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TOPICAL REVIEW

Wireless and Optical Convergent Access Technologies Toward 6G

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ABSTRACT The sixth generation of mobile communication (6G) systems is recently rising a lot of interest, introducing new futuristic and challenging use cases that will demand much more than just communications to become a reality. Higher throughput, lower latencies, higher number of connections will push the requirement of the future mobile networks to a new level, but also sensing, positioning and imaging will play an important role in the new foreseen use cases. The integration of techniques developed for wireless communications with those conceived for optical links will be essential to provide the infrastructure for the 6G networks. In this context, this paper presents a review on wireless and optical convergent access solutions towards the 6G systems. The manuscript brings the use cases, requirements and enablers for 6G networks including a discussion about the state-of-the-art on THz and sub-THz communications, wireless and optical convergence, visible light communication, integrated and free-space optics, new antenna designs, power-over-fiber deployments and the use of machine learning in the physical layer of future networks. By reviewing the most relevant contributions available in the literature for wireless and optical communications and presenting their main contributions, this paper clearly shows that, more than a technological trend, the convergence of wireless and optical technologies is a fundamental step towards the development of the 6G network infrastructure.

INDEX TERMS 6G, antennas, FSO, optical-wireless convergence, physical layer, PIC, PoF, THz, VLC.

I. INTRODUCTION

The evolution from the first generation of mobile communications (1G) to the fourth generation of mobile communications (4G) has been mainly focused on increasing the system capacity in terms of data rate and number of users. The fifth generation of mobile network (5G), on the other hand, has been designed to support three main scenarios according with international mobile telecommunications (IMT)-2020 vision [1], [2], [3]: enhanced mobile broadband

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communication (eMBB); massive machine-type communication (mMTC); ultra-reliable low-latency communications (URLLC) [1], [2], [3], [4], [5]. Additionally, remote and rural access have been also triggering a lot of interest, mainly in continental-sized countries [6].

The 5G network has been recently standardized in its first release, 3rd generation partnership project (3GPP)-Release 15 [7], which focuses on eMBB. Release 16 [8] is focused on the URLLC scenario, whereas Release 17 [9], scheduled for early 2022, expects to address both mMTC and enhanced remote area communication (eRAC) scenarios. Beyond 5G, the sixth generation of mobile network (6G) is a vision for the 2030s, which will require a much wider and holistic approach to identify the system needs [10], [11], [12], [13]. Latva-aho et al. claim that the main idea for the future mobile system is to be a network based on the term ''Ubiquitous Wireless Intelligence'' [12], which means services following users everywhere and seamlessly, with wireless connectivity and context-aware smart services and applications for both human and non-human users.

The advent of 5G networks brought the possibility of new services that will increase the importance of mobile networks for the modern society. Although these new generation is still being deployed and evolving, it is clear that even more profunding changes will be needed to support the application scenarios foreseen for 2030. Several research projects around the world have shown that innovative solutions for spectrum allocation, network integration and coverage improvement are key to provide solutions for applications that cannot be supported by the restrictive frame and waveforms introduced by the 5G new radio (NR). The next generation of mobile communication needs to seamlessly connect the user by using the proper available network, being it a satellite, optical, wired or wireless network.

Particularly, our research group has contributed to 5G and 6G projects worldwide. The Radiocommunications Reference Center (CRR) has its goal of researching, evaluating, and developing technologies and solutions aimed to Brazilian society demands, considering specific demographics, geographical, and economic features [14]. It is focused on five subject areas including long-range, high-capacity radio links, wireless broadband access, 5G networks and satellite communication links [14]. Under the CRR scope, multiple projects have been also proposed including the development of a 5G transceiver using flexible and manageable waveform applied to long-range communications [15], [16]. The 5G Range project, for designing, developing, implementing and validating mechanisms to enable 5G networks to provide an economically effective solution for Internet access in remote areas [15], [16], [17]. The 5G Internet of things (IoT) project, which has aimed its research on developing IoT technical solutions embedded into a 5G network [18] and, finally, the ''6G Brasil'' [19], [20], which is the first Brazilian project focused on 6G and has established a formal partnership with 6G Flagship Project from University of Oulu in Finland, which is one of the main 6G research group worldwide coordinated by Latva-aho [21].

The requirements imposed by the future applications also bring challenges for the transport network, the proposed access network is nominated as centralized/cloud radio access network (C-RAN), which needs to support high data rates and low latency. The transport network also needs to support physical and virtual network functions, providing the infrastructure for all foreseen use cases [5]. In C-RAN architectures [22], the core network is connected directly on a central office (CO), containing the baseband unit (BBU) pool, through a backhaul (BH), typically using wavelength division multiplexing (WDM) systems. A BH can also connect multiple COs to each other. COs provide the baseband processed signals to a distributed unit (DU) or directly to remote radio unit (RRU). The connections between BBUs and DUs are named midhaul (MH) and between BBUs and RRUs are named fronthaul (FH). FHs are also used to connect DUs to RRUs and MHs are also used to provide high data traffic to femtocells [23]. Some wireless FH could be assisted by a photonic MH, resulting in a hybrid Xhaul [22], [23], [24]. The proposed architecture has to jointly use wireless [25] and photonic [26], [27], [28] techniques for increasing the spectral efficiency and, as a result, the data traffic in both optical MH and wireless FH. Furthermore, supercells operating with reasonable throughputs (up to 600 Mbit/s) can manage a massive number of micro and femtocells in its coverage area, creating extremely high throughput hotspots reaching up to 20 Gbit/s per user [29], [30], [31], leading to a heterogeneous networks (HetNet).

Wireless and optical convergent technologies might enable mobile network systems to meet the wireless systems needs, such as high throughput, latency, coverage and geographical positioning. For example, eMBB can benefit from the available wide bandwidth from optical communication followed by millimeter waves (mmWaves) and tera-hertz (THz) communications [24] in order to ensure very high throughput wireless access. Latency might be reduced in HetNet systems, by employing analog radio-over-fiber (A-RoF) systems for reducing processing time at remote radio head (RRH), jointly with edge computing [32], bringing core functions closer to the users to achieve dynamic orchestration, storage, and computing resources [32], [33]. Additionally, coverage can be enhanced by using new waveforms to increase power efficiency and lower frequency bands in the wireless domain, whereas fiber-based FH is potential to take RRHs even further [15], [16], [17]. Finally, accurate positioning becomes feasible by properly using visible light communication (VLC) communications as access technology [34], [35].

In this paper, we are focusing on identifying state-of-the-art research related to radiofrequency (RF) and optical communication systems, to be applied in 6G networks. The manuscript is structured in five sections, in which Section II presents the use cases, requirements and enablers for 6G networks. Section III describes the main wireless technologies trends and features, including channel losses and capacity, THz communications, antenna design and high altitude platform as IMT base stations (HIBS). The optical and wireless convergent systems towards 6G are presented in Section IV, which includes fiber/wireless systems, free space optical (FSO), VLC, integrated optics, power-over-fiber (PoF) and also the use of machine-learning (ML) in optical fronthauls. Finally, Section V outlines the conclusions and future researches.

II. USE CASES, REQUIREMENTS AND ENABLERS FOR 6G NETWORKS

During the conception of the 5G networks, the IMT 2020 defined several audacious and futuristic use cases scenarios that posed very challenging requirements for the physical layer (PHY). Contrasting requirements, i.e. high throughput and low latency, were necessary to support applications such as remote surgery, autonomous driving, and many others. A very innovative PHY was necessary to provide the flexibility demanded by those applications. However, the standardization procedure that resulted in the 5G NR can be considered conservative and the frame structure and waveforms might be seen as an evolution based on the 4G PHY. As a result, several applications scenarios foreseen by IMT-2020 are not feasible with the 5G networks.

Besides the technical limitations from the 5G networks to cover all IMT-2020 visions, new applications have being proposed for future mobile networks [10], [11]. For example, during the COVID-19 pandemic, it was clear the bi-dimensional video and stereo sound were not enough to provide emotionally comforting communications. Multisensory holographic communication enhanced by haptic data is considered to be the next step for advanced remote communication [11], requiring high data rate and fast response from the network to achieve acceptable quality of experience (QoE). The International Telecommunication Union - Telecommunication Standardization Sector (ITU-T) vision for future remote communications agrees that holographic and multi-sense media will have an important role in future remote interactions [10]. ITU-T highlights four emerging scenarios, named as Holographic-Type Communications (HTC), multi-sense networks (MSN), time engineered applications (TEA) and critical infrastructure (CrI) [10], [11].

Clearly, personal communication is not the only class of applications that will benefit from the expected high data rate and low latency supported by 6G networks. The low latency achieved by the future infrastructure can be exploited to control remote devices, while instantaneous feedback allows for precision operation. These are the key enablers for the remote surgery, remote driving and many other applications.

Besides the enhanced communication capabilities, the 6G networks will need new features to support all upcoming services and applications. Imaging, sensing and mapping will be as important as communications for the next generation of mobile networks [36]. The use of frequencies in the sub-THz and THz bands have being seeing as a solution for increasing the data rate while also providing sensing, imaging and mapping capabilities for the network. The tiny wavelength at these high-frequency bands allows the signal to interact with the materials at the molecular level, opening the opportunity to exploit the RF front-end as a spectroscopic imaging system. On the other hand, the use of such high frequencies leads to several challenges where channel modeling and channel attenuation deserve special attention.

Since the 6G networks must support a multitude of scenarios, applications and services, it is clear that the future network will need a multi-radio access network (RAN) approach to deal with all demands. Fig. 1 depicts the main foreseen applications, enablers and requirements, organized according with the necessary cell size.

In this vision of the 6G networks, the small cells will provide connectivity and functionalities to support the applications that require very high data rates (up to 1 Tbit/s), very small latencies (below 0.1 ms) and very precise positioning and map resolutions (below 1 cm). Here, THz communications, VLC and ultra massive multiple-input multiple-output (umMIMO) are the key technologies to address these requirements. The challenges within the macro cells are still impressive. Because coverage now increases to up to 5 km from the base station (BS), THz communications becomes very difficult. Signals at millimeter wave are more likely to succeed in providing data rates of up 100 Gbit/s with latencies below 1 ms and precision up to 10 cm. However, intelligent reflecting surface (IRS) and smart beamforming aided by artificial intelligence (AI)-based antennas will be important to provide reliable communication over a doubly-dispersive channel, while light detection and raging (LiDAR) can help to increase the mapping and positioning capabilities of the 6G networks. In the future mobile systems, the super cell is expected to provide reliable connectivity in remote and rural areas, a task that, so far, has not been satisfactorily performed by any network. In this case, long-range links of up to 50 km are necessary to offer digital services for farms, mines, planes, ships, trains and cars. Even in remote areas, data rates up to 1 Gbit/s and latencies below 10 ms are necessary for remote controlling and video and data acquisition, while precision up to 0.1 m is necessary for autonomous machinery operation in mines and farms. In this case, radio over fiber (RoF) can be used to reduce deployment costs in remote areas and multiple-input multiple-output (MIMO) for diversity can improve the signal robustness to increase the coverage range and feasibility. TV white space (TVWS) can also play an important role in reducing the operational cost, since licences are not required to exploit the vacant ultra high frequency (UHF) channels. Finally, satellite networks can be jointly used with terrestrial networks to complement coverage or provide backhauling for terrestrial BS.

