most WLANs nowadays experience capacity bottlenecks due to backhaul networks. For instance, copper backhaul technologies such as asymmetric digital subscriber line (ADSL) have quite low capacity compared to WiFi, and do not provide enough bandwidth to support upcoming applications such as AR/VR devices. Hence, the WiFi network cannot operate at its full capacity. Similarly, cellular network-based backhauling also has intermittent capacity issues. The most common solution to this issue is the use of fibre backhaul technologies. For instance, passive optical networks (PONs) provide guaranteed high-capacity backhaul links for WLANs. At the same time, recent developments in 5G fixed wireless access also provides better connectivity for WLANs [137]. However, when we use passive optical networks as the backhaul of VLC/ OWC/the latest WiFi standards, careful consideration should be given to the QoS requirements and policies of each network. This is mainly because WLANs implement contention-based/contention-free scheduling mechanisms and PON uses queue-oriented QoS mechanisms. Therefore, to guarantee the reliability and low-latency requirements of 6G applications, resource scheduling and QoS mapping between networks need further investigations.

9.3. Enabling Time-Sensitive Networking (TSN)

Some emerging applications, such as industrial controls that heavily depend on predictable and reliable network services, demand precise and exact timing. The availability of an accurate and high-resolution understanding of time is used for their optimal operation. Further, providing guaranteed access to services is also a key requirement in the 6G ecosystem. However, time-sensitive networking is still a challenge in most WLANs. WiFi 7 is addressing this issue with the IEEE 802.1 TSN standard. As discussed in Section 5.7, recent WiFi networks achieve better performance in terms of TSN. However, the other WLAN technologies are yet to incorporate features to support time-sensitive traffic. Most VLC standards still operate in contention-based modes, which cannot cater for TSN. Therefore, it is necessary to explore other MAC protocols that can enable time-sensitive networking to provide guaranteed services in VLC and OWC.

9.4. Enabling Intelligence at the Edge

Providing intelligence at the network edge is a key feature in 6G. Having intelligence at the network edge allows for better coordination of resources, as well as resource management and planning in the core network [138]. Adding and managing intelligence to the network edge via artificial intelligence and machine learning is already happening in the cellular networks [139], as the network operators own the base stations and other equipment. However, incorporating intelligence into WLANs has received minimal attention so far. This is mainly because WLANs are highly distributed, and the network deployment is not centrally controlled. Hence, adding intelligence to the WLANs is a challenging task. However, distributed machine learning techniques such as federated learning make it viable to introduce intelligence into WLAN. How these techniques can be used at the edge requires further investigation.

9.5. Context- and Network-Aware Resource Allocation

The heterogeneity of the 6G ecosystem is useful only if the resources can be allocated and managed effectively for the required users. When there are multiple WLANs in a given indoor space, assignment of a network to a particular user needs to be carried out considering the complete traffic load of the space, the QoS requirements of the user application, the current loading of the WLAN, the support for mobility, and other practical considerations. Hence, novel resource management algorithms are required to manage the resources associated with indoor WLANs in 6G deployment for the optimal operation and to satisfy the requirements of emerging applications. Further, regarding the complexity of the heterogeneity of networks used, the handover between networks needs to be carried out with the knowledge of user context and network performance. Handover mechanisms that can be used in WLAN converged networks need to be further explored to support highly reliable and uninterrupted access.

9.6. Edge Computing-Enabled WLANs

Edge computing has brought paradigm-shifting capabilities to many applications that need stringent QoS such as ultra-low latency, higher computation power, and storage. For instance, IoT devices that do not have computational capabilities often offload their computational functions to the cloud servers [140]. However, there is high latency and energy consumption involved, as well as certain security and privacy concerns with transferring data in multiple communication links and networks. WLANs, when equipped with edge computing capabilities, can address these issues in an effective manner. This is mainly because edge computing processes data close to its source compared to cloud computing solutions. Further, adding edge computing capabilities lets the user add custom features to their networks. Even though this presents a promising alternative to cloud-based solutions in some user scenarios, bringing edge computing into the WLAN domain poses challenges such as integrating it with the current architecture and hardware. Hence, it is worthwhile to explore the mechanisms and low-cost architectures that can be used to add computational capabilities into WLANs to better serve 6G demands.

10. Conclusions

With the development of 5G, networks were highly defined by the services they offer rather than the underlying technologies. When it comes to 6G, the definition of the network is further attached to a broader set of services and requirements. Hence, underlying technologies such as cellular networks do not set the boundaries of the 6G ecosystem. The latest 6G networks span across indoor/outdoor spaces, deep sea, and space. Therefore, the 6G ecosystem is inherently heterogeneous and consists of number of communication technologies, in addition to cellular networks.

Providing multi-Gbps access in the indoor spaces is something that cellular networks have always struggled with, due to numerous reasons such as propagation loss and absorption. The WLANs so far have also not provided a reliable connectivity that the user applications require. Hence, merging the WLANs with 5G or previous generations was not an effective solution.

Nevertheless, the recent developments in WLANs, such as WiFi, VLC, and OWC enable the use of WLANs in the 6G ecosystem to support indoor user applications. In particular, WiFi introduces guaranteed access and low-latency communication through changes in the MAC layer. Furthermore, the extension of the frequency band to the 6 GHz range provides a significant amount of bandwidth for upcoming WiFi networks. Therefore, WiFi networks are becoming suitable candidates to provide ubiquitous connectivity with guaranteed QoS. Devices ranging from laptops and mobile phones to IoT sensor nodes will benefited from these novel features of WiFi. On the other hand, VLC and OWC networks are still in the early stages of their developments. Yet, the massive bandwidth available in the optical range has enabled them to operate at multi-Gbps rates with simple transceiver designs. Hence, these networks could provide the multi-Gbps links required by the AR/VR and 8k/16k video streaming devices. Furthermore, the directionality of the optical links allows for the reuse of wavelengths and increases the security of the links. It can be seen that each of these upcoming WLANs has their own strengths and weaknesses, which takes the heterogeneous approach as the best way forward for 6G deployments in indoor spaces.

In this paper, first, we discussed the requirements of the upcoming user applications in the indoor spaces. Next, we presented the novel features of the latest WLAN technologies and critically evaluated the strengths and weaknesses of each technology. We discussed the suitability of integrating these emerging WLANs in the 6G ecosystem, identifying the major challenges that need to be overcome. The review and analysis presented in this paper provide insights into the future directions for the development in WLANs aiming to support the 6G ecosystem.

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