A Survey of 6G Mobile Systems, Enabling Technologies, and Challenges

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***Abstract*—More releases of 5G operating in the millimeter wave (mmwave) range are now underway. In conjunction with the actual 5G updating process, researchers have already begun designing a new core for the 6G system. As expected, by 2030, the 6G mobile system will be employed internationally. 6G will operate at the THz gap, where Free Space Path Loss (FSPL) and atmospheric absorption loss become significant challenges. This means that new technologies need to be invented and tested to overcome these challenges and make the 6G system a reality. Among these technologies, 6G will be entirely Artificial Intelligence (AI) based. Several 6G applications are discussed in this paper, along with the general characteristics of the sub-Terahertz band and channel losses. An evaluation of the most significant 6G enabling technologies is also conducted in this paper, including AI technology, Cell-Free Massive Multiple-Input-Multi-Output (CF massive MIMO), THz band antenna technologies, Non-Orthogonal Multiple Access (NOMA), energy harvesting scenarios, Free Space Optic (FSO) backhaul technology, and 6G security technologies. The non-technological challenges issue was also considered in this paper.**

***Index Terms*—6G, Artificial Intelligence (AI), Cell-Free Massive Multiple-Input-Multi-Output (CF massive MIMO), Free Space Path Loss (FSPL), Free Space Optic (FSO), Non-Orthogonal Multiple Access (NOMA), quantum computing, terahertz-band, security**

I. INTRODUCTION

The 5G mobile system, working in the mmWave band, was applied in 2020 to support the exponential growth of data capacity in different applications supported by an effective available band of 222 GHz [1]. The Internet of Everything (IoE), Virtual Reality (VR), autonomous driving, holographic communication, and the terrestrial cellular-space network for linking remote or uncovered regions, are a few examples of new applications that form the foundation of the 6G system architecture and will require faster data rates and lower latency than 5G networks can offer. Even though the upcoming releases of beyond 5G (B5G) include some of the key concepts defined by the 6G vision, the vision of 6G should be focused on the important factors that 5G cannot cover and that require more development. The primary task of 6G technology is to provide the smart society requirements around the year 2030 [2]–[5].

The overall vision of 6G can be constituted by four keywords, which are: "deep connectivity", "intelligent connectivity", "ubiquitous connectivity" and "holographic connectivity" [4], [6], [7]. These kinds of applications will be supported by a Free Space Optical (FSO) backhaul rather than optical fiber [8] and it will require data rates at the level of Tera bits per second (Tbps) and latency at the level of microsecond (μs) level. However, these requirements cannot be met without increasing the system operating bandwidth. So, by allocating the Terahertz gap (0.1 THz to 10 THz) for the future 6G system, a huge band resources will be achieved to support such applications [2], [3], [9].

Research has begun on the future 6G networks after the rollout of 5G systems. According to Fig. 1, which illustrates the ten-year cycle rule in the mobile sector, 6G deployment is anticipated to begin in the year 2030.

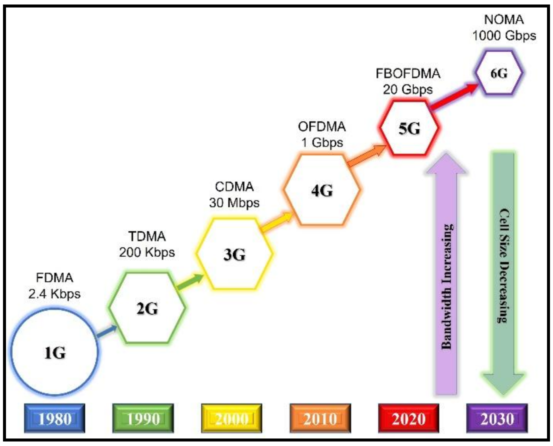

Fig. 1. Evolution of mobile system technologies.