The 6G networks are being designed to fully fulfil the IMT visions but also to support new applications. The requirements, architecture and enabling technologies are still under discussion in several initiatives and research projects around the world, but it is clear that THz and sub-THz communications, wireless-optical integration, VLC and new antennas

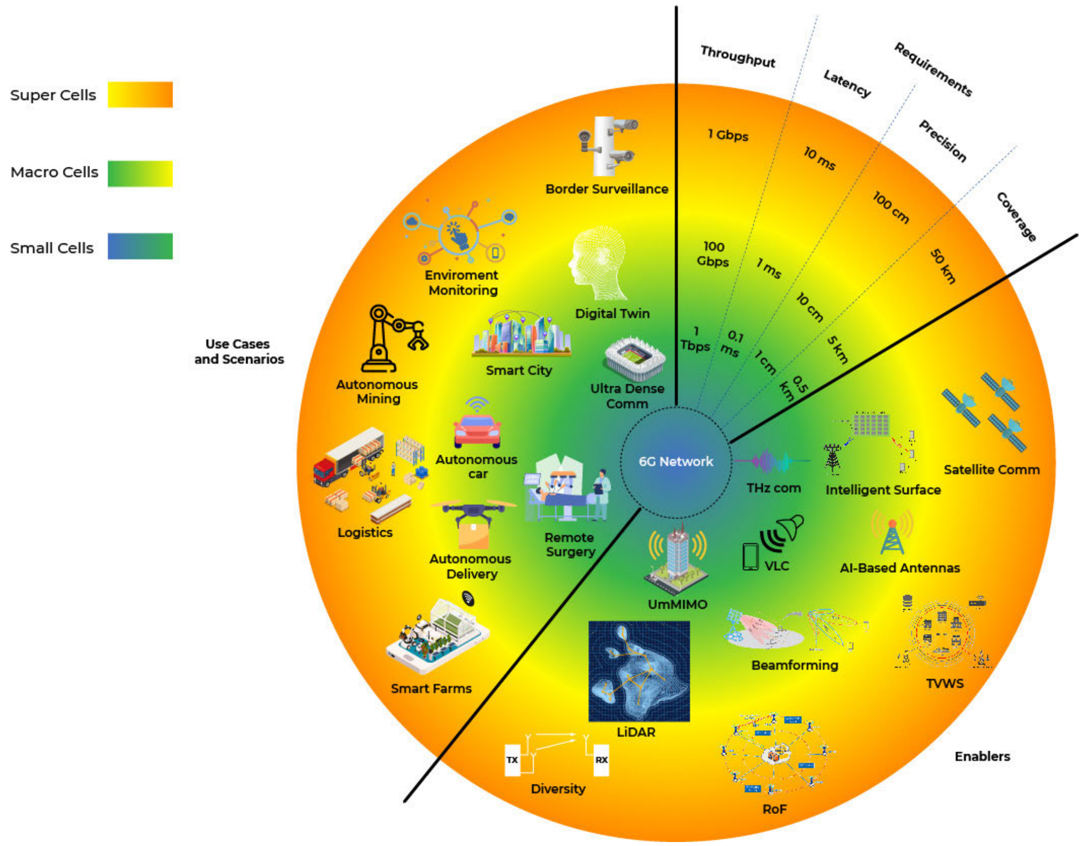

FIGURE 1. Main use cases, enablers and requirements for the 6G networks.

designs are important players in the definition of the next generation of mobile networks.

III. WIRELESS TECHNOLOGY TRENDS

Technologies for wireless communication will be the main enablers for several applications and services. As mentioned in Section II, new frequencies bands and new requirements will demand innovative solutions. This Section describes the main wireless technologies for the future mobile networks.

A. CHANNEL CHALLENGES AND CAPACITY FEATURES

As the data traffic increases throughout the mobile generation systems, exploitation of higher frequencies is necessary as illustrated in Fig. 2. For example, from 1G to 4G the mobile communication system has been allocated at different frequencies between 400 MHz and 2.9 GHz worldwide. Techniques of carrier aggregation has enabled throughput up to 1 Gbit/s in 4G by using multiple channels of 5-, 10-, 15- or even 20-MHz bandwidth simultaneously. By allocating theses multiple channels, it has been possible to increase the system capacity for enabling high-throughput applications [37], [38]. The 5G network was the first generation of mobile communication that uses two different frequency range (FR), i.e, FR 1 from 410 to 7,125 MHz and FR 2 from 24.25 to 52.6 GHz [7], [37]. 5G was the first network to use mmWaves as a solution for the RAN, also employing

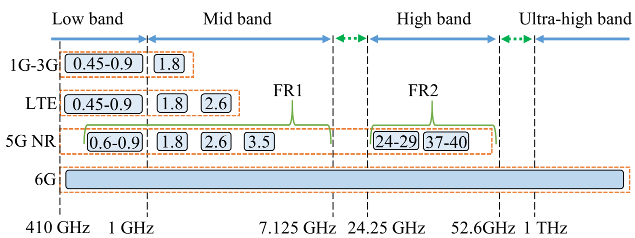

FIGURE 2. Evolution of wireless communication frequency range from 1G to 6G.

bandwidth up to 400 MHz. These new frequency allocation has increased the system complexity, requiring high cost RF components. The high propagation and penetration losses in in the FR 2 range is one of the biggest challenges related with the use of mmWaves in the RAN [38].

Many techniques have been proposed in the literature to overcome the high path loss from mmWaves. Classical methods of MIMO technique can be used to improve the reliability of the links, in which diversity can be achieved by multiple transmitting and receiving antennas, increasing the signal-to-noise ratio (SNR) at the reception and minimizing the outage probability. Spatial multiplexing, on the other hand, consists of using multiple transmitting and receiving antennas for improving the spectrum efficiency by sending multiple parallel data streams. Beamforming is another technique that can use the multiple transmit antennas to create a well-defined, high-gain and manageable beam. The basic idea is to increase the system link budget by pointing the beam to a specific location, or, in other words, only to a specific user equipment (UE) [37], [39].

The high operating frequency introduced by the mmWaves allows for reducing the antenna sizes. A high number of small antennas elements can be packed into antennas array, resulting in massive MIMO (mMIMO). This large number of antennas can be used to provide precise beamforming using maximum ratio transmission (MRT), in which the data transmitted to a given user is weighted by the complex conjugate of the channel response among the transmit antennas and the user receive antenna. This procedure allows for spacing multiplexing, since the high number of transmit signals will be cancelled out in any other location other than the position of the desired user. Therefore, it is possible to take advantage from the massive number of paths on scattering environments for enabling also multiple access. If jointly used with time-division duplexing (TDD), mMIMO can acquire channel state information (CSI) from the uplink (UL) and use it in the downlink (DL) due to the channel reciprocity. No prior assumptions on the propagation environment and no predetermined beams are needed. Pilot subcarriers are transmitted by the UE, allowing for the BS to estimate the channel responses in the UL, which will be used to precode the data to be sent to the respective user. It is important to guarantee that the total TDD frame duration is smaller than the channel coherence time, which means that this technique might suffer performance loss in high mobility scenario [40], [41], [42].

The use of high frequencies bands in mobile communications brings several challenges for the RF front ends. Solutions based on new algorithms for the base band processing and integrated with new RF designs has shown to be promising. New antennas array design and precise channels estimation algorithms based on AI has proved to be a powerful tool for improving system capacity in mobile communication systems [43], [44].

The 6G system should be even more ambitious. Researchers are already expecting that 6G should be the first mobile network to allocate sub-THz and even THz bands for the RAN, as illustrated in Fig. 2. The idea is to provide Tbit/s per user in the next decade [13], [45]. Due to the importance of THz communications for future mobile networks, this subject will be further detailed following.

B. THz COMMUNICATIONS

In this sub-section, we briefly review the fundamentals of THz communications. In fact, following the use of the mmWaves and sub-mmWaves band (above 20 GHz) as carrier frequencies for 5G, the need for tens of Gbit/s data rates will require the use of THz (from 0.1 to 10 THz) carrier frequencies in 6G. However, for this to become a reality, there are several technological hurdles to be addressed. Considering the state-of-the-art in THz technologies, some of these hurdles can be understood with the help of Shannon theorem, which relates the channel capacity (C), with the available bandwidth (B) and the SNR, in the form:

$$C = B \log_2(1 + \mathrm{SNR}). \tag{1}$$

Unlike current mobile systems operating below 6 GHz, in the THz range the main issue is not the available contiguous bandwidth, but rather the SNR, directly related to the output power at the THz transmitter. An interesting consequence is a shift in design paradigm, since the use of higher-order modulation formats, which require a more stringent SNR, is not necessarily advantageous in terms of system performance [46].

Apart from that remark, THz behave as any other wireless system: the link budget is mostly dictated by the very high free-space path loss, which reaches 140 dB for a 1-km link at 300 GHz [47]. In addition, atmospheric absorption and rain attenuation (in outdoor applications) also come into play. To circumvent this signal loss, an increase on the link budget can arise from a combination of high gain antenna systems, phased-array-based beamforming and ultra-mMIMO techniques. Another way to improve SNR consists on the increase of the transmitted power and/or the receiver sensitivity, focus of the following discussion.

Historically, the THz band has not been widely considered for communications applications, mostly due to the lack of efficient THz transceivers. In fact, this portion of the electromagnetic spectrum (0.1-10 THz) has suffered from the so-called THz technological gap. Specifically regarding the analog front-end, the two most usual pathways present hurdles to be overcome. On one hand, from the electronics side of the spectrum, the output power of frequency-multiplier circuits was too low at such high frequencies. On the other hand, in the corresponding wavelength range from the photonics side, apart from the quantum cascade laser [48], no efficient laser was available to generate far-infrared and THz low-energy photons required in those communications systems.

This is the reason why in most early demonstrations, the THz signal carrier is generated in high-speed photoconductors and photodiodes, by means of down-conversion in a photomixing processes [49]. In other words, a down-converted THz-wave carrier can be generated by heterodyning two distinct wavelengths, arising from laser sources. The output carrier frequency is widely tunable, being defined by the difference between wavelengths λ_1 and λ_2. However, since the two lasers are not synchronized, both frequency and phase should be stabilized and the spectral distance between the two laser lines has to be kept fixed, to assure low jitter and low phase-noise [50]. Some of the most popular alternative techniques to achieve this locked spectral behavior include the use of dual-mode lasers [51] or optical frequency comb generators [52], [53].

Before photomixing, the photonic modulation can be based on two configurations: double sub-carrier modulation, in which both sub-carriers are modulated, or single sub-carrier modulation. The double modulation scheme usually provides higher SNR. However, the output power after photomixing is still low and most configurations require a electronic power amplifier operating in the THz range, before the signal carrier can reach the transmitter antenna. Finally, to establish a THz wireless link, the receiver can be based on direct detection (typically Schottky or uni-traveling-carrier photodiode (UTC-PD)) [54] or heterodyne detection, using sub-harmonic diode mixers to obtain an IF frequency in the mmWaves or microwave range [55].

There are other emerging photonic technologies capable of generating THz waves. Among those, we can mention quantum cascade laser (QCL) which operates emitting photons whose wavelength is dictated by electronic transitions between conduction band energy-levels in a sequence of quantum wells [48]. The operating principle results in photon emission the high-frequency range, above 2 THz, and current devices typically requires cryogenic operation in order to provide a useful output power, around a few hundred mW [56]. These drawbacks make very unlike that QCL-based THz transmitters will be used in communications systems, at least in the short and medium terms.

Another alternative would be to rely on the oscillation surface plasmon-polariton (SPP) waves, particularly in graphene or other two-dimensional (2D) materials such as molybdenum disulfide (MoS2) [57]. This plasmonics-based approach is very promising, particularly regarding the possibility of small footprint and high frequency operation. Unfortunately, this technology is still on its infancy, particularly concerning output power and it is not likely to be mature enough for 6G.

Indeed, output power is also a limitation for photonic systems based on photomixing. Even using state of the art UTC-PDs for down-conversion, these system can typically produce less than 10 mW at a few hundreds of GHz [58]. It is then inevitable that even these photonics-based transceivers will have to incorporate THz-electronics power amplifiers. As a consequence, if that is the case, it is probably convenient to approach the THz transceiver configuration from the other end of the THz gap, namely, to seek an all-electronic transceiver. As an additional advantage, such all-electronic implementation would be much more familiar to the wireless industry, thereby likely to facilitate future 6G deployments.

