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6G TECHNOLOGIES

Key Drivers, Core Requirements, System Architectures, and Enabling Technologies

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The key drivers of 6G result not only from the challenges and performance limits that 5G presents but also from the technology-driven paradigm shift and the continuous evolution of wireless networks. Intelligent driving and industry revolutions create core requirements for 6G that will lead to service classes of ubiquitous mobile ultrabroadband (uMUB), ultrahigh-speed-with-low-latency communications (uHSLLC), and ultrahigh data density (uHDD).

Emerging uMUB, uHSLLC, and uHDD services require an end-to-end codesign of communication, sensing, and

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computing, and they inspire the convergence of photonics and artificial intelligence (AI), resulting in two candidates for 6G-enabling technologies: computational holographic radio and photonics-based cognitive radio. Two candidates for 6G system architectures emerge: 1) the multipurpose, converged, full-spectral, and all-photonic radio access network (RAN) and 2) the 100-Gb/s, hyperspectral, space-terrestrial integrated network with laser-millimeter wave (mm-wave) convergence.

Research Activities of 6G and Article Overview

Although 5G will be deployed commercially at the end of 2019, 6G research is under way in several countries and organizations. In July 2018, the International Telecommunication Union established the Network 2030 focus group aimed at exploring the development of system technologies for 2030 and beyond. Network 2030's concepts of 6G include new holographic media, services, network architecture, and Internet Protocol (IP) [1].

The University of Oulu, Finland, operates a groundbreaking 6G research project as part of the Academy of Finland's flagship program, 6G-Enabled Wireless Smart Society and Ecosystem (6Genesis) [2], which focuses on the study of wireless technology and explores the development of the 6G standard. The 6Genesis initiative was the first to focus on 6G investigation. Its research cluster combines several challenging areas, including reliable, near-instant, unlimited wireless connectivity; distributed computing and intelligence; and materials and antennas to be utilized for future circuits and devices [2].

Other 6G research has covered vision, requirements, and system architectures [3], [4]. In our previous work, we described the most comprehensive 6G system concept and proposed a photonics-defined 6G mobile system architecture as well as a next-generation, fully coherent CloudRAN [4]. In this article, derived from the challenges and performance limits of 5G, technology trends, and network evolution, we offer three 6G use cases. To realize them, we bring forward two technologies: computational holographic radio and photonics-based cognitive radio. In addition, we suggest two candidates for 6G system architectures, analyze the key drivers of 6G mobile communication, arrange 6G's basic prerequisites and provide illustrations, and discuss system designs and technologies.

Key Drivers

5G Limitations

In many aspects, 5G faces challenges. Although the 5G cellular system supports ultrareliable, low-latency communications (URLLC), it has the drawback of short-packet, sensing-based URLLC functions that limit the delivery of high-reliability, low-latency services with high data rates, such as augmented reality (AR), mixed reality (MR), and virtual reality (VR). Emerging Internet of Everything applications will require a convergence of communication, sensing, control, and computing functionalities, which has been largely overlooked in 5G.

According to Rethink Technology Research's recent survey of 74 mobile operators, the obstacles to commercial deployment of superior technologies include the uncertainty of the virtual network function's pricing and management, the cost of new investment in RAN physical equipment, lack of confidence in the robustness of the platform, and so forth. The deployment of virtualization RAN (vRAN) is much slower than that of other network elements, more so than many industry observers predicted a few years ago. The biggest obstacles to large-scale vRAN installation have been vendor hostility and the fronthaul issue. From 4G, operators have attempted to build an open interface between the baseband unit and remote radio unit, but the transition from the common public radio interface to the evolved common public radio interface seems to fall far from this goal [5]. The demands of low latency with high data rates, communication and sensing convergence, and open interfaces require the novel network architecture of 6G.

Photonic Technology and AI

With the slowdown of Moore's law (which is expected to expire between 2021 and 2025), it becomes increasingly difficult to reduce chip linewidths. The current solution is to use optical signal processing (photonic chip and photonic computing) and AI, which will produce new opportunities for the development of novel wireless technology.

Through the European Union's Heterogeneous Advancement and hybrid integration of polymer and tripLEx platform for Integrated Microwave PhoTonics (HAMLET) project (directed by the Institute of Communications and Computer Systems at the National Technical University of Athens, Greece, with partners LioniX, Enschede, The Netherlands; Solmates, Enschede; SATRAX, Enschede; Linkra, Cornate d'Adda, Italy; and the Fraunhofer Heinrich Hertz Institute, Berlin, Germany), an international consortium of companies and research institutes works to develop a transceiver for future mobile networks in the frequency band of 28 GHz [6]. To meet the technical challenges of 6G's higher subterahertz frequency and full-spectral convergence, photonics and photonics-integration technology will stand out through their commercial potential. The convergence of integrated coherent optics, integrated microwave photonics, and photonic digital signal processing (DSP) resulted in the concept of photonics-defined radio, which is a new and possibly standardized paradigm that is expected to dominate the designs of future communication and sensing systems [4].

Recent advances make it possible to apply machine learning (ML) to radio-frequency (RF) signal processing, spectrum mining, and RF spectrum mapping [7].

EMERGING INTERNET OF EVERYTHING APPLICATIONS WILL REQUIRE A CONVERGENCE OF COMMUNICATION, SENSING, CONTROL, AND COMPUTING FUNCTIONALITIES.