It is expected that by the year 2030, the traffic capacity per user can reach the value of 257 GB per month. Compared with the year 2020, this traffic increases by a factor of 50 [10], [11]. Moreover, in 2030 the subscriptions numbers belong to Machine-to-Machine (M2M) will increase by 422 folds compared with that of 2020 [10], [12]. However, working with this band (THz) has many challenges and issues, including high path loss due to atmospheric absorption and FSPL, limitations in the transmission link distance, hardware constraints, etc. This paper addresses all these challenges as well as the required technologies for the 6G infrastructure.

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This paper is organized as follows: Section II establishes the comparison between the main parameters of 5G and 6G mobile systems. Section III discusses the main points leading to the emigration from 5G to 6G technologies. The main areas of the 6G applications are also discussed in this section. Section IV focuses on the main characteristics of the terahertz band. Section V focuses on the evaluation of the FSPL and the atmospheric absorption loss. The 6G based technologies are also discussed in this section, including Artificial Intelligence (AI) technology, Cell-Free Massive Multiple-Input-Multi-Output (CF massive MIMO) systems, THz band antenna technologies, Non-Orthogonal Multiple Access (NOMA) systems, energy harvesting scenarios, FSO backhaul technology, and system security. Section VI focuses on the main non-technological challenges like battery-recharge period, economic and environmental challenges, and health challenges. Finally, section VII represents the conclusion of this work.

II. 5G Verses 6G

In 2012, the International Telecommunication Union (ITU) launched an initiative to develop International Mobile Telecommunications (IMT) systems for 2020 and beyond as part of its transition to 5G. In 2016, it was revealed that Verizon's proprietary 5G radio technology would undergo pre-commercial testing. The European Union (EU) is promoting public and commercial 5G infrastructure investment. In 2016, the United States Federal Communications Commission (FCC) awarded high-band spectrum for 5G wireless services. In 2017, the 3rd Generation Partnership (3GPP) gave permission for the first 5G release. This was a big step toward making 5G networks available for business use. Commercialization and employment of the 5G system was established at the end of 2020 based on the Release 16 standard, and it is now widely commercialized in several countries.

The 3GPP release 17 standards were already postponed in 2020 due to the pandemic of COVID-19 [13], [14]. Moreover, Release 18 and later iterations of the upcoming 5G cellular standard, which was unveiled by the 3GPP in April 2021, will be referred to as 5G Advanced. In order to establish intelligent network management and a multi-antenna performance improvement, 5G Advanced will take advantage of recent developments in AI and machine learning (ML). However, according to AT&T Labs, Release 18 won't be finished until the beginning of 2024 [15]. While, services like telemedicine, augmented reality (AR), virtual reality (VR), networked robots, autonomous systems, and human nano-chip implants, are now being developed and improved for widespread deployment in the near future [3]. In addition, due to the anticipated growth in M2M communications, there will likely be hundreds of billions of internet-connected devices [16]–[18], whereas the 5G system can only cover a few billion devices [19]. As a result, the next significant update to the mobile network, represented by the 6G technologies, will be scaled to support an unprecedented connectivity and a densely infrastructure never seen before [13], [14], [20]. The year 2030 is anticipated to undergo a significant shift toward automation, with 6G serving as a crucial communication and data backbone. Consequently, the scientific community and businesses should enhance these networks in the light of this future goal [20], [21].

In conclusion, the 5G download speeds outperformed the current 4G LTE networks, with lower latency times. On the other hand, the 6G networks are estimated to raise the bar even higher, with speeds that may reach 100 times faster than 5G to keep users more and always connected [22]. Moreover, the 6G mobile system is envisioned to be employed in 2030 to connect everything. It is expected to provide superior performance over that of 5G due to ultrahigh reliability, universal connectivity, users' heterogeneity, high throughput, ultra-low-power consumption, large network dimensions, efficient network operation, efficient system maintenance, and intelligence.

Table I illustrates the comparison between the main parameters belong to the 5G and 6G systems [2], [9], [23]–[26].