Although oscillators using two-terminal devices, such as resonant tunneling diode (RTD), have already pushed the 1-THz boundary [59], most work on THz carrier generation by electronic means is based on the concatenation of a chain of frequency multipliers, in such way to up-convert a mmWaves carrier to the THz band. Early demonstrations of such schemes have used radio-astronomy hardware on GaAs technology [60]. Today, although Si-based technologies are gaining ground, particularly on the basis of SiGe Heterojunction Bipolar Transistors [61], best results are achieved using InP high electron mobility transistors (HEMT), as transmission powers of hundreds of mW at hundreds of GHz have been already demonstrated [62], which are well above the current results for photonic down-conversion. As the technology evolves and the maximum oscillation frequency of high-speed transistors has already surpassed 1 THz [63], the short-term trends should favor all-electronic THz transceiver configurations, due to the increasing availability of several useful integrated circuits. For instance, an InP-based, higher power density amplifier has been already demonstrated, with a bandwidth as high as 235 GHz [64].

TABLE 1. State-of-the-art on antenna for 5G towards 6G.

Ref.	Antenna type	Number of elements	Bandwidth [GHz]	Application
[65]	Slot with S-PIN	1	27.75 to 27.35	Switched-beam
[66]	Dipoles integrated cavity	1	27 to 29.5	Ommidirectional coverage for broadcast
[67]	PCB-stacked Luneburg lens	1	26 to 37	Switched-beam
[68]	Patch	18	3.6 to 3.8	MIMO
[69]	Dipole with cavity	16	4.9 to 6	Analog Beamforming
[70]	Dipole with reflector	128	3.8 to 4.3	TDD-based digital mMIMO
[71]	Tapered slot	16	24.5 to 27.5	Digital Beamsteering
[72]	Patch	64	5.17 to 6.1	Multiple-beam
[73]	Patch based on suspended plate	18	4 to 4.7	TDD-based digital mMIMO
[74]	Patch	256	26.5 to 29.5	Beamforming
[75]	SWAA	4	27.6 to 30.8 36.8 to 38.4	Dual-band sectorial coverage at mmWaves
[22]	FSS-based Focal-point/ Cassegrain parabolic	2	6.9 to 8 25.85 to 30.15	Point-to-point link
[76]	SWAA	1	23.45 to 24.54	Omnidirectional indoor femtocell
[77]	SICL-based Slot	64	24.5 to 26.5	TDD-based digital mMIMO

C. ANTENNA TECHNOLOGIES FOR SUB-6 GHz AND mmWaves

This sub-Section presents the state-of-the-art on antennas and antenna arrays for sub-6 GHz and mmWaves, focusing on disruptive technologies and application-oriented antenna proposals for 5G that could also be applied to 6G systems. Manuscripts published from 2016 to 2021 have been preferred for this literature review, as complied in Table 1.

A 28 GHz switched-beam slot antenna based on surface PIN (S-PIN) diodes has been proposed for 5G systems in 2017 by Yashchyshyn et al. [65]. This research goal was to achieve multiple beams and enable switching among them. The designed reconfigurable structure was composed of 15 reconfigurable slots with embedded S-PIN diodes. In this way, the slots could be reconfigured by appropriate biasing them, with the purpose of enabling or not radiation through them. The authors have been able to switch among five beams, pointed towards 0°, ±30° and ±45°. In the worst-case scenario, the proposed antenna has provided 600 MHz bandwidth centered at 28.05 GHz, reaching up to 7 dBi gain.

In [66], Mao et al. have proposed a planar sub-mmWaves array antenna with enhanced gain and reduced sidelobes for 5G broadcast applications at 26 GHz. The proposed prototype was based on two dipoles and a substrate integrated cavity as a power splitter. The dipoles were placed side-by-side to create an uniform pattern in the azimuth plane. The authors have been able to combine the dipole and cavity resonance to provide a wide bandwidth from 27 to 29.5 GHz. Finally, they have structured an eight-element array for enhancing its gain, reaching up to 12 dBi omnidirectional coverage for broadcast applications. A wideband printed-circuit board (PCB)-stacked Luneburg lens antenna with a flared open edge for multi-beam scanning application at 5G mmWaves band was proposed in 2021 by Wang et al. in [67]. They were aimed to fulfill the increased data traffic in mobile communications, by proposing a high-gain (15.4 dBi) and wideband antenna (from 26 to 37 GHz) for switched-beam applications. It consists of 11 resonant elements, shifted among each other by 15°, around a unique circular Luneburg lens. We can notice the possibility of applying distinct technologies for encompassing all 5G demands. For instance, multiple probes [67] or S-PIN-based SWAAs [65] could be employed for switched-beam applications, whereas waveguide-based slot antennas [65], Luneburg lenses [67] and cavities could be used for increasing the antenna gain [65].

There are also some important works from literature on MIMO and mMIMO systems, which define the antenna array requirements. In 2016, Gao et al. proposed a dual-polarized patch antenna array with low mutual coupling [68], which is a very important MIMO requirement [78]. The proposed system was composed of 144 ports operating at 3.7 GHz and 18 low-profile subarrays for allowing 360° coverage. Each subarray was based on four patch antenna elements with two ports, one for each polarization, which allowed to reach mutual coupling lower than −35 dB.

A dipole-based and dual-polarized 16-elements antenna array was proposed by Komandla et al. in 2017 [69]. They have proposed the usage of cross-polarized dipoles, one on each side of a substrate, with a back cavity acting as a reflector. The coupling among the array elements was kept lower than −20 dB through the entire operating bandwidth from 4.9 to 6 GHz. Finally, they have numerically demonstrated beam-steering feature over 50°, four beams for a multi-user environment and gain higher than 20 dBi for all evaluated scenarios.

The research conducted by Yang et al. [70] in 2017 was regarding the design and implementation of a TDD-based 128-element mMIMO system, including an analytical model and a link-level simulation. The prototype was divided into 8 sub-arrays of 16 printed-dipoles mounted above metallic reflectors and arranged as a planar antenna array spaced by 0.8λ (at 4.1 GHz). From the antenna point-of-view, 0.8λ spacing is acceptable for creating a unique directive beam, without prohibitive levels of grating lobes. However, such a spacing could degrade mMIMO performance due to lack of channel diversity. Nonetheless, since the array has been divided into 8 sub-arrays, the spacing among the array elements was approximately 3.2λ, which ensured channel diversity and, consequently, high mMIMO performance, as a result of a maximum −25 dB mutual coupling. As a final result, authors reached up to 69.12 bit/s/Hz spectral efficiency using quadrature phase-shift keying (QPSK) modulation, which provides only 1 bit/s/Hz in a conventional single antenna system.

Hu et al. have proposed a digital multi-beam array with 16 elements for the 26 GHz band in 2018 [71]. The manuscript has focused on the beamsteering feature instead of mMIMO application. The array element was a dual exponentially tapered slot antenna (DETSA), which is a variation of a conventional Vivaldi antenna. Each element was excited by transverse electric (TE) propagation mode using substrate integrated waveguide (SIW) in order to ensure mutual coupling lower than −20 dB for an element spacing of 6 mm. Moreover, a Jerusalem Cross planar lens enabled to increases the array gain from 20 to 25 dBi and beamsteering from −50° to 50°, by properly managing the element phase.

In 2020, Li et al. [72] proposed the use of a metasurface lens antenna in a 64-element dual-polarization patch antenna array, envisaging to cover both multibeam and mMIMO applications. The manuscript reported bandwidth form 5.17 to 6.1 GHz, a scanning angle of ±25°, gain up to 22.4 dBi with 3.3 dB variation and mutual coupling lower than −20 dB. The switched-beam feature comes from selecting a port or a combination of ports of the array feeding network. In this way, either multiple beams at the same frequency or frequency division multiplexing for each beam, aiming to increase the system throughput, might be implemented.

Two important researches on the array topology are presented in [73] and [74]. In [73], Temiz et al. investigated the impact of the antenna array geometry in the mutual coupling and channel correlation, by exploiting a directional wideband single antenna element for the antenna array and UE. Particularly, two planar antenna arrays were considered in the channel correlation analysis: a uniform antenna array and a shifted antenna array. The uniform one was composed of equally distributed elements, aligned in both horizontal and vertical directions, whereas the shifted array consisted of shifting lines of radiating elements in the matrix, increasing the spacing between adjacent elements without compromising the array area. The obtained results proved the shifted array outperforms the uniform conventional array in terms of network capacity, due to a lower level of mutual coupling and lower channel correlation (lower than −15 dB for the linear array and −20 dB for the shifted array), especially in lineline-of-sight (LOS) propagation. Additionally, an element spacing periodicity investigation on the array topology was made by Aslan et al. [74] in 2021. They considered four different array topologies for evaluating the interference among multiple users and demonstrating aperiodic element distribution has the potential of increasing the system quality of service (QoS) in terms of inter-user interference reduction. Using element spacing of at least λ increases the inter-user interference due to side-lobe level (SLL) increment in a LOS environment. The advantages of using more spaced elements in this scenario are thermal dissipation and creating space for electronics in active antenna deployments at a limited impact on quality of service (QoS).

Most papers on beamforming and MIMO applications from literature are only regarding the array antenna element (mainly patch, dipole or slot antennas) or feeding network, as summarized by [68], [69], [70], [71], [72], [73], and [74]. Regardless the application, reducing mutual coupling is an important performance metric that was required to be lower than −20 dB in most papers, using element spacing from 0.5 to 1λ for beamforming and multiple beams applications. On the other side, MIMO systems make use of channel diversity, the array elements need to be further spaced.

Operating frequency and application are also important pieces of information from Table 1. Fig. 3 compiles the most common antenna types related to their application and frequency ranges. It is noticed that classical dipoles, patch and Vivaldi antennas are mostly used in the sub-6 GHz band, whereas in mmWaves more types of antennas and antenna arrays, waveguide-based antennas, have been proposed for encompassing different access scenarios. Undoubtedly higher frequencies enable high-order antenna arrays, due to smaller wavelengths. However, most papers on antenna arrays from literature are focused on the sub-6 GHz band, probably due to the complexity and high-cost of mmWaves components and pieces of equipment. Furthermore, it has been noticed there are more published solutions for beamforming, beam steering and multiple-beam than TDD-based digital mMIMO applications. Once again, this is related to implementation costs, since beamforming techniques can be applied with a smaller number of RF chains. However, it is important to emphasize that analog beamforming and steering techniques consider communication with few users (some manuscripts are applied to only one user). On the other hand, TDD-based digital beamforming guarantees multiple-access for multiple users, as a result of the channel diversity in a non line-of-sight (NLOS) scenario, which is more realistic in a dense urban environment.

Our research group from the Laboratory Wireless and Optical Convergent Access (WOCA) has been intensely contributing to the development of mmWaves antennas for 5G in the past few years, as complied in Table 1 [22], [75], [76], [77], [79], [80], [81], [82] and illustrated by prototypes shown in Figure 4. In 2017, da Costa et al. have reported the first optically controlled reconfigurable slotted-waveguide antenna array (SWAA) (Fig. 4(a)) for mmWaves from literature [75]. The physics behind its design was managing the

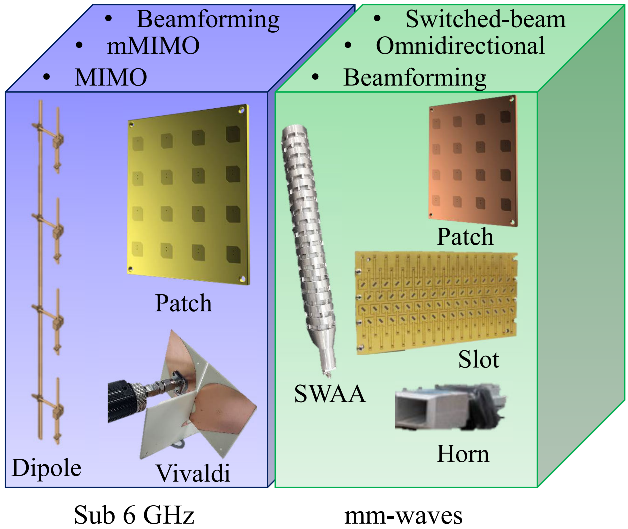

FIGURE 3. Most common antenna types related to their usual applications and frequency range.

slots electrical length by partially covering them with photoconductive switches in order to enable frequency tunability and radiation pattern reconfiguration over the 28 and 38 GHz bands.