Because AI can greatly help with precision capacity forecasts, coverage auto-optimization, network resource scheduling, and slicing, operators are using it and ML to boost network performance and cut costs in deploying 5G networks. AI offers the best opportunity to achieve the high levels of automation necessary to optimize and manage the complexity of 5G system performance, allowing providers to shift from managing networks to managing services.

Although AI cannot provide better performance to the physical layer in developing 6G technologies, it brings agility and flexibility to the air interface, with improved efficiency. Unfortunately, due to the limited bandwidth and low flexibility of the hardware platform, traditional AI-based cognitive radio faces a huge gap between flexible, effective building modules and mobile network deployment. Combining photonics-defined radio with ML will be a key evolution of AI in 6G [4]. Extreme broadband, photonics-defined radio can generate a large amount of data from spectrum sensing and provide significant and quality data about the RF spectrum, so that ML can effectively train and learn a large parameter space. Neuromorphic photonic concepts have been implemented for RF fingerprinting of complex and crowded environments in cognitive radio applications. Applying operations at the front end of RF transceivers could offload complex signal processing operations to a photonic chip and address the bandwidth and latency limitations

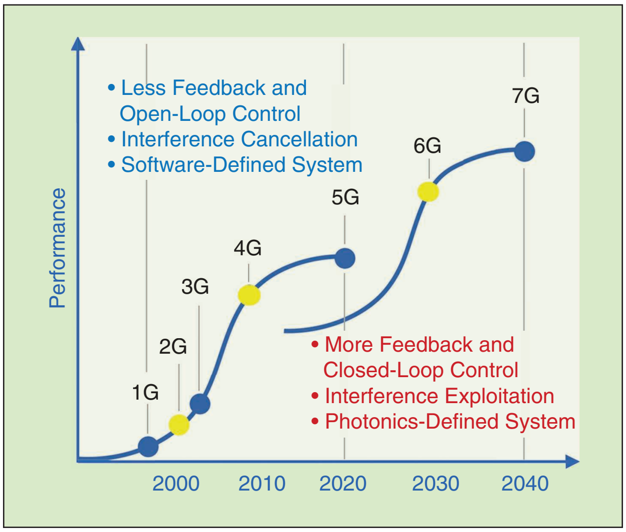

FIGURE 1 The hyper-S curve of the mobile-communication technology revolution and paradigm shift.

of current DSP solutions [8]. By combining AI and photonics technology, low-latency, high-reliability, scalable AI can be achieved in 6G infrastructures.

6G Needs a New Paradigm

Today's 5G follows the technological path of previous mobile communication systems and is an extension of 4G, which results in it hitting a performance wall. Any improvements are expected to be marginal. The traditional abstraction of channel states using simplified modeling and less feedback, especially at higher carrier frequencies, is not sufficient because oversimplified models often have no capability to emulate unknown channels. A paradigm shift will be necessary for the closed-loop feedback on exactly emulating channels.

Dense networks with smaller cell sizes and more antennas, such as massive multiple-input, multiple-output (MIMO), produce a commensurate increase in intercell and intracell interference. Although the employment of massive MIMO in 5G enables the cancelation of interference using simple linear operations, the beamforming design typically strikes a tradeoff between eliminating the intercell interference and maximizing the signal-to-interference-plus-noise ratio. Traditional interference-cancellation techniques are no longer optimal, and innovative ways of utilizing interference are emerging. Because more aggressive resource sharing and tighter cooperation are foreseen in future wireless networks, interference management will be a growing challenge [9]. It is essential to further these perspectives so that we can achieve more efficient radio resource utilization in advanced wireless concepts, such as interference exploitation, where the scope exists to exploit intracell and intercell interference as a source of useful signals and improve system performance. Interference exploitation produces gains through large-scale cooperation between distributed wireless network transceivers and by enabling high spatial-multiplexing gain via multiuser transmissions.

The next generation of 6G systems will have higher carrier frequencies for smaller antennas and broadened bandwidth for increased resolution. A significant challenge for future radio systems will be to instantaneously analyze and process RF signals over an extremely broad bandwidth of 100 GHz or more in real time and without any prior knowledge of the signals, carrier frequency, and modulation format [10]. A photonics-defined system provides extreme bandwidth and full-spectrum capacity, so it would be an ideal platform for future 6G radio. In contrast to traditional microwave photonics, the new photonics-defined system is an extension of microwave photonics through the introduction of digital photonics (photonic DSP and optical computing), photonic analog-to-digital/digital-to-analog conversion (ADC/DAC), and coherent optics.

Figure 1 shows the hyper-S curve of the mobile communication technology revolution and paradigm shift.

Interference cancelation, software-defined systems, reduced feedback, and open-loop control have formed the paradigm of system designs, including 5G. Over time, performance suffers between the system's acceleration phase and its saturation and technological limit. For 6G, there may be a sharp change in the technology—a radical innovation—resulting in a new S-curve, which would mean a new paradigm built on full closed-loop control, interference exploitation, and a photonics-defined system.

FOR 6G, THERE MAY BE A SHARP CHANGE IN THE TECHNOLOGY—A RADICAL INNOVATION—RESULTING IN A NEW S-CURVE, WHICH WOULD MEAN A NEW PARADIGM BUILT ON FULL CLOSED-LOOP CONTROL, INTERFERENCE EXPLOITATION, AND A PHOTONICS-DEFINED SYSTEM.