TABLE I: 5G VERSES 6G COMPARISON

Parameter	**5G**	**6G**
Peak data rate (Gbps)	20	1000
Latency (ms)	1	0.1
Maximum frequency (GHz)	90	10000
Spectral efficiency (bps/Hz)	30	100
Mobility (km/h)	500	1000
Traffic capacity (Tbps/km^2)	10	100
Localization precision (cm)	10 on 2D	1 on 3D
Autonomous vehicle	Partial	Fully
Artificial intelligent (AI)	Partial	Fully
Satellite integration	Non	Fully
Energy efficiency (Tb/J)	NA	1
Connection device	10^6	10^7
Channel bandwidth (GHz)	1	100
Core	Internet of	Internet of every
Real time	No	Yes
Architecture	Massive MIMO	CF massive MIMO

A. Real Time Borders

Compared with the 5G system, 6G will be completely based on AI infrastructure, it will behave as an "Intelligent Connectivity System" and will increase the boarder of the real time operation by a factor of 0.5% of the human computational power according to the following calculations [8], [27]–[29]:

- Brain computation speed (about)=20×10^{15} operations per second (ops).
- Brain storage (about) = 100 TB.
- Today's state-of-the art computer technology performs about 10^{12} computations/sec, which is four orders of magnitude less than the speed of the human brain.
- 6G or 7G (by the year 2035) are likely to allocate up to 10 GHz RF channels for each user in the THz regime, supporting data rates of 100 Terabytes/sec, so the real time border (RTB) is given by (1)

$$\mathrm{RTB} = \frac{100\times10^{12}}{100\times1015} = 0.5\% \qquad (1)$$

which provides 0.5% real-time human computational power.

B. Emigration from 5G to 6G

The 5G system outperforms the previous generations of mobile phone through the realization of IoT technology and many applications based on massive communication principles. 5G is characterized by its high speed, where the target peak rate is 20 Gbps for the downlink and 10 Gbps for the uplink. The excessive use of data and emerging applications such as brain computer interface (BCI), remote surgery, VAR, teleportation, holographic communication, and so on, have become really beyond the capacity of the actual 5G systems. Thus, the emigration to a new technology, represented by the 6G mobile system, becomes so urgent to fully support the above-mentioned services [16], [30], [31].

We discuss here below the main factors that prompted the issue of emigration from the current 5G system to the future 6G technologies:

1) Transmission Data Rate

One of the main objectives of 5G technology is to enable communication networks with enhanced mobile broadband (eMBB) to achieve a data rate of up to 20 Gbps. However, in the near future, this rate of transfer speed will be unable to support the requirements of mobile technology, and the 5G network will reach its maximum saturation point by 2030. In less than ten years from now, the future of data transmission will require technological support to reach speeds of data transmission in the range of 1Tbps to 10Tbps, and this is what prompted academics and industry leaders to enter into the development stage of 6G technologies, which will achieve these speeds by utilizing the terahertz band [30].

2) Connection Density

Based on the projected growth in M2M connections, services such as tele-medicine, connected robotics, AR, human nanochip implants, and autonomous systems are currently being developed and improved to be widely deployed in the near future. The number of devices linked to the Internet is predicted to reach roughly 100 billion. Only 1 billion devices will benefit from the performance trade-offs that 5G will provide. As a result, the 6G system, the next generation of mobile networks, will be able to support more connections between devices [3].

3) Link Latency

In the coming years, numerous real-time-dependent services will be incorporated into the network. Services can range from providing a modern way of interacting with the environmental elements, such as VR, exoskeletons, and prosthetics, to assisting in the development of smart cities, with the use of autonomous vehicles and automated factories. In order to ensure an efficient operating mode, the majority of these services rely on stringent latency time requirements in their design (10 milliseconds or less). This was taken into account in the latest version of the 5G standards, and the control time is limited to, at best, 1 millisecond [32]. In many applications, the required latency time is less than one millisecond (0.1-1 millisecond), which is 10 times lower than current 5G standards and a high ceiling in the field of automated control [33]. For instance, if an e-commerce website generates $100,000 per day, a one-second page delay could cost $M2.5 in lost sales annually. Optimizing page speed for 1 second increases daily revenue by $7000 [34]. If Amazon's pages loaded 1 second slower than usual, it could cost the company $1.6 billion in lost sales annually. Furthermore, link reliability, latency time, and allocation of data rate for different applications have not been completely taken into consideration in the 5G network and are still inefficient, so research has begun with the 6G project that achieves short latency time on the order of less than 0.1ms [3].