Two novel mmWaves antenna designs were introduced in 2018 [79]. First, a 28-GHz omnidirectional SWAA based on metallic rings for disturbing a traveling wave inside a dielectric waveguide was manufactured, as displayed in Fig. 4(b). Furthermore, dual-band and dual coverage SWAA (Fig. 4(c)) for simultaneous operation in the 28 and 38 GHz band was proposed, using two groups of slots with different electrical lengths on the opposite faces of a retangular waveguide. Such dual-band SWAA has been applied to a switched-beam MIMO system by Vilas Boas et al. [80] in 2019, by arranging four SWAA elements as shown in Fig. 4(d). Experimental results demonstrated mutual coupling lower than −35 dB through the entire evaluated bandwidth (24 to 40 GHz).

Vilas Boas et al. have further investigated SWAA antennas at mmWaves in 2020 [81]. In this new research, a low-profile and high-gain SWAA (Fig. 4(e)) was developed for point-to-point links and self-backhaul applications. Six pairs of metal grooves have been integrated to the SWAA structure, which implied in aperture efficiency of 20% and 9 dB gain enhancement, reaching 27.7 dBi without using metallic parabolic reflectors. Finally, the grooved-assisted prototype provided a bandwidth of 900 MHz, which is compatible with the 5G-NR standard from 3GPP.

Another approach for point-to-point links was implemented in 2019 [22], by making use of a dual-band wireless fronthaul using a frequency selective surface (FSS)-based focal-point/Cassegrain antenna (Fig. 4(f)) [25], assisted by an optical midhaul. That innovative 5G-Xhaul fiber-wireless architecture takes advantage of digital pre-distortion in order to guarantee up to 18 Gbit/s throughput in accordance to the 3GPP requirements. Particularly, the antenna consisted of two feeders individually operating at 7.5 and 28 GHz, a main reflector and a FSS based sub-reflector. The latter one acts as a conductor at 28 GHz and is electromagnetic transparent at 7.5 GHz, enabling the dual-band feature using a unique main reflector.

We have also developed an omnidirectional high-gain SWAA (Fig. 4(g)) operating at 24 GHz for femtocell applications [76]. It was based on a novel approach for designing wideband SWAA, which relies on using trapezoidal-shaped slots with two different electrical lengths, as well as a twisted distribution of slot groups along the array longitudinal axis. The trapezoidal slots are formed by gradually increasing the slot length between the waveguide interior and exterior surfaces. In this way, a smoother impedance transition between waveguide and air is obtained for increasing the array operating bandwidth. In addition, the twisting technique allows to improve the omnidirectional pattern, by reducing the gain ripple in the azimuth plane. Experimental results have demonstrated 1.09 GHz bandwidth centered at 24 GHz (4.54% fractional bandwidth), gain up to 14.71 dBi over the operating bandwidth and only 2.7 dB gain variation in the azimuth plane. Such novel SWAA is promising for mmWaves applications, including 5G eMBB communications in indoor scenarios, as demonstrated in in 2021, as a result of its implementation in a 91-m^2 indoor femtocell [82].

Recently, Filgueiras and Sodre Jr. [77] have conceived and fabricated a 64-element, slot-based, dual-polarized and substrate integrated coaxial line (SICL)-fed antenna array applied to TDD-based digital mMIMO applications. The prototype from Fig. 4(h) has 64 independent feeding points and each radiating element provides a 2-GHz bandwidth, from 25 to 27 GHz, beamwidth of approximately 85° in both main orthogonal planes and 7.5-dBi gain.

D. ANTENNAS FOR THz

The specialized literature also presents antennas for THz, as summarized in Table 2 [83], [84], [85], [86], [87], [88], [89], [90], [91], [92], [93], [94]. Many of them are conventional microwave and mmWaves antenna design, re-tuned for higher frequencies. For instance, horn antennas, planar antennas, dielectric lens-based antennas, reflectarrays and resonant cavities designed for THz were exploited not only in the Review Paper [91], which presented many manufacturing techniques and antenna types, but also in [94]. Particularly, 3D printing typically achieve up to 0.01 mm precision. If higher precision is required, micro-milling still represents a more appropriate choice, such as Computer numerical control (CNC)-based manufacturing, electric erosion and Low-temperature co-fired ceramic (LTCC). A conventional cavity-based radiating structure at 135-GHz fabricated by 3D printing and a SWAA antenna operating at 141 GHz were reported in [85] and [86], respectively. In the last one, authors have used gap-waveguide for overcoming the electric contact issue associated with mechanical mounting at high-frequencies, enabling to manufacture it using simple micro-milling techniques.

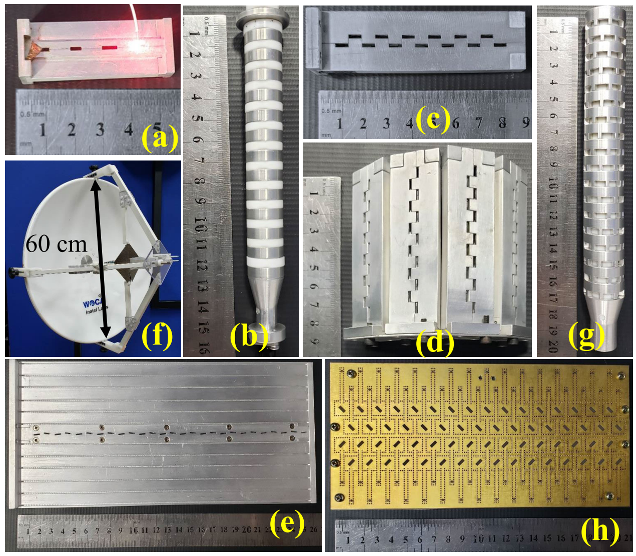

FIGURE 4. Laboratory WOCA antenna array prototypes for 5G and towards 6G. (a) Optically-controlled SWAA from [75]; (b) Omnidirectional SWAA from [79]; (c) Dual-band SWAA from [79]; (d) 4-element SWAA from [80]; (e) High-gain SWAA from [81]; (f) Dual-band Focal-point/Cassegrain from [22]; (g) Omnidirectional SWAA from [76], [82]; (h) mMIMO slot antenna array from [77].

TABLE 2. State-of-the-art on THz antennas.

Ref.	Technology	Bandwidth [THz]	Fabrication method
[83]	SIW	0.124 to 0.158	LTCC
[84]	SIW	0.54 to 0.56	PCB
[85]	Resonant Cavity	0.125 to 0.144	Metallic and dielectric 3D printing with post-metallization
[86]	Gap-waveguide (gapWG)-based SWAA	0.134 to 0.148	Micro milling
[87]	Cassegrain	0.22 to 0.31	CNC-based micro milling
[88]	Waveguide	0.22 to 0.30	Micro milling
[90]	Printed slots	0.39 to 0.41	CNC and PCB
[95]	Dipoles and plantennas	302 to 541	Numerical design only
[96]	Photoconductive antenna	9 to 47	Numerical design only

In [83], authors have proposed using a SIW feeding line for exciting wideband dipole-based radiators from 124 to 158 GHz. Similarly in [84], authors have achieved a 20 GHz bandwidth at 550 GHz, by properly manufacturing a PCB-based antenna with SIW. Additionally, A. Kosogor and Y. Tikhov manufactured a Cassegrain parabolic antenna with a polished gold-plated for reducing losses associated with its paraboloid roughness and conductivity [87]. It provided bandwidth from 220 to 310 GHz and gain of 48 dBi at 265 GHz. Beam-steering capability from −75° to 30° at 260 GHz in conjunction with 28.5 dBi gain have been ensured by a waveguide-based antenna filled with dielectric material [88]. Its authors claim the achieved high performance and their silica micro-milling technique, aimed for mass production, make their antenna a low-cost and potential solution for many THz applications, including radars and 6G systems. The fabrication of a travelling-wave antenna with reduced SLL operating from 390 to 410 GHz was described in [90], using CNC and PCB techniques. Finally, plasmonics-based antennas [96], photoconductive antennas [94] and new materials, including graphene [97], have also been investigated for THz generation and detection. A photoconductive antenna is basically composed of a gap-based antenna, an electrode and a photoconductive substrate. On the other hand, the main advantage of using graphene is its resistivity, which is lower than that of copper and gold [97], [98].

E. HIBS - HIGH ALTITUDE PLATFORM AS IMT BASE STATIONS

Studies involving high-altitude plataform systems (HAPS) for communications started in the 1990s. The first spectrum for their use in the Fixed Services from Radio Regulations was made available in 1997. Industry initiatives have started from 1990 to 2000, but the technological aspects blocked the airborne platform evolution. Particularly, HIBS has the potential of providing connection to the use many cases, such as health emergencies, rural areas, natural disasters and drone operations, as properly elucidated in our previous publication [99]. As a consequence, the HIBS-based mobile network can complement terrestrial IMT services, by covering remote and unconnected areas. The COVID-19 pandemic has demonstrated the major Internet inequalities among countries, proving more then never the need for increasing connectivity and guarantee digital inclusion in poor regions [99], [100].

Non-terrestrial solutions are focused on global attendance. In this context, low Earth orbit (LEO) satellites and HIBS represent potential options for overcoming coverage flaws. Even though LEO satellites have been gaining attention for mobile communication services, due to the aerospace market growth, their user equipment has to be specific. On the other hand, HIBS shares the spectrum already in use by the terrestrial IMT networks worldwide, allowing UE connection using conventional handsets. The HIBS operational altitude in the stratosphere, around 20 km, ensures lower propagation delay compared with the LEO satellites, enabling low-latency applications, such as industrial remote security sensing and control [99], [101].

HIBS is versatile in terms of deployment and supporting the existing network infrastructure. An airborne platform is placed at a quasi-stationary position above the deployment area, typically using a cruise speed of 110km/h. Furthermore, they can be equipped with 4G, 5G, or even future 6G standard technologies, maintaining a reliable connection over a cell coverage from 180 to 200 km. In September of 2020, HAPSMobile has successfully tested a LEO-based HIBS, by means of making a video call between members in the United States of America and Japan. The flight at the stratosphere spent 5 hours and 38 minutes at an altitude of 19.81 km, in which the wind speed reached around 30 m/s and temperature was as low as −73° C [102]. Fig. 5 presents the "Sunglider" camera spot perspective of the long-term evolution (LTE) test flight with the Earth horizon view around 500 km of distance from HIBS Nadir. The LTE payload test has been conducted at Spaceport America, New Mexico (USA), where it was obtained the following experimental licenses from the Federal Communications Commission (FCC): service link at the Band 28 (700 MHz); feeder links at 5.8 GHz and from 70 to 80 GHz; payload control and data collection channel from 902 to 928 MHz and 1200 to 1700 MHz, respectively [103].

FIGURE 5. **"Sunglider" HIBS Platform flying at the stratosphere during an LTE video call communication test between United States and Japan. [Courtesy of HAPSMobile/Loon].**

The three-dimensional (3D) coverage expectation from the future 6G technologies is one of the remarkable and unique capabilities for HIBS. It is also important to highlight that HIBS is a sustainable solution, due to the carbon neutrality, the low impact on the environment and no use of any kind of fossil fuel. Such unmanned platform uses solar panels to generate energy during the day and uses batteries power during the night flight. The IMT-2030 technical requirements, aiming for future technologies as 6G, have been continuing discussed in International Telecommunication Union (ITU) Working Party 5D (WP 5D) in the document named as "*IMT-2030 to assess the trends of IMT for 2030 and beyond*" [99], [101], [102].

In 2014, Google and Facebook have launched HAPS initiatives trying to provide global connectivity. In 2019, HAPSMobile and Loon started an alliance and in February of 2020, a group of aerospace and telecommunications companies joined efforts to create HAPS Alliance, to promote HIBS connectivity around the globe. Since then, HAPS Alliance has been promoting the technology and some trials and flight tests have been conducted. Fig. 6 presents the Sunglider airborne platform in HAPSMobile facility [102], in which solar panels cover the top of the HIBS fuselage.

FIGURE 6. "Sunglider" HIBS Platform at HAPSMobile facility [Courtesy of HAPSMobile].