Mobile Network Evolution

Every successful evolution of mobile network capability has been redefined in terms of fundamental technology, system architecture, and mobile terminal (MT) types. For example, dumb MTs, digital radio technology, and circuit-switching networks in 2G were redefined as smartphones, software radio technology, and IP CloudRAN in 4G. If 6G is to succeed, it must be redefined in the same way. The 6G MT type will no longer be the smartphone, the fundamental technology will no longer be software-defined radio, and the network architecture will be an upgrade of CloudRAN. Figure 2 shows the possible evolution paths. Generally speaking, MT types correspond to killer applications, such as dumb handsets for 2G voice service and smartphones for 4G/5G Internet access. Smart driving and smart industry will be the singular 6G services, corresponding to smart vehicles and smart mobile robots, which are discussed in the next section.

As previously mentioned, 6G's higher subterahertz frequency and full-spectral convergence will spur a photonics-based system to optimize and simplify the extreme-bandwidth design. As a fundamental technology, a photonics-defined radio system is the natural evolution to 6G; here, a photonic RF front end, photonic ADC/DAC, and photonic DSP optimally perform various radio functions [4]. Currently, 5G incorporates distributed base station architecture with central unit (CU), distributed unit (DU), and arrayed antenna unit (AAU) splits. An unprecedented penetration of AI into wireless communication is driving the intelligent evolution of RAN nodes, resulting in a 6G system architecture based on distributed computing and intelligence.

Mobile communication, including 5G, faces challenges that must be considered during the evolution of 6G. The technology-driven paradigm shift and network evolution provide hints about and a starting place for the design of 6G networks. Figure 3 shows, according to our analysis, 6G's logical beginning, which could produce several key technical requirements, as shown in Figure 4, namely, AI, photonic technology, and RF holography.

Core Requirements and 6G Scenarios

With 5G not yet commercially deployed and still lacking killer applications, it seems a bit out of place to talk about 6G requirements. The history of the industrial and information revolutions shows that the expansion of fundamental needs is often brought about by a technological revolution and that the possibility of technology determines the scope of human requirements. Apple's revolutionary smartphone boosted the demand for and development of the mobile Internet and promoted the 4G network's success. The requirements for 6G will follow upcoming technological trends, such as smart cars and smart manufacturing.

On the roads and in industry, a ubiquitous network of intelligent vehicles and robots will require not only an

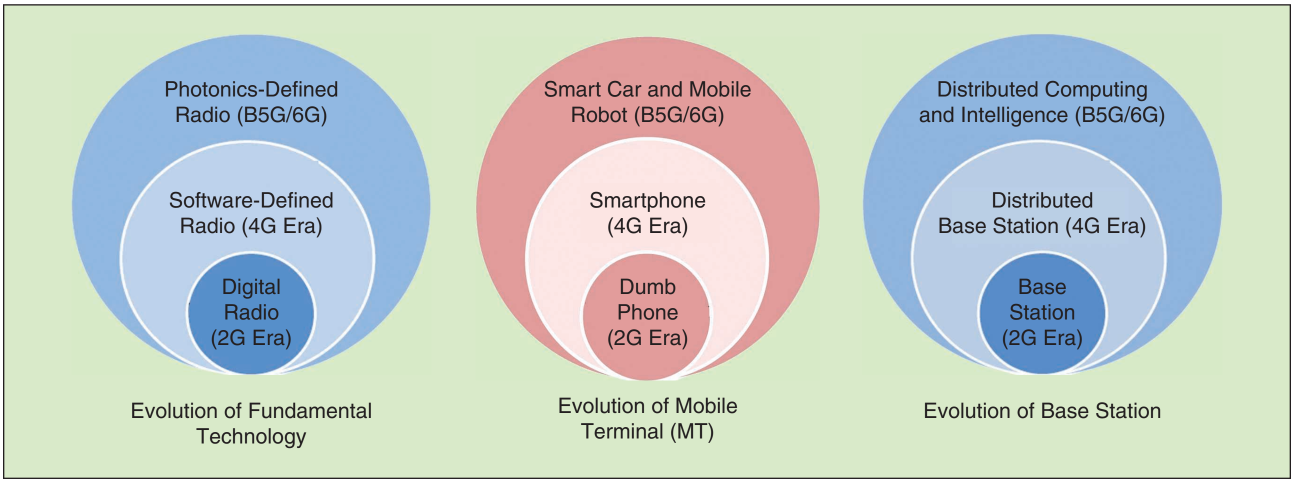

FIGURE 2 The possible evolution paths of MT types, fundamental technologies, and system architectures of 6G. B5G: beyond 5G.

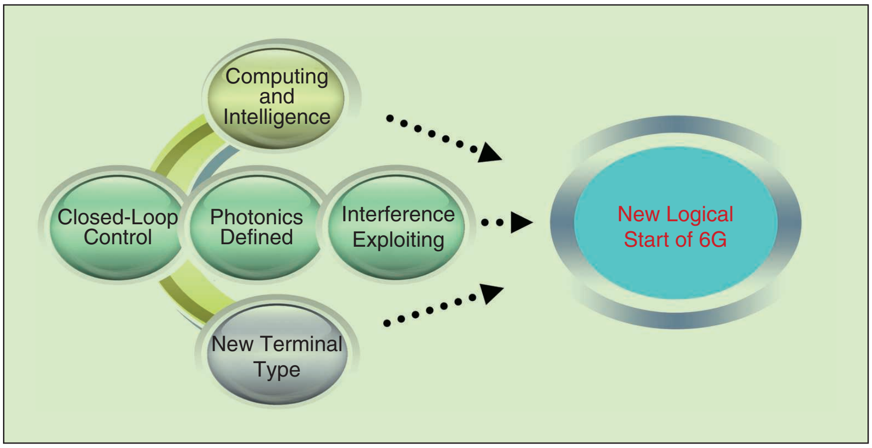

FIGURE 3 The new logical start of 6G.