According to the ITU Radio Regulations from the Article No. 5.388A, HIBS may use the following frequency bands; from 1,885 to 1,980 MHz, from 2,010 to 2,025 MHz and 2,110 to 2,170 MHz in ITU Regions 1 and 3; the 1,885 to 1,980 MHz and 2,110 to 2,160 MHz bands in Region 2. The ITU Agenda Item 1.4, for the World Radiocommunications Conference 2023, addresses the discussions on the HIBS technical and operational features, including sharing and compatibility studies with other services in the frequency bands lower than 2.7 GHz, identified for IMT.

The IMT terrestrial evolves to new requirements and uses cases, due to the final user demand applications. HIBS is a part of the IMT system, as the non-terrestrial solution is categorized as unmanned aerial vehicles (UAV) equipped with Base Stations, which was standardized by the 3GPP Release 17 [99], [101], [102], [104], [105]. In this context, looking forward to the future 6G technologies, HIBS could be considered potential to provide the Global spectrum usability for attending remote areas and complementing future 6G terrestrial networks in order to reduce the digital divide.

Our research group has recently published a paper entitled "High- Altitude Platform Stations as IMT Base Stations: Connectivity from the Stratosphere" [99], in which we have explained into details the HIBS current scenario, use cases, regulatory aspects and sharing studies. Furthermore, we have presented a coexistence analysis between HIBS and Fixed Services at adjacent channels to support decisions to be made at the World Radiocommunication Conference 2023 (WRC-23). In [105], authors have presented the HIBS concept, spectrum aspects and initiatives in 3GPP. Furthermore, the challenges associated with super macro base station constellations using HAPS are discussed in [101]. Complementary, Dong Zhou *et.al.* presented an overview of the HIBS regulatory aspects and challenges from the International Telecommunication Union - Radiocommunication Sector (ITU-R) community and Study Groups [104]. Finally, Global System for Mobile Communications Association (GSMA) has released a report on HIBS in 2022 on its use cases, benefits, and opportunities, implementation scenarios, market analysis, regulation and spectrum standard, comprising aviation regulation and business model scenarios [106].

IV. OPTICAL AND WIRELESS TECHNOLOGY TRENDS

The RAN architecture has evolved over the years to support mobile communications networks demands, which include the recent 5G networks standardization efforts as well as early discussions regarding 6G and its requirements, as mentioned in Section II. The RAN evolution points out to the convergence between fiber and radio system interfaces, as depicted in Fig. 7, a configuration known as fiber-wireless (FiWi) systems [23]. Important trends also include heterogeneous networks (HetNets) [107] and C-RAN [108] architectures. In addition, optical wireless communications (OWC) systems, which are based on FSO [109], have emerged as a promising candidates for the next RAN generation, providing a bandwidth of the order of GHz, to work in combination with the other technologies mentioned above. Among the variations of OWC, VLC, and infrared communications, in particular, beam-steered infrared light communication (BS-ILC) stand out [109].

The C-RAN deployment is very important for optical/wireless convergence. In distributed radio access networks (D-RANs), BBU and RRU are physically located at BS, increasing the management effort and operational costs in a scenario with a large number of small cells. On the other hand, the C-RAN architecture allows the use of simplified RRU at the antenna location, by means of moving BBUs to a CO and, consequently, centralizing their baseband processing, which gives rise to the concept of BBU pool [108].

A centralized network brings notable benefits, including infrastructure reuse, operational and management simplification, multiple technologies coexistence and lower energy consumption, as well as lower capital expense (CAPEX) and operating expense (OPEX) [107], [108]. In addition, the C-RAN architectures also take benefits of innovative technologies such as software-defined networking (SDN) [110] and network function virtualization (NFV) [111]. SDN enables the physical/link layer functional splitting, such as the separation of control and data planes at higher layers, supporting advanced management techniques. The application plane is based on network monitoring and security, which is directly connected to the control plane. The latter consists of SDN controllers, e.g., Open Network Operating System [112] and OpenDayLight [113], responsible for managing network devices positioned in the data plane. The OpenFlow protocol has been widely adopted to achieve the interconnection between control and data planes [114].

In addition, the NFV approach provides flexibility and scalability, by sharing network resources in a dynamic way [115]. These functionalities allow the deployment of network functions as specialized devices or virtualized as virtual network functions (VNFs) [116]. The optimal split can be dynamically achieved by software-based orchestration

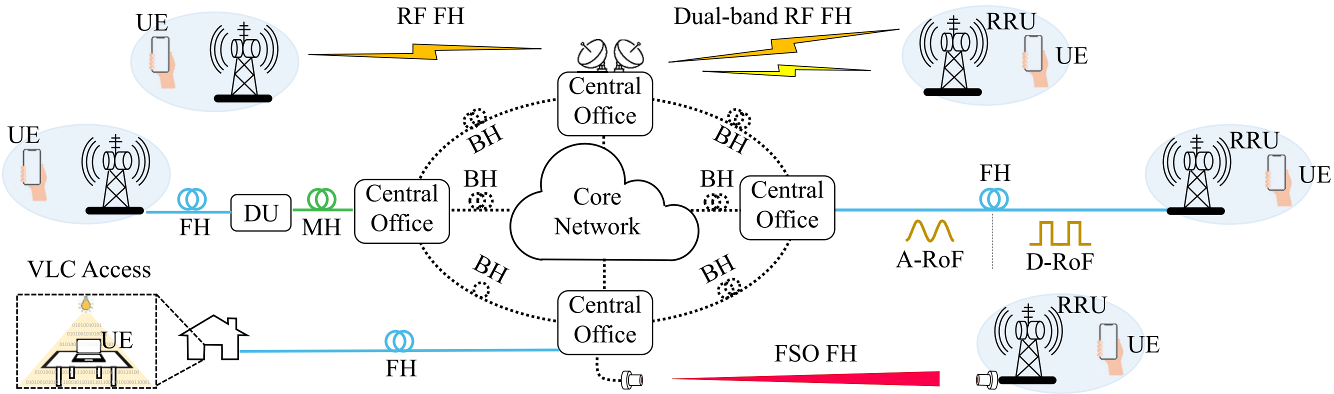

FIGURE 7. Diagram of a fiber-wireless system: RF- radio-frequency; MH- midhaul; BH- backhaul; FH- fronthaul; A-RoF- analog radio over fiber; D-RoF- digital radio over fiber; DU- distribution unit.

and control, based on the service requirements and failures. Therefore, the optimal physical/link layer functional splitting can be achieved depending on the vertical application, for instance, low latency, reliability, or high throughput [117]. Overall, an optimal combination of network function virtualization (NFV), SDN and C-RAN is fundamental for integrating optical and wireless systems in a flexible and reliable mobile network [118]. In this context, landmark C-RAN solutions have been developed over the years, such as: Soft-RAN [119], SoftAir [120], FluidNet [121], FlexCRAN [122] and O-RAN [123].

The remaining of this Section encompasses the main optical-wireless technology trends based on the C-RAN concept. We describe challenges and potential solutions, discussing FiWi system implementations, incorporating technologies based on FSO and VLC. In addition, we also discuss PoF and integrated optics applications.

A. FiWi–Fiber/WIRELESS SYSTEMS

FiWi systems play an important role in the current and future mobile communication networks, since they can be used to support a wide range of applications and services. Indeed, a full integration of 5G enabling technologies with FiWi systems is expected [24], [28]. Fig. 7 illustrates a fiber/wireless system within the C-RAN framework, in which the FH link can be implemented using a series of distinct technologies: radio link, radio-over-fiber (RoF), free-space optics (FSO) or even a combination of those. The BH optical link connects multiple COs to the core network and can also connect multiple COs to each other. A DU can be implemented as an extension of the FH link. In this case, a MH link is used to connect CO to the DU.

Table 3 summarizes the state-of-the-art on FiWi systems, addressing diverse applications. All listed works are based on the C-RAN architecture and demonstrate implementations to enable 5G solutions integrated to FiWi systems. Remarkable advances include carrier aggregation for 5G communications; MIMO use for increasing capacity; 5G coexistence with legacy technologies; distribution of 5G signals over passive optical network (PON); and photonics-based signal amplification and FiWi systems fed by a PoF scheme.

An important challenge from FiWi systems is the fiber-radio integration, typically achieved by applying the RoF technology, which is classified in at least two types: digital radio over fiber (D-RoF) and A-RoF [24]. The D-RoF schemes digitize RF signals for launching them into the optical fronthaul using commercial interfaces, such as common public radio interface (CPRI), open base station architecture initiative (OBSAI) and open radio equipment interface (ORI). CPRI-based D-RoF links found commercial success with 4G networks, supporting multiple radio standards and the C-RAN functional split is expected for 5G. Such approaches also bring the advantages of interoperability with diffused small form-factor pluggable (SFP) modules and robustness against dispersion-induced power fading from microwaves and millimeter-waves over fiber [108]. However, the following drawbacks arise from the D-RoF solution when considering the requirements of 5G and 6G: the need of digitization equipment and RF conversion stages at the remote site, even more critical when introducing the mm-waves access that requires complex and expensive hardware remotely; the total data rate that D-RoF links require, which is significantly higher than peak rates achieved on the radio interface and demands a huge fixed bandwidth in the optical fronthaul; the increase on the number of optical transceivers for addressing the data rate [108], [124].

On the other hand, the A-RoF schemes concentrate the most complex radio functions at CO and distribute radio signals at the wireless carrier frequency through the optical fibers. Such methodology has been gradually becoming attractive as the envisaged throughput in the air increases and the industry begins to deploy mm-waves access. The A-RoF advantages include: the capability of transporting RF signals through optical fibers at low processing complexity, i.e. without the need for digitization and RF remote conversion; optical bandwidth and computational power saving, due to the digitization absence; remote site simplification.

TABLE 3. State-of-the-art on FiWi systems.

Ref.	Application	Frequency Range	Throughput
[28]	5G signal distribution over PON	FR1 and FR2	4.4 Gbit/s
[134]	Carrier aggregation for 5G communications	FR2	24 Gbit/s
[135]	5G communications	FR1	21 Gbit/s
[136]	5G communications	FR2	1 Gbit/s
[137]	Beam steered for 5G communications	FR2	8 Gbit/s
[138]	3×3 MIMO	Not Specified	132 Gbit/s
[139]	5G and 4G communications coexistence	FR1	Not Specified
[140]	5G signal distribution over PON	FR1 and FR2	1.4 Gbit/s
[141]	Photonically amplified FiWi for 5G	FR1 and FR2	16 Gbit/s
[142]	Optically-powered FiWi for 5G	FR1	500 Mbit/s

Despite these remarkable advantages, drawbacks might also be listed as follows: the non-direct compatibility with established passive optical networks, since requires A-RoF modules instead of SFPs; susceptibility to nonlinear effects from the electro-optic components; susceptibility to chromatic dispersion [24], [125].

To make D-RoF powerfull for 5G/6G, technical solutions toward a bandwidth-efficient digital fronthaul have been proposed, such as data compression, new functional splits and enhanced CPRI interface design. High capacity (hundreds of Gbit/s) optical transceivers have also been designed to deal with the expected throughput in the optical link [108], [126], [127], [128]. In parallel, techniques to compensate dispersion and combat power fading have been successfully demonstrated to maintain A-RoF attractive for 5G/6G [125], [129]. The possibility of using A-RoF in WDM overlay topologies has also been highlighted as an alternative for integration with PONs [26], [28].

Once there is no standardization for the 5G/6G transport schemes, combinations of D-RoF and A-RoF in a hybrid solution has been proposed as an optimum solution [130]. In this context, hybrid digital-analog transport approaches based on diverse techniques have been developed in the last years, including WDM overlay, polarization division multiplexing [131], subcarrier multiplexing [132], A-RoF signal allocation at the null point of the D-RoF spectrum [133] and non-orthogonal multiplexing [130].

B. FIBER-OPTICS-BASED FRONTHAUL ASSISTED BY MACHINE LEARNING

As indicated in Fig. 7, the FH link might be implemented using distinct technologies, including fiber-optics. In this case, both D-RoF and A-RoF have been considered and extensively discussed in the literature [143]. Although D-RoF presents some scalability issues, it has been widely employed in the FH link [108]. Scalability is an issue in D-RoF because the radio signals are sampled and directly digitalized into baseband data at the Remote Radio Head (RRH) from the cell site. 5G and 6G systems, operating at mm-wave and THz-wave ranges will demand ultra high-speed analog-to-digital conversion (ADC) and digital-to-analog conversion (DAC) components which are not available. To overcome this problem, A-RoF becomes attractive, since it enables higher spectral efficiency and remote radio unit simplification, when compared to D-RoF configurations [24]. In addition, the reduced signal processing in A-RoF results in diminished latency.

Considering an A-RoF-based FH architecture, a seamless signal distribution is achieved by using linearization techniques [28], [144], [145]. Fig. 8 illustrates an A-RoF assisted by linearization techniques. Such techniques are usually based on digital signal processing (DSP) solutions, including digital pre-distortion (DPD) and equalization. More recently, ML techniques have also been considered attractive to implement the DPD and equalizer processing blocks, since they are capable of performing complex computational tasks without excessive computational effort.

The remarkable generalization and representation capability of ML algorithms might be considered a powerful tool to further improve the development of convergent fiber-wireless systems. However, there are a couple of technical challenges to be overcome. Particularly for the fiber-optics based fronthaul assisted by machine learning, one important challenge is related to the need for representative data-set for training neural networks. Researches have pointed out reinforcement learning techniques, which do not demand a previously generated data set, since the reinforcement learning model is trained on the fly [146]. In parallel, recent mobile communication systems have embraced a plurality of new services and applications, which increase the demand for computing processing and storage capabilities. Moreover, quantum computing with machine learning has been recently proposed to increase efficiency, enhance and speed up the system computing capabilities [147]. When considering the ML-based linearization techniques, another important challenge must be considered. Once the response of the devices that compose the A-RoF-based FH varies with time, a non-re-calibrated linearization technique is desirable. Otherwise, it will be necessary re-training the linearization algorithm, which will generate considerable expenses, since the communication system must be turned off for re-training, leaving customers without coverage. To overcome this issue, a ML-based scheme able to generalize possible variations of the A-RoF response was proposed by our research group, enabling a non-recalibrated linearization technique [148].

In this context, Andres Najarro *et.al* have demonstrated a neural network-based approach to compensate the nonlinear distortions in RoF systems. The neural network is employed to compute the RoF system inverse response, which is

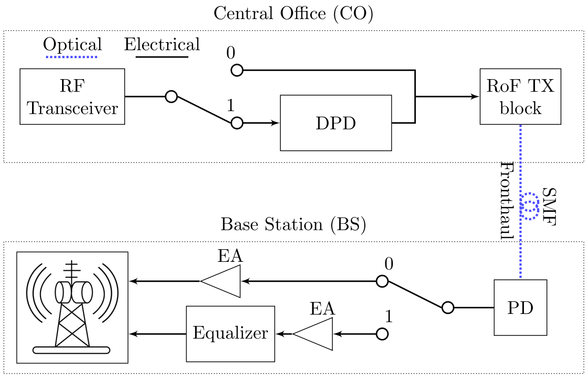

FIGURE 8. Block diagram of an A-RoF assisted by a linearization technique.

then used to compensate the inherent nonlinear degradation. Liu et al. and Liu et al. have employed a neural network as an equalizer [149], [150]. In this case, the neural network processing block is placed at the base station to eliminate the signal nonlinear distortions before the wireless transmission. Indeed, our research group have proposed and implemented DPD and equalizer schemes based on a multi layer perceptron (MLP) neural network [151]. The proposed implementation allows increasing the operating RF power, with no significant distortions, thereby providing more flexibility for telecommunication operators making use of dynamic RF power allocation to the several antenna sites.

C. FSO–FREE SPACE OPTICS

FSO wireless communication systems have attracted increasing interest and undergone strong development in the last decade [152].Some of the key advantages of FSO technology are large bandwidth, immunity to electromagnetic interference, no need for spectrum licensing, and high data rates. These features make FSO highly attractive to meet the increasing traffic demand [153]. However, a FSO transmission requires tight alignment tolerances and it is prone to impairments arising mainly from non-ideal propagation conditions. In other words, a FSO beam is highly vulnerable to weather conditions such as turbulence, rain, fog, haze, and dust, which will attenuate the light beam or even disrupt the entire propagation link [154]. Hence, the FSO system should be thoroughly characterized under severe weather conditions, to assure that the received optical power is higher than the receiver sensitivity, allowing the signal processing.

FSO systems operate in the wireless medium, consequently, alignment losses can be quite common [155], [156]. A precise alignment in an FSO system can be well-achieved when transceivers operate in LOS with no physical obstacles obstructing the optical beam propagation. In a practical FSO system, the primary reason for misalignment is the base motion (building sway) in buildings, especially for FSO systems installed on skyscrapers, which are heavily subjected to sway [155], [157]. To minimize the misalignment loss, an automatic pointing and tracking system can be integrated into the FSO apparatus, in such a way this tracking system consistently adjusts the transceivers for an optimal alignment.

To minimize losses due to adverse weather conditions one of the key methods for determining the FSO proper operation is the link budget. The latter is used to predict how much margin or extra power will be needed in a link under any particular set of operating conditions. The margin is then integrated with a model of atmospheric attenuation to calculate the expected losses from both, scattering and scintillation. Typically, a FSO link budget includes inputs for the transmitted optical power, receive sensitivity, link attenuation, geometric and alignment losses [158].

FSO systems can be used for high data rate communications between two fixed points over distances from hundreds of meters up to a few kilometers. They have initially been proposed as an efficient solution for the "last mile" problem, in order to bridge the gap between the end-user and the fiber optic infrastructure [159]. More recently, FSO systems are also appealing for a wide range of applications such as metropolitan networks, inter-building communication, backhaul for wireless systems, indoor links, fiber backup, service acceleration, security, military purposes and satellite communications [160].

Table 4 summarizes some of the state-of-the-art FSO-based configurations for high transmission capacity links [139], [161], [162], [163], [164], [165], [166]. In [161] the authors combined FSO and FiWi techniques to transmit a 100 MHz bandwidth signal using 64-QAM modulation. Performance is evaluated by exposing the RoF/FSO section to atmospheric turbulence. The authors demonstrated that a 100-meters free-space-optics link span, even under strong turbulence, can still deliver acceptable error vector magnitude (EVM) below 9% with SNR levels of 22 dB. Esmail et al. [162] have experimentally analyzed the effect of dust storms on the performance of an FSO link carrying a RF signal at 28 GHz. The results indicate that the FSO link operating at an optical carrier frequency of about 193 THz is significantly affected by low visibility. In addition, the analysis showed that dust storms condition introduces a flat fading over the frequency range under study, i.e., 21–29 GHz bandwidth. Also, a comparison between the FSO and RF channels under the same dusty conditions was performed. The results showed that the effects of the dust storm are negligible for the RF link which makes it a suitable backup for FSO link in case of severe dust conditions. Finally, a 8 Gbit/s transmission over the RoF/FSO link has been demonstrated for a 40 GHz signal. System penalties have been measured under distinct thermal-induced turbulence distributions along the FSO channel [163].

A heterogeneous RoF/FSO/Wireless non-standalone (NSA) transmission of LTE-A and 5G NR signals in the 2.2 and 3.5 GHz bands, respectively, has been carried out in [139]. The experimental results demonstrated the benefits of employing hybrid analog/digital heterogeneous transmission. The authors have achieved [164] the transmission of high-speed radio signals in the 90 GHz band over a seamless fiber–FSO system in both DL and UL directions, by using the

TABLE 4. State-of-the-art FSO solutions for mobile fronthauls.

Ref.	Architecture	RF frequency [GHz]	DL throughput [Gbit/s]
[161]	FSO/FiWi	24 to 26	10
[162]	FSO/Wireless	28	4
[163]	RoF/FSO	26 to 40	8
[139]	RoF/FSO/Wireless	2.2 to 3.5	Not Specified
[164]	RoF/FSO/Wireless	90	80
[165]	RoF/FSO/Wireless	39	3
[166]	RoF/FSO/Wireless	0.788 3.5 and 26	1.4

intermediate-frequency-over-fiber (IFoF) method. Specifically, a transmitted data rate of approximately 80 Gbit/s over a seamless RoF/FSO/Wireless system in the DL direction has been demonstrated. In addition, the authors established reliable full-duplex transmission of millimeter-wave signals over a hybrid single-mode fiber (SMF) and FSO link for the 5G radio access networks [165]. 3 Gbit/s data rates have been transmitted over a hybrid system, composed of 10 km SMF and 1.2 m FSO link. In particular, our research group has proposed an architecture which relies on a novel and efficient heterogeneous optical-wireless network using RoF, FSO and wireless technologies for 5G and beyond applications [166]. A hybrid fronthaul, which encompasses a 12.5-km RoF link followed by a 1-m FSO link and an 8-m indoor wireless access network, has been implemented. Specific combinations of multi-standard and multi-band optical-wireless network reached throughputs up to 3 Gbit/s and 1.4 Gbit/s based on hybrid RoF/FSO and RoF/FSO/Wireless configurations, respectively.

D. VLC–VISIBLE LIGHT COMMUNICATIONS

Visible light communications based on light emitting diodes (LEDs) have emerged as a cost-effective, energy-efficient and secure wireless access technology to address the demands brought about by the future 6G network [167], [168]. In this technique, the lightning infrastructure can be exploited for simultaneously providing multiple wireless services for offices, aircrafts, homes, and hospitals, as well as vehicular applications such as vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) [109]. The VLC system offers important advantages when compared to the conventional RF systems, such as absence of licensing requirements and immunity to electromagnetic interference, enabling access to areas restricted to RF and frequency reuse. In addition, VLC systems offer a huge amount of available bandwidth (BW) for modulation, enhancing indoor security and privacy [169].

For these reasons, VLC technology represents an attractive alternative to RF wireless communications. A carrier in the visible light wavelength range (380-780 nm) enables a bandwidth of up to one thousand times greater than RF communications [168], allowing high data throughput, in the order of Gbit/s [170], [171]. Also, the use of the non-regulated visible light spectrum allows for a reduced cost for the deployment of the VLC technology.

The literature registers several investigations of LED-based VLC systems for indoor applications. Sifaou et al. [172] numerically demonstrated the benefits of using precoding techniques. They also established the improvement of the signal-to-interference-plus-noise ratio (SINR) in systems with multiple MIMO users, when the receivers are placed at different beam arrival angles. In [173], the authors experimentally demonstrated the joint implementation of WDM and MIMO techniques to transmit modulated data streams in discrete multitone (DTM). Mejia and Georghiades [174] presented an overview of color-shift-keying (CSK), based on red, green and blue (RGB) LEDs, by considering different coding methods, with emphasis on CSK trellis-coded modulation (TCM) and CSK finite-state-machines (FSM) codings, which provided higher SNR. In [175], an experimental work discussed DPD and pre-equalization techniques to mitigate the degrading nonlinear effects of VLC systems.

In the context of VLC systems applied to 5G networks, many investigations are also available in the technical literature [176], [177], [178], [179], [180], [181], [182], [183]. In [176], the authors performed a numerical performance analysis of the asymmetrically clipped DC-biased optical OFDM (ADC-OFDM) waveform in a relay-assisted VLC system employing two radiant sources. The simulation results show that the proposed configuration improves the system performance [176]. In [177], the researchers numerically analyzed the discrete wavelet transform OFDM (DWT-OFDM) waveform performance for the combined use of power line communication (PLC) and VLC technologies. The theoretical and simulation results, as a function of bit error rate (BER), show that the DWT-OFDM outperforms a OFDM-based PLC-VLC system. In [178], a numerical study was carried out to optimize the number of optical attocells accordingly to the number of users and the required throughput. The simulated results showed that an attocell can guarantee the quality of service of up to four users with a large half-power half-angle [178].