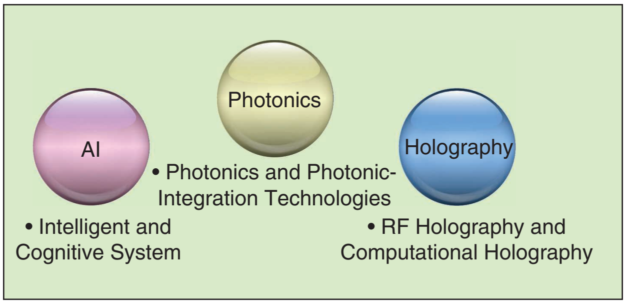

FIGURE 4 The three key technologies of 6G.

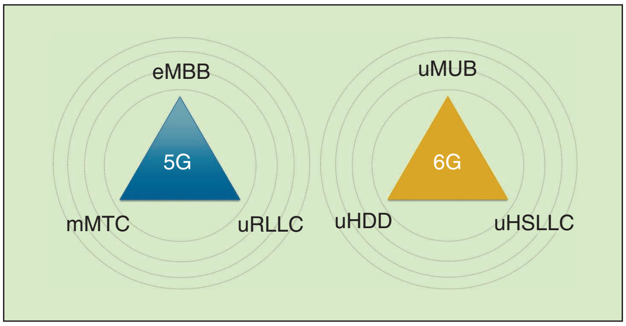

FIGURE 5 Comparisons of key requirements for 5G and 6G.

ultrabroadband mobile network but also an ultrahigh-rate wireless bus with excellent reliability and ultralow latency, providing new types of mobile-as-a-service and mobile-as-manufacturing applications. As smart hyperMTs and computing nodes, intelligent vehicles will need high-rate, bus-like wireless links and a convergence of radar/lidar communication and sensing to achieve precise beam control and 3D scene interaction. As mobile life and work spaces, smart vehicles will require all-weather, ultrabroadband, real-time services, such as 8K/4K video, AR/VR cloud gaming, and 3D holographic video. In the 6G network, the peak data transmission rate will be 100 Gb/s–1 terabyte/s and the latency will be 1–10 μs. To accommodate planes, ships, and trains, space and terrestrial networks will need to be interconnected and integrated, which will result in uMUB.

In the future, intelligent factories will consist of dense concentrations of intelligent mobile robots that require wireless access to high-performance computing resources. This will form a distributed intelligent network that has terabytes of computing capacity. The robots will need to react quickly to changing conditions, including interactions with humans, and run in time-critical control loops [11]. They will demand tremendous computing capacity to process data amounting to tens of teraflops, and their connection network will be similar to a supercomputer's parallel bus. This huge wireless capacity will require uHDD, roughly 100 Gb/s/m^2, and ultralow latency of fewer than 10 μs. These applications will exceed the original 5G goal of supporting short-packet, sensing-based URLLC services, and there is no technology to meet their stringent requirements. Only terahertz wireless and optical wireless are considered viable candidates because they can provide the large bandwidth to achieve the required data density. Therefore, other 6G prerequisites and use-case scenarios include uHDD and uHSLLC.

The wireless data center network (WDCN) is emerging due to its low cost, reduced complexity, high space utilization, configurability, and flexibility. WDCNs deliver higher throughputs and data density, and they enhance fault tolerance, latency, and reliability. WDCNs are also 6G uHDD networks, implying that mm-wave, terahertz, and optical wireless communications are potential candidates.

Figure 5 compares the 5G and 6G core requirements and case scenarios. Enhanced mobile broadband (eMBB), URLLCs, and massive machine-type communication (mMTC) in 5G and 6G will provide service classes of uMUB, uHSLLC, and uHDD. In addition, uMUB enables 6G systems to deliver any required performance within the space-aerial-terrestrial-sea area, uHSLLC provides ultrahigh rates and low latency, and uHDD meets the data density and high-reliability requirements. Emerging uMUB, uHSLLC, and uHDD services will require an end-to-end codesign of communication, control, and computing functionalities, which are largely lacking in 5G.

Stretching these requirements into the far future requires significant trend accretion. A six-F trend set for 6G is proposed as follows:

- *Full spectra*: There will be a hyperspectral and full-spectral system, from microwave, mm-wave, and terahertz to laser (free-space optical communication).
- *Full coverage*: Ubiquitous mobile ultrabroadband will be available everywhere in the terrestrial, aerial, space, and sea domains.

- *Full dimension*: There will be fully coherent holographic radio and communication. The 6G network will be highly precise, requiring accurate operation in RF space, and move from simple averaging toward fine-grained analysis, modulation, and manipulation in the intensity-phase-frequency space.
- *Full convergence*: Communication, control, sensing, computing, and imaging will converge. The 6G network will be a multipurpose system that disrupts 5G's exclusive function of wireless communications. Multipurpose systems can deliver many more killer applications and multiple services.
- *Full photonics*: 6G will be based on photonics-defined radio with a uni-traveling-carrier (UTC) photodetector (PD)-coupled antenna array, photonic engine, and spectrum computing. Full photonic processing will provide an energy efficiency benefit.
- *Full intelligence*: There will be ubiquitous and distributed computing and intelligence from the application layer to the physical layer.