Chou and Tsai [179] implemented and experimentally analyzed a micro-projection enabling short-range communication (SRC) system for a personal communication device in a 5G application using LEDs with a micro liquid crystal display. 4-PAM, 8-PSK and 16-QAM waveforms were transmitted and a maximum throughput of 892 Mbit/s was reached for a distance of 0,65 meters between transmitter and receiver [179]. Shi et al. [180] experimentally demonstrated the implementation of the 5G NR standard in a VLC system. The transmission of QPSK modulated signals was carried out, and a maximum throughput of 14.4 Mbit/s was achieved for a distance of 0.55 m [180]. Valluri et al. [181] experimentally demonstrated the reduction of the peak average power of the DC-biased optical OFDM (DCO-OFDM) waveform,

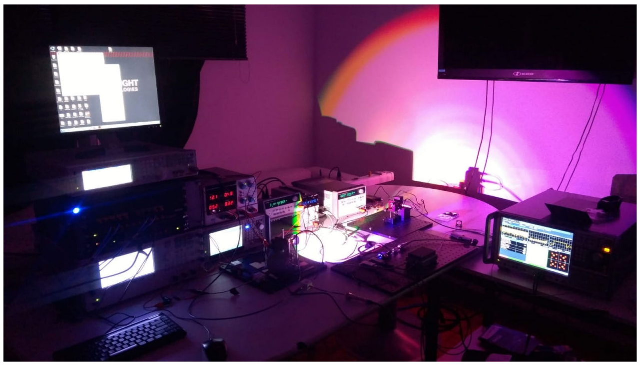

FIGURE 9. Photograph of the visible light communication setup for experiments.

by means of a channel estimation algorithm. The experimental results indicated a significant reduction in peak-to-average power ratio (PAPR) without affecting the real-time channel response [181]. Monteiro et al. [182] carried out a experimental performance analysis of the orthogonal frequency division multiplexing (OFDM), generalized frequency division multiplexing (GFDM) and filter bank multi-carrier (FBMC). The results suggested that the GFDM provides improved performance for the analyzed system, reaching a throughput of 9.94 Mbit/s for a distance of 2 m [182].

Our research group has also contributed to the advancement of the VLC technology. For instance, in [183], we developed an RGB-based VLC system using the 5G NR standard. In this proposition, a four LEDs array with the red, green, blue and amber (RGBA) colors was used in order to enable WDM transmission while still generating white light for environment illumination. During the experiments, we decided not to use the amber wavelength, due to its low optical output power. Yet, it was possible to transmit signals at 872 Mbit/s. Transmission is based on the VLC technique, operating simultaneously in three remaining RGB colors. Additionally, M-QAM signals were also transmitted, making use of the DPD in order to increase the data throughput, which reached 1.92 Gbit/s. Fig. 9 depicts a photograph of the experimental setup implemented in our laboratory [183].

Although VLC systems present remarkable advantages in comparison to traditional wireless links, there are several implementation hurdles that must be overcome to enable a commercial VLC system with all the required features. One of the challenges refers to throughput enhancement since there is a huge bandwidth available in the visible light spectrum and the commercial LEDs 3-dB bandwidth is limited, reaching only a few MHz [184], [185]. For this reason, several techniques have been proposed to overcome the LED bandwidth limitation. A simple and low-cost approach is to place a blue optical filter at the received for enhancing the 3-dB bandwidth, however, throughput remains low in contrast with the available bandwidth [186]. Laser diodes have also been employed as a VLC transmitter, enabling higher bandwidths. For instance, Wei et al. reported a 6.9 Gbit/s VLC system with functional transmission distance based on white-light phosphor laser [187]. In addition, as reported in some of the previously highlighted works, techniques to linearize and compensate the LED response over the frequency can be used, applying pre-distorter or equalizer, and also MIMO techniques, to enhance the total throughput [172], [173], [175], [183].

Other VLC systems challenges are concerning the uplink. VLC links in an indoor environment focus on the use of white LED broadcasting characteristics to enable lighting and communication, typically downlink. Accordingly, there is a need to establish an uplink, in order to create a bidirectional communication [188]. The deployment of an uplink connection using VLC is not an alternative, since the connected devices might have multiple LEDs pointing in random directions, which increases cost and can cause discomfort to the user eyes [189]. In this context, a hybrid solution must be used in bidirectional VLC links. Thus, the VLC provides a high throughput downlink, whereas RF [190], [191], [192], [193] or infrared [194], [195] communication enables the uplink, combining the advantages of each technology.

E. IMWP–INTEGRATED MICROWAVE PHOTONICS

Integrated microwave photonics (IMWP) [196] can support widespread applications in the fields of radar, broadband wireless access networks, optical processing, as well as in emerging areas such as FiWi convergence, Terahertz systems for medical imaging, personal area networks (wireless-body), among others [141], [197], [198], [199], [200]. Although part of this potential can be unleashed by conventional microwave photonics (MWP) [201], [202], several applications are limited by its high cost and complexity, which establishes typical ranges of size, weight and power (SWaP), of the order of 0.04 – 0.2 m^2, 1.5 – 10 kg, and 15 – 20 W, respectively [112]. Such values are detrimental for practical applications and unfeasible for large-scale production. Thus, approaches based on integrated optics have emerged, aiming to reduce research, development, and prototyping costs, as well as the photonic integrated circuits (PICs) processing time, by more than an order of magnitude [196], [203], [204], [205].

A major challenge in microwave photonics implies reducing SWaP characteristics of its devices, subsystems and systems. However, all-in-one platform integration is also challenging for this technology. Integrated photonics has the potential to change the scaling laws of high-bandwidth systems through proper architectural choices, which combine photonics with electronics to optimize performance, power, footprint, and cost. Drastic space and weight reductions are immediate gains from integration [206], [207]. This technology is transformative as it enables the integration of complete sets of microwave and optical components, such as light sources, analog and digital signal processing circuits, light detectors, optical control circuits, and others RF circuits, all-in-one platform to achieve high-performance and low-cost mixed signal optical links. In addition, integrated photonics offers much more than a reduction in footprint and complexity. For example, confining light in the small mode volume enhances its interaction with matter, most of the time through nonlinear optical processes, which resulted in new technological tools for IMWP, such as Kerr microresonator combs, hybrid organic–plasmonic modulators and on–chip stimulated Brioullin scattering (SBS) [197].

Generally, such integration technologies are composed of highly standardized photonic integration processes which allow the implementation of a range of application-specific photonic integrated circuits (ASPICs) from a small set of basic building blocks (BBB) [203]. Then, it becomes possible to support a number of different applications, reducing the PICs development cost and achieving improved performance and reliability [208]. Also, several different designs can be combined on the same wafer, the so-called multi-project wafer (MPW), also reducing manufacturing costs, as they will be divided among different users [203], [208].

Technologies and integration platforms available for IMWP can be classified into monolithic, heterogeneous, and hybrid [196]. Monolithic approaches require either a single material system or a single-chip implementation. Heterogeneous integration can be accomplished by combining two or more materials technologies into a single PIC. Meanwhile, hybrid integration is a process which employs two or more PICs, generally from different materials technologies, into a single package [209], [210]. Typical components manufactured in integrated optics include lasers, modulators, photodetectors, optical amplifiers and filters, as well as passive components such as couplers, splitters, and delay lines. It is worth mentioning that the performance characteristics of each integrated component vary accordingly to the technological platform used. Among the various available integration platforms, the five most common are those based on indium phosphide (InP), Silicon Photonics (SiPh), Silicon Nitride (Si_3N_4), Lithium Niobate ($LiNbO_3$) and polymers [196], [209], [211]. Fig. 10 illustrates typical integrated components within the PIC platform.

InP platforms enable the high-bandwidth lasers, modulators, photodiodes, and optical amplifiers, offering a pathway to optoelectronic monolithic integration and good reliability [212], [213]. SiPh leverages existing complementary metal–oxide–semiconductor (CMOS) process technology, thereby offering a more cost-effective implementation and a more compact footprint [214], [215]. The Si_3N_4 platform provides very low propagation losses, low fiber coupling loss, enabling filtering and beam shaping applications, at a potentially low cost [216], [217]. $LiNbO_3$ technology provides a strong E/O effect and relatively low loss, making it suitable for wide-bandwidth modulators, by taking advantage of a well-established technology base [218], [219]. Regarding the electro-optic (EO) polymer technology, it offers intrinsic advantages such as a large EO coefficients, low dielectric constant and loss, as well as excellent compatibility with other material systems [220], [221]. In recent years, transmitter

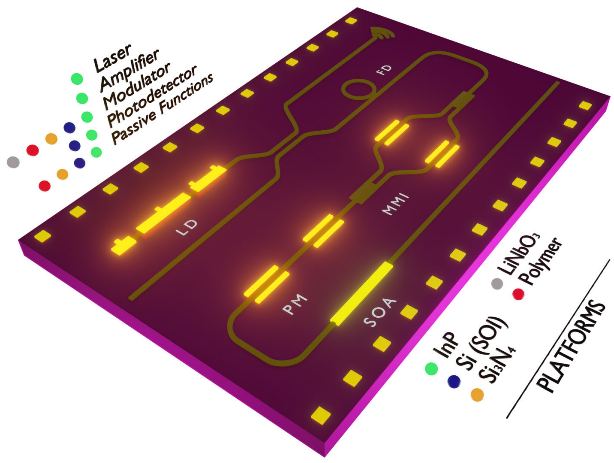

FIGURE 10. Integrated components within the photonic integrated circuits platform.

and receiver modules using IMWP are being presented in the literature as show in [222] and [223].

The development of photonic transmitters based on wavelength-tunable lasers arrays is an example of integrated optics research which has been addressed in the literature because it is a required building block for many microwave photonics applications. The multi-wavelength transmitter (MWT) are considered promising for short-distance links in data center networks, mobile backhaul, and access networks [201]. In addition, the MWTs can be employed to feed phased array antennas, allowing beamforming/beam steering capabilities [224].

The MWTs investigations reported in the literature are based either on the directly modulated lasers (DMLs) or externally modulated lasers (EMLs) configurations. Implementations based on EMLs are less compact, more complex and expensive, requiring a larger footprint, due to the use of external modulators. On the other hand, it offers the benefit of low chirp, which is a limiting impairment in systems employing DMLs. In [225], the authors reported a transmitter based on the integration of four widely tunable EMLs on a InP substrate. Each generated beam passes through a semiconductor optical amplifier (SOA) and an external electro-absorption modulator at 10 Gbit/s in baseband operation [225]. Yao et al. [226] demonstrated a six-channel array based on EML using Mach-Zehnder modulators integrated into a InP platform. The baseband non-return to zero (NRZ) optical signals were transmitted at 20 Gbit/s and 30 Gbit/s throughputs. The photodetected signals were analyzed using the eye diagram and BER [226].

In [227], the authors implemented an array of eight InP-based DMLs in the wavelengths around 1550 nm. A 2^{31}-1 NRZ pseudo random binary sequence (PRBS) was transmitted at 10 Gbit/s in the back-to-back (B2B) condition as well as for a baseband-over-fiber (BBoF) link of 2km over SMF [227]. In [228], the authors described an array of four DMLs with a 17 GHz electrical bandwidth, in the wavelength range between 1295 and 1310 nm, for Local Area Network WDM (LAN-WDM) applications. Data transmission tests was performed with the standard 2^{31}-1 NRZ PRBS, at 25 Gbit/s per channel, analyzing the B2B condition and the impact of 30-km propagation in BBoF link from SMF [228]. Andriolli et al. [229] implemented an integrated MWT, manufactured with eight channels with a 12 GHz electrical bandwidth between 1541.4 and 1547.0 nm, in which each laser could be tuned around 4 nm. The experiments demonstrated baseband transmission of 15 Gbit/s over 2.1 km of SMF [229].

It is noticed that the investigations described so far concern the optical transmission of baseband signals. However, the use of multi-wavelength transmitters is also promising for WDM-based RoF and/or FiWi systems [24], [230]. Regarding the 5G networks, MWTs can be useful for fronthaul architectures using the WDM technnique.