6G System Architectures and Technologies

According to the key drivers and core requirements described in the previous sections, we proposed several candidates for key 6G technologies and system architectures, namely, all-photonic RAN architecture, photonics-based cognitive radio, computational holographic radio technology, and a laser–mm-wave converged, 100-Gb/s hyperspectral space and terrestrial integrated network.

Holographic Radio and Photodiode-Coupled Antenna Arrays

Interference has always been the core concern in terms of satisfying the growing demand for service quality in modern wireless communication systems. Standard methods aim at minimizing, eliminating, and avoiding it. Contrary to the traditional view that unwanted signals are a harmful phenomenon, 6G regards interference as a useful resource for developing energy-efficient and highly precise holographic communication systems. The technology with the most potential and highest level of interference exploitation is entire-space RF holography, or computational holographic radio. Holographic radio achieves precise control of the entire space and the full closed loop of the electromagnetic field through spatial-spectral holography and spatial wave field synthesis, greatly improving spectrum efficiency and network capacity and even realizing the integration of imaging and wireless communication as well as uHDD 6G services.

In the uplink, the radio's spatial-spectrum holography converts an RF signal, transmitted by the terminal from each antenna element, to the optical frequency through a photodiode-coupled antenna array. The optical signal output is aggregated into an optical Fourier transform processor based on SLMs. Finally, the optical signal that was processed by holographic interference is converted from a 2D addressable PD to an electrical signal. Signals from different MTs have been accurately separated, and the whole process is similar to real-time, 3D RF "light" field imaging. Moreover, a limited RF aperture has been transformed into a nearly infinite optical one, which enables RF signals to be precoded and multiplexed in a nearly continuous spatial spectrum, achieving extremely high data throughput. A 3D RF "phase-frequency space" can be obtained through spatial-spectral holography, providing precise feedback for the spatial wave field synthesis of the downlink. Figure 6 shows the implementation and system architecture of computational holographic radio.

As mobile life and work spaces, smart vehicles will require all-weather, ultrabroadband, real-time services, such as 8K/4K video, AR/VR cloud gaming, and 3D holographic video.

The spatial wave field synthesis of the downlink accurately controls multiple systems, including the signal simulator, channel simulator, and wave field synthesis module, based on the phase-frequency space of each MT built up by spatial-spectrum holography processing. The complex and accurate distribution of the electromagnetic field in the target space is realized by a series of PD-coupled antenna arrays controlled by a signal simulator, channel simulator, and wave field synthesis module to transmit specific RF signals. The whole process is similar to a real-time RF holographic "light" field projection.

To achieve spatial-spectrum holography and spatial wave field synthesis, the antenna array has a flexible transmission aperture; that is, the transmission aperture can radiate the distribution of holographic RF signals. To cope with this challenge, a photodiode-coupled array antenna is required, in which a photodiode is the current source for the excited coupled-dipole element. Due to the inherent planar dipole structure and the current sheet's potentially large bandwidth, the antenna can maximize the relative bandwidth, scanning angle, and low-profile performance. A high-power UTC-PD is bonded to antenna units by flip-chip technology, and the coupling between the antenna units is formed. The output current of the UTC-PD directly drives the antenna unit, so the whole system has a maximum bandwidth of approximately 40 GHz [12].

Multipurpose Converged, Full-Spectral, and All-Photonic RANs

The 6G uMUB, uHDD, and uHSLLC case scenarios require ultrabroadband and ultralow latency simultaneously, which

5G cannot satisfy. Complex CU–DU splits and massive electronic signal processing (such as massive MIMO) increase latency because the traditional method they employ is approaching its limitations due to a grooving manifestation of the electronic bottleneck. Because many investigations have described the performance and capabilities of an all-optical network featuring low latency, it is believed that ultrafast signal processing based on all-optical integrated devices (passive, active, or both) could play an important role in future RANs, even though an all-optical/photonic RAN is still a great challenge due to the lack of a high-power RF photonic front end.

The 6G all-photonic RAN is based on two key elements: a photonic engine (PE) and an all-photonic AAU based on a photodiode-coupled antenna array. The PE provides extreme broadband signal generation and processing in the optical domain, such as photonic AI, an optical Fourier transform based on spatial light modulators (SLMs), electro-optic modulators (EOMs), and optical sampling by a 2D addressable PD. At the downlink of all-photonic AAUs, the optical signals are forwarded to the integrated coherent receivers (ICRs), where they are detected and processed. The UTC-PD has a high power output [13], and its arrays convert optical signals to electrical signals that are directly used to drive the array antenna elements. At the uplink, the array antenna elements feed RF signals to graphene-based electro-absorption modulators (GP-EAMs), in which RF signals are upconverted to optical signals by optical in-phase/in-quadrature modulation. The optical signals are multiplexed and sent to the optical engines. Thus, all-photonic AAUs, photonic engines, and spectrum computing build an all-photonic RAN. ICR arrays and GP-EAMs can slice the RF and optical spectra in a very large bandwidth, resulting in a full-spectrum RAN. The function framework and a typical implementation of all-photonic RANs are illustrated in Figure 6.

If its array is arranged as a hybrid of RF and optical antennas, an AAU can be used as an RF and optical wireless system at the same time. For RF wireless systems, radar and RF wireless communications are typical applications. For optical wireless systems, lidar and coherent free-space optical (FSO) communication are practical functions. Spanning RF to optics, all-photonic RANs can implement a full-spectral or hyperspectral converged system for sensing, imaging, and communication, as shown in Figure 7. This converged system of cellular radar/lidar has the potential to deal with many sensing tasks and services. Sensing and communication-converged systems can be deployed in 6G networks for autonomous driving scenarios, so cellular radar/lidar seems to be an extremely promising concept. In contrast to 5G, the convergence of sensing and communication will provide multiple functions and establish 6G as a multipurpose system to deliver numerous services that are particularly appealing and even necessary for applications such as MR, AR, and VR as well as RF mapping of the radio environment across different frequencies. Investigations of radar-aided beam alignment in mm-wave vehicle-to-infrastructure (V2I) communications confirm that radar can be a useful source of side information that helps configure the mm-wave V2I link [13].

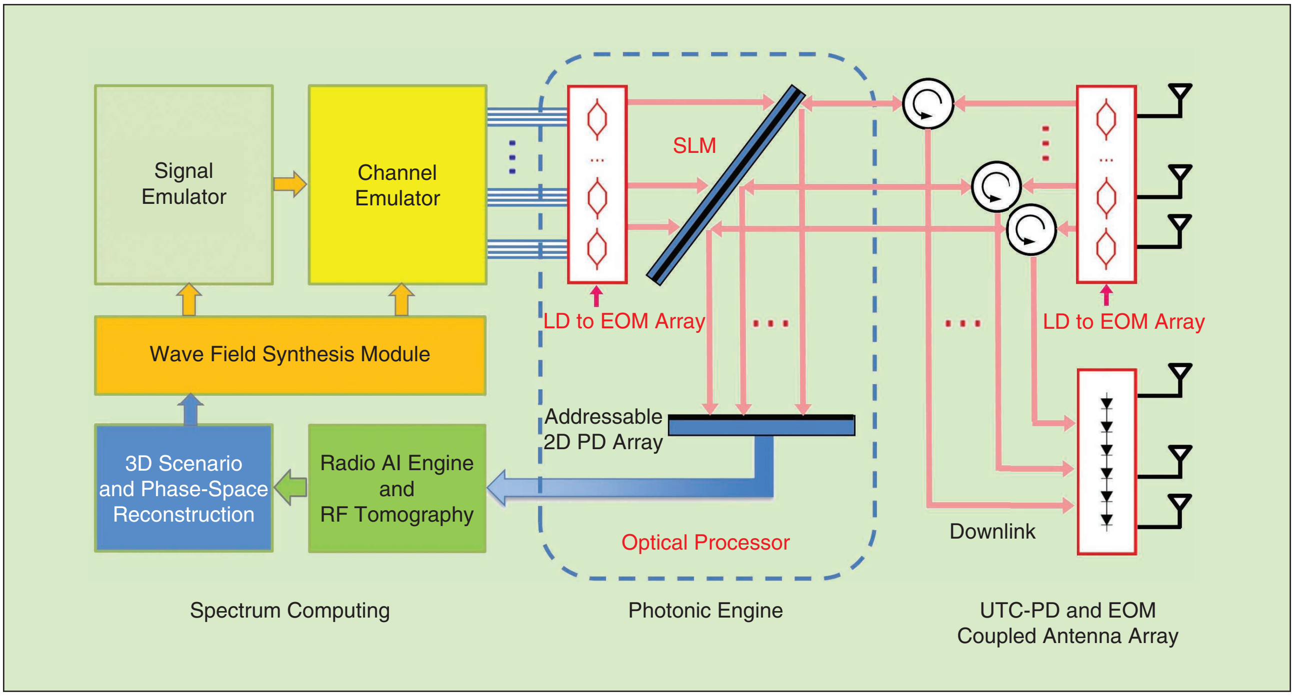

FIGURE 6 The implementation and system architecture of all-photonic RANs for computational holographic radio (as described in the "Holographic Radio and Photodiode-Coupled Antenna Arrays" section). LD: laser diode.

AI and Photonics-Based Cognitive Radio

Combining photonic technologies with ML will not only drive a key evolution of AI in 6G but will also spur a photonics-based cognitive radio system with ultrabroadband, low latency, high reliability, and scalability. Although 5G introduces AI, the intelligence is limited to the operation, management, and maintenance of the network, with the goal of smart management and maintenance. The 6G mobile network will be a genuine intelligent system architecture and a true cognitive radio network. Each network node is intelligent, which supports AI from the application layer to the physical one. Photonics-based cognitive radio comprises a hierarchical and heterogeneous AI architecture that includes all-photonic AAUs based on a UTC-PD and an EOM-coupled antenna array, a photonic neural network embedded in the photonic engine, and a spectrum computing unit with graphics processing unit (GPU)-based neural network accelerators. Figure 8 shows the general framework of the photonics-based cognitive radio system.

Although neural network processing is typically performed using a traditional GPU, such equipment will be extremely energy inefficient when implementing 6G's massively dense signal processing. Photonics-based neural networks are of great interest because they can perform computations in parallel while using less energy than GPUs, which could clear a major bottleneck to energy-efficient and scalable AI systems. In the proposed 6G photonics-based cognitive radio system, multiband and multipurpose signals, such as mm-wave communication and radar, terahertz imaging, and laser lidar, are processed, identified, and split through a photonic neural network embedded in the photonic engine. Because the training step is a very computationally expensive part of the implementation of the neural network, performing it optically is key to improving the efficiency, speed, and power consumption of artificial neural networks.