In this regard, our research group described in [231], a 4G/5G shared optical fronthaul implementation on the basis of an integrated MWT [229]. The experiments were carried out in two conditions, the first scenario based on WDM, where each RF signal was transmitted on a different optical carrier, and the second scenario based on subcarrier multiplexing (SCM), where the RF signals were combined in the electrical domain and then transmitted by a single laser. Maximum throughput of 1.04 Gbit/s was demonstratd, by means of two signals in the 5G NR standard and one signal in the LTE standard, through a 12.5-km optical link [231]. Next, we reported a FiWi architecture using the integrated MWT [232]. Three RF signals were transmitted in WDM by a 12.5-km long RoF link and radiated through an indoor wireless link within a 10 m range or an outdoor wireless link of about 115 m. A maximum throughput of 1.36 Gbit/s and 230 Mbit/s were experimentally demonstrated, in the 10 m and 115 m scenarios, respectively [232]. Finally, in [233] we reported a RoF/FSO system employing the integrated MWT combined with the use of BS-ILC. In these experiments, an M-QAM signal was transmitted over a 12.5 km RoF link followed by a 1.5 m FSO link. The RoF/FSO combination achieved a maximum bit rate of 160 Mbit/s using a bandwidth of only 20 MHz [233].

F. PoF–POWER-OVER-FIBER

The PoF technology has become an attractive solution to transport electrical power to remote locations. In short, this technology consists of transmitting power by means of an optical fiber, which provides excellent electrical isolation and immunity to RF, magnetic fields, sparks, and interference. Other features include galvanic isolation, weight reduction, and resistance to corrosion, moisture, and extreme temperatures [234], [235], [236]. In this context, PoF may be considered as an attractive alternative to increase safety and reliability of a number of applications by replacing conventional power supplies, metallic cables, and batteries. PoF systems typically employ three main components: a high-power laser diode (HPLD), responsible for generating high optical power; an optical fiber as the light transmission medium; a photovoltaic power converter (PPC), which performs the optical-to-electrical (O/E) conversion [237]. One of the key performance metrics in a PoF system is power transmission efficiency (PTE), defined as the ratio between the HPLD output power and total electrical power delivered by the PPC [238]. As simultaneous data and power transmission has become feasible, delivered power levels have reached over 40 W [239], [240], PoF has been employed to power devices in a wide range of applications, including 5G and future mobile networks.

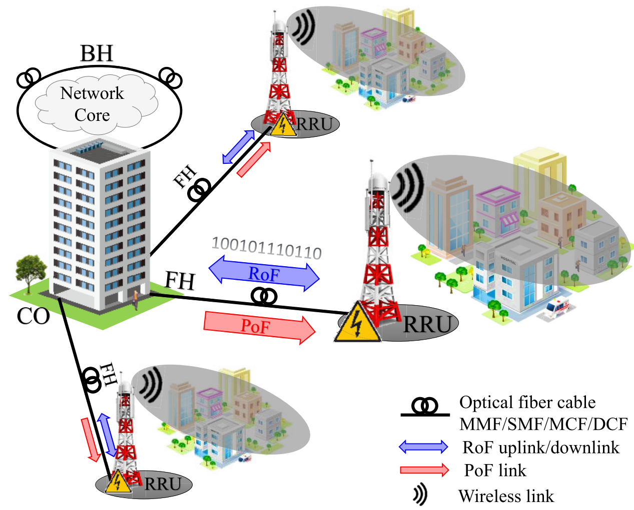

FIGURE 11. Optically-powered FiWi system towards 6G mobile networks (modified from [142]). CO - central office; BH - backhaul; FH - fronthaul; PoF - power-over-fiber; RoF - radio-over-fiber; RRU - remote radio unit.

Cell densification is a promising approach to meet the coverage and capacity requirements of future 6G networks. An effective way to achieve the required desinsification is to reduce the cell size and to increase the number of deployed BSs. However, the BS typically consumes around 60% of the total available power of mobile systems, leading to a substantial rise in power consumption [241]. Consequently, it is crucial to provide solutions to properly supply the required power to BSs, ensuring network operation stability, safety and robustness. In this context, PoF may be considered a potential approach to power BSs in future wireless networks. Fig. 11 depicts an optically powered FiWi system based on the C-RAN architecture and employing PoF and RoF technologies. This implementation consists of a CO from which power and data are simultaneously transmitted through an optical fiber cable, which can be composed of multimode fibers (MMFs), SMFs or multicore fibers (MCFs). Although the PoF technology typically provides lower PTE compared to the conventional power lines, it can still be extremely efficient, thereby contributing to the required significant increase in the number of BSs across 5G and 6G networks [240].

Several architectures employing the PoF technology have been reported in literature regarding mobile fronthaul configurations. Table 5 reports the main performance parameters for the state-of-the-art PoF solutions for mobile fronthauls. In particular, an optically-powered RoF system employing a MCF link has been proposed [242]. A 12-Gbps OFDM signal with intermediate frequency (IF) of 92 GHz was simultaneously transmitted with a 0.8-W optical power beam to feed an UTC-PD and an RF amplifier, aiming at 5G applications. Regarding high-power delivery, Matsuura et al. [238] demonstrated a 150-W optical power transmission over a 300-m double-clad fiber (DCF) link. Four 808-nm HPLDs and 18 PPCs were used for providing 40 W of electrical power, resulting in PTE of approximately 30%. A PoF system capable of delivering roughly 2-W of electrical power over a 100-m MMF link was reported in [243]. A RRH control board was developed and different sleep mode configurations were implemented aiming at efficient 5G C-RAN fronthauls. Al-Zubaidi et al. [244] reported the use of a SMF link for optically powering remote antenna units (RAUs) of 5G systems. Approximately 870 mW was delivered to an optical power meter (OPM). Also, a 5G fronthaul configuration has been deployed in [245]. In this work, 10-W optical power and 1.5-Gbit/s 5G NR signal carrier centered at 3.5 GHz were simultaneously transmitted over a 1-km SMF link. Over 7 W electrical power was delivered to an OPM, resulting in PTE of 25.1%. Lopéz-Cardona et al. [246] reported a PoF-based 5G NR network employing RoF technology and a MCF link. More recently, the simultaneous transmission of a 5G NR signal and 60-W energy light has been reported in [247] employing 1-km of weakly-coupled seven-core fiber (WC-7CF). Over 11.5 W electrical power was delivered in this scheme.

Our research group, WOCA, from National Institute of Telecommunications (Inatel), has implemented an optically-powered 5G NR FiWi system employing PoF and RoF technologies, aiming at high-throughput short-range 5G NR cells [142]. Our approach enabled the simultaneous transmission of a 5G NR signal at 3.5 GHz with bandwidth up to 100 MHz as well as a 2.2-W optical power signal employing dedicated fiber-optics links. The proposed PoF system was able to deliver up to 516 mW electrical power, by means of a 100-m MMF link, in order to optically power a 5G NR RAU. An overall PTE of 23.5% was achieved with this configuration.

One may notice from Table 5 that the main challenge regarding PoF systems is the fiber link reach. In a shared scenario, in which a single optical fiber is used for simultaneous power and data transmission (see Fig. 11), long-distance fronthaul links are not feasible due to the higher attenuation at the shorter wavelengths employed in PoF systems, e.g. 808 nm and 980 nm, which limits the power transmission link to a few kilometers. On the other hand, in a dedicated configuration, data and high-power signals are individually transmitted through dedicated fibers. In this context, a centralized power supply station (CPSS) could be implemented for distributing power to each RRU by means of a dedicated PoF link, as reported in [142], and the PoF link distance

TABLE 5. State-of-the-art PoF solutions for mobile fronthauls.

Ref.	Optical Power [W]	Distance [m]	Electrical Power [W]	PTE [%]
[242]	0.8	-	0.05	6.25
[238]	150	300	43.7	30
[243]	5.4	100	2.343	43.4
[244]	2	100	-	-
[245]	10	1000	2.51	25.1
[246]	1.26	10000	0.133	10.5
[247]	60	1000	11.5	19.2
[142]	2.2	100	0.516	23.5

limitation would not have any impact on the fronthaul link distance.

The PoF system capacity of delivering high power is also critical. As reported in Table 5, the maximum electrical power delivered by a PoF system reported in literature is 43.7 W. However, the typical maximum power consumption of a 5G site is currently higher than 11 kW [248]. Consequently, current PoF systems would not deliver enough power to feed an RRU in 5G sites. On the other hand, PoF systems could be employed to enable low-power small cells. For instance, a commercial femtocell typically consumes up to 24 W [249]. In addition, base stations operating in sleep mode have been proposed, saving up to 60% energy in networks and enabling PoF integration [238]. Nevertheless, PPCs conversion efficiencies are expected to improve as the technology matures, increasing the capacity of power delivery in PoF systems.

V. CONCLUSION

This paper presented a review on wireless and optical convergent access solutions towards 6G systems. The manuscript started with an brief overview on the mobile communication systems evolution trends, focusing on the challenges and the vision for the future 6G RAN. Next, the use cases, requirements and enablers for 6G networks were discussed. It was pointed out that they are still under discussion worldwide, suggesting that THz and sub-THz communications, wireless-optical integration, VLC and new antennas designs can be considered major building blocks for the future wireless systems. The manuscript also presented the main wireless technology trends, which encompassed the channel capacity opportunities and issues, considering the expected high frequencies, including mmWaves and THz communications and last mile solutions such as HIBS technologies. Also, the paper conducts a discussion on the state-of-the-art on antenna design for sub-6 GHz, mmWaves and THz frequency ranges. It was concluded that the literature on beamforming and MIMO applications from literature are usually concerned with the array antenna element (mainly patch, dipole or slot antennas), feeding network or scanning range enhancement. In any case, regardless the application, reducing mutual coupling is an important performance metric. Furthermore, THz antenna design is divided in two main categories: conventional microwave and mmWaves antenna design, re-tuned for higher frequencies and photoconductive antenna design for THz signal generation, by using antennas, photonics and concepts and plasma physics concepts.

Next, the manuscript presented the RAN evolution towards optical and wireless convergence, to support current and future mobile communications networks requirements. In this context, FiWi systems within the C-RAN architecture and fiber-optics-based fronthaul assisted by ML were considered candidates to solve flexibility and scalability issues. In addition, OWC systems, specially FSO and VLC, have emerged as promising candidates for enabling optical-fiber like performance. Also, new approaches in photonic integration have emerged, aiming to reduce research, development, and prototyping costs of MWP devices. Finally, the PoF technology was proposed as a joint solution to transport data and electrical power to remote locations.

All discussed technologies are still ongoing research, which brings many opportunities as future works for researchers worldwide. For example, the manuscript has pointed out that antenna design is continuously evolving towards higher frequencies, up to THz frequency range. This leads to the conclusion that active and integrated circuits, jointly with new materials, should be investigated for covering these unprecedented frequency bands. FiWi systems are limited if employed as D-RoF due to the need for high-speed ADCs and RF conversion in remote sites, whereas A-RoF drawbacks are related to the compatibility issues with established passive optical networks. If a ML-based linearization technique is employed, FiWi systems challenges are related to the need for a representative data set for training a neural network. FSO systems can be unfeasible in case of low alignment precision and stability, whereas VLC systems provide an extremely wide bandwidth in the optical domain, but are limited by the electric bandwidth from the LED components, which is quite narrow. A major challenge in microwave photonics implies reducing the SWaP characteristics of its devices, subsystems and systems. Finally, on joint deployment of PoF and communication links, the main challenge is the fiber spam length. Long-distance fronthaul links are not feasible due to the high attenuation at the shorter wavelengths employed in PoF systems.

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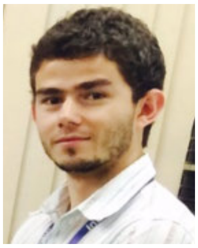

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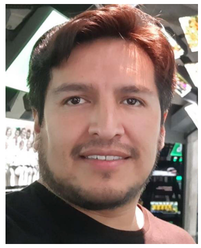

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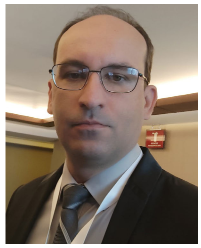

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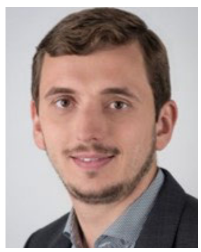

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