However, using GPUs rather than their photonic counterparts for training most often makes the process more accurate, so GPU-based neural network accelerators in spectrum-computing units implement deep-learning filters, deep-learning modulator/demodulators, automatic codecs, and other baseband functions. A hierarchical, heterogeneous, and hybrid AI cognitive radio architecture brings agility and flexibility to the air interface, with improved efficiency, especially for multipurpose converged and full-spectral 6G systems.

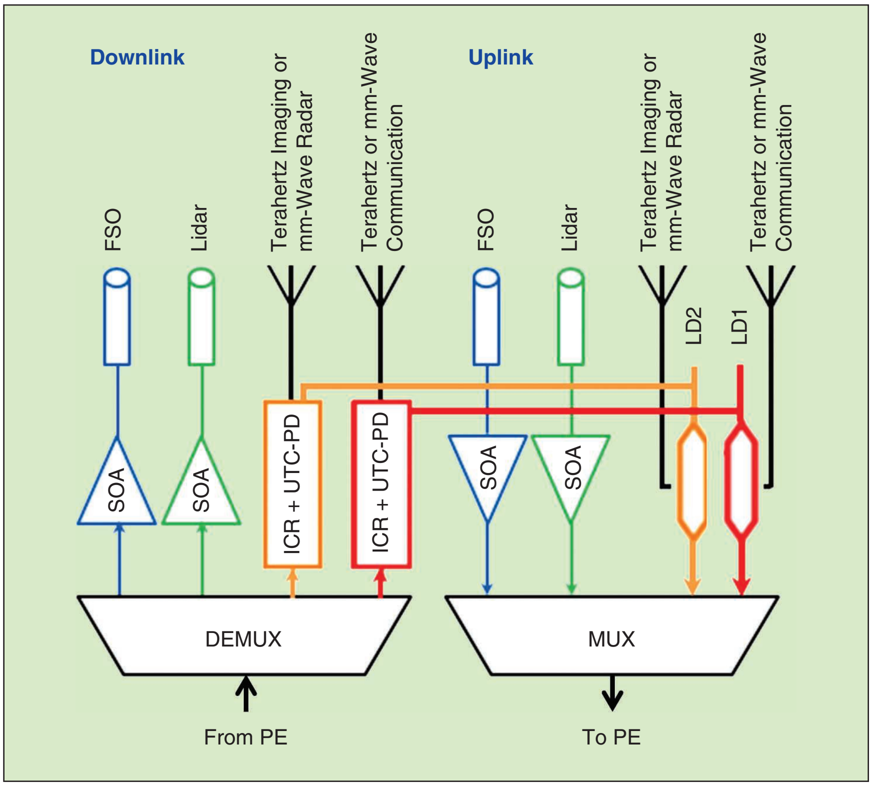

FIGURE 7 The full-spectral or hyperspectral converged AAU of sensing, imaging, and communication in 6G. DEMUX: demultiplexer; MUX: multiplexer; SOA: semiconductor optical amplifier.

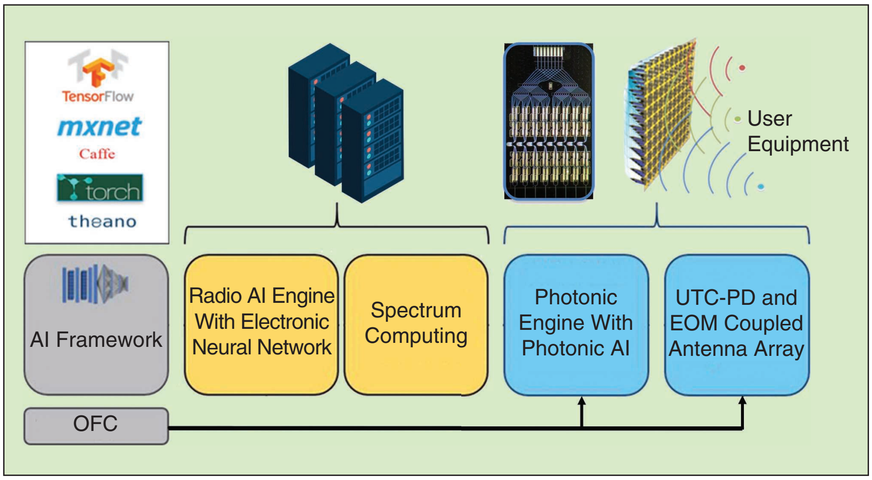

FIGURE 8 The general framework of the photonics-based cognitive radio system. OFC: optical frequency comb.

Hyperspectral Space–Terrestrial Integration Network

A typical aerial–space–terrestrial integrated network can be divided into three layers: a space-based network composed of various orbit satellites, an aerial network composed of aircraft, and a ground-based network that includes terrestrial cellular mobile networks, satellite ground stations, and mobile satellite terminals. The space–terrestrial integrated network can make full use of the characteristics of large space coverage, large line of sight, and low-loss transmission to achieve seamless high-speed mobile coverage in global 3D space. The 5G-defined space–terrestrial integrated network is a high-throughput satellite system that uses microwave or mm-wave bands to provide 100-Mb/s broadband services by employing centralized point beams [14].

Because the free-space coherent optical communication system has a large capacity, it can basically accommodate communication among space–space, aerial–space, and space–terrestrial nodes. In a 6G uMUB scenario, the space–terrestrial integration network adopts a new architecture, the 100-Gb/s hyperspectral space–terrestrial integration network, based on laser–mm-wave convergence. Key technologies include

1) low cost; a size, weight, and power advantage; and all-photonic satellite payloads
2) low-latency, high-reliability dynamic networking
3) aggregation of mm-wave and coherent laser communications
4) integrated hybrid optical and mm-wave transceiver technologies, including servo tracking systems
5) adaptive optics technology to compensate for wavefront distortion caused by atmospheric turbulence
6) laser–mm-wave aggregation and diversity technology.

The network architecture includes mm-wave and laser hybrid arrays as communication links between the space-based, aerial, and ground-based networks; adoption of low-cost coherent optical links as relays between space-based and ground-based networks; and the concept of converting cellular network cells to vertical space–ground coverage through dynamic beamforming technology, as shown in Figure 9. Because the mm-wave has rain fading but no fog and cloud fading and laser has fog and cloud fading but no rain fading, it is necessary to have spatial and spectral diversity between the two.

The 6G hyperspectral aerial–space–terrestrial integrated network includes the space-based optical backbone system consisting of satellite relay nodes (SRNs) and satellite access nodes (SANs), the space access network composed of SANs and user satellites, the aerial access network with airplane hotpots, and the terrestrial access network composed of nomadic access nodes and gateways (GWs). The access link can dynamically adopt optical links, mm-wave links, and optical–mm-wave hybrid links according to circumstances and requirements. Figure 9 demonstrates a 6G hyperspectral aerial–space–terrestrial integrated network architecture based on laser–mm-wave convergence.

As the core component of SRNs and SANs, 6G's satellite payload needs to deal with multiwavelength optical and multiband mm-wave wireless links simultaneously, which is unimaginable for traditional implementation schemes. Fortunately, the photonics-defined system has unique parallel signal processing characteristics, and it has been able to achieve very broad bandwidth to handle the practical application of multiband RF signals and multiwavelength optical signals. The all-photonic satellite payload will be an important feature of 6G, as shown as Figure 7.

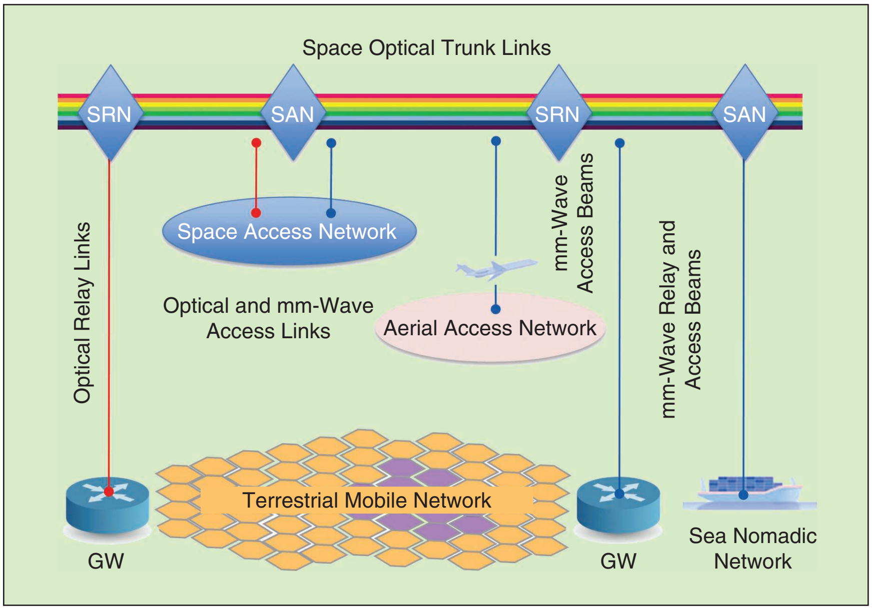

FIGURE 9 The hyperspectral aerial–space–terrestrial integrated network architecture of 6G, based on laser–mm-wave convergence.

Conclusions

The key drivers of 6G result from the challenges and performance limits posed by 5G as well as the technology-driven paradigm shift in and evolution of wireless networks. With their commercial potential, photonics and AI are bound to stand out as breakthroughs and disruptive technologies in 6G. But, if 6G is to succeed, it must be redefined in terms of its fundamental technologies, network architecture, and MT types. The 6G-oriented MT types will include smart vehicles and intelligent mobile robots, creating core requirements that will lead to service classes of uMUB, uHSLLC, and uHDD. Those services require an end-to-end codesign of communication, sensing, and computing and will inspire the convergence of photonics and AI, resulting in the two key technologies of computational holographic radio and photonics-based cognitive radio that will likely become the leading 6G technology candidates.

A hierarchical, heterogeneous, photonics-based cognitive radio architecture brings agility and flexibility to the air interface, with improved efficiency, especially for multipurpose converged and full-spectral 6G systems. Computational holographic radio could greatly improve spectrum efficiency and network capacity and even facilitate the integration of imaging and wireless communication. Meanwhile, multipurpose converged, full-spectral, all-photonic RANs, as well as the 100-Gb/s hyperspectral space–terrestrial integrated network with laser–mm-wave convergence, are scheduled to match all novel 6G uMUB, uHSLLC, and uHDD services.

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