4) Link Reliability

Communication channel reliability is evaluated in general in terms of frame error rate. To provide low incident rates, ultra-reliable scenarios are required by many critical applications like railway system control, vehicle-to-everything (V2X) connectivity, and factory automation. In terms of frame error, a 10^{-9} rate is required for some industry 4.0 applications, however, 5G only promises to support not more than 10^{-5} [4]. So, in order to achieve the goal of the realization of smart cities, smart industries, and smart healthcare, the connection reliability should be increased by many folds. In the 5G system, the link availability, which is synonymous with link reliability, is expected to be five-nines, or 99.999% of the time. Nonetheless, control and automation configuration in a specific factory, will necessitate service availability of six-nines or 99.9999% [35]. However, some researchers suggest a service availability of seven-nines or 99.99999% for the future 6G network [3].

5) Social Impact

The current 5G system pays scant attention to users' rights to access their personal data, operators' subscription plans, or social awareness of users in the community and individuals sharing data with one another. Considerable public opinion shifts on controversial issues can be attributed to the information presented here, so it has significant societal value. This highlights yet another responsibility for 6G networks to unite the globe through the deployment of network infrastructure everywhere, especially in the underdeveloped nations, where there is limited access to the Internet. This became abundantly clear in 2020, when COVID-19 compelled the entire world to almost entirely transition to digital methods of operation [36], [37].

6) Promising Technologies

One of the most promising technologies currently under development is known as "quantum computing" technologies, which will not be taken into account by the 5G network infrastructure. In quantum computation, a rapidly expanding field, numerous advances have been made in recent decades. Quantum computation is transitioning from an emerging branch of science to a mature research field in science and engineering, and it will be expected to lead to a big revolution in the digital world. Quantum computing is already planned to be used by the 6G to meet all future requirements beyond 2030 [38].

7) System Security

Despite the continuous updating of the 5G infrastructure, there are still important gaps in the security aspect. The 5G network core is based on Software-Defined Networking (SDN) and Network Function Virtualization (NFV). SDN and NFV make heavy use of the hypertext transfer protocol (HTTP), the Representational State Transfer (REST) protocol, and the Application Programming Interface (API) protocol. These protocols are well known and widely used on the Internet. Tools for finding and exploiting vulnerabilities are available to any adversary. Similarly, SDN integrates network control logic into SDN controllers, which will facilitate the task of hackers in breaching system privacy by adopting resource exhaustion or denial of service (DoS) attacks. Accordingly, it is required to create a high level of security for the 6G systems by adopting the principle of quantum computing, which will dominate all traditional security solutions currently prevailing [39].

III. The Area of 6G Applications

In the next few years, the 5G networks will become uncapable of following the fast growth of automated systems and data-centric systems, and they will not be able to fulfill the demands of future emerging intelligent and automated systems 10 years later. However, AI will be completely integrated into the 6G communication systems, giving 6G a high capability for future advanced applications.

The main areas of applications for the 6G wireless communication will be illustrated below:

- Extended reality (XR): 6G will offer AR, VR and Mixed Reality (MR) in communication systems. The VR content is created using digital technologies, which is also called digital reality, and totally immerses the user in a fully artificial environment. AR is an overlay of virtual objects in the user's environment. MR combines AR and VR. XR has applications in education, entertainment, medicine, and many other fields. A true XR experience requires the 6G systems to achieve real-time operation [3].
- Robotics and autonomous systems: The deployment of robots and autonomous systems in 6G wireless technology will change everyday lifestyles. A good example is self-driving cars that perceive their surroundings using sensors such as GPS, light detection and ranging, sonar, radar, and an odometer [40].
- Super intelligent society: An intelligent society can be created based on 6G infrastructure, so the quality of life will be enhanced accordingly. Environmental monitoring and automation will be accomplished through the use of AI and energy harvesting. To mention a few examples, any company will be able to remotely control everything by owning smart mobile devices and self-driving cars. Once we reach the point where we can control all equipment remotely, smart homes will become a reality [41].
- Brain-Computer Interaction (BCI): The concept of BCI is based on the principle of direct transmission of signals from the brain to digital devices, which will work to extract these signals, process them digitally, and convert them into actions in real-approaching times thanks to the adoption of 6G technology [42], [43].
- Smart healthcare: 6G, based on AI, 3D imaging, and mobile computing, will play a vital role in supporting the health aspect, especially the so-called healthcare services and remote surgery. The future health system will be based on the real-time feeding of a database system via a wireless communication system, through which a huge amount of health information will be exchanged, which will be directly reflected in the improvement of the health care aspect [41].
- Automation and manufacturing: With the approaching dawn of the 5th industrial revolution, the IoE, supported by 6G technology, will have an effective role in the industrial field and turn into the so-called Industrial Internet of Everything (IIoE). IIoE will be able to receive a huge amount of data related to various smart industrial equipment and belonging to different production lines via embedded smart sensors. This data will be analyzed, processed, and directed according to the requirements of the technological paths. Entering the 6G era, there will be billions of devices and equipment connected to the 6G network, so smart industries will become a reality [44].
- Holographic communications: Holographic communications, which are not supported by 5G, will demand data rates in the order of Tbps. By employing multiple view cameras, holographic communication refers to the real-time capturing, encoding, transporting, and rendering of 3D representations. Interaction with all kinds of objects from any location can be established using hologram technology. Go to the supermarket without leaving home; hold face-to-face meetings with people far away; and participate in the parallel world that the metaverse promises to become possible based on such technology [4], [34], [45].
- Space-Air-Ground Integrated Network (SAGIN): SAGIN is a global network that includes satellite systems, aerial networks, and terrestrial cellular systems. SAGIN is used to provide services in remote or uncovered regions where there is a lack of coverage by the current mobile cellular due to economic reasons or technological difficulties. SAGIN is divided into three infrastructure layers, which consist of air, ground, and space. The air network is a mobile aerial system employing unmanned aerial vehicles (UAVs). The ground system represented by the actual mobile cellular infrastructure, and the space system represented by

different types of satellites situated at different altitudes [46]–[48].

The area of application of the 6G system was considered by many literature references as depicted in Table II.

TABLE II: MAIN LITERATURE REFERENCES ON THE AREA OF 6G APPLICATIONS

Reference	Applications	Objective	Short descriptions
[41][5][49]	Super intelligent society	Development of smart societies	Improving living quality by introducing self-driving cars, flying taxis, and smart houses has become a reality.
[3][5][50]	Extended Reality (XR)	XR supplemented by cloud gaming, revisits the way how humans interact with computers, networks, and each other.	Extended reality (XR) is a term that combines virtual reality (VR), augmented reality (AR), and mixed reality (MR). Human perception of real objects is based on five basic senses: sight, hearing, touch, smell, and taste. If a virtual object can deliver the same synthesized senses as a real object, it seems that the virtual object does exist.
[5][40][51]	Autonomous and connected robotics systems	Commercialization of self-driving automobiles and connected robotics systems.	A main domain of 6G applications is connected robotics and autonomous systems, which include self-driving cars, drone delivery systems, and autonomous robotics. Self-driving cars perceive their surroundings using sensors such as GPS, light detection and ranging, sonar, radar, and an odometer. Based on the ultra-low latency and ultra-fast data speed provided by 6G, the autonomous system will become so efficient in reducing collision accident rates and improving safety aspects in a dramatic way.
[42][43]	Wireless Brain-Computer Interactions (BCI)	BCI enables communication between the brain and external electronic devices and equipment.	BCI is the process of establishing a direct communication path between the brain and external devices in order to perform actions. 6G can facilitate the transfer of the five human senses data, so as to neatly and remotely move with the environment.
[41][52]	Smart healthcare	Achieving an intelligent healthcare system, that will be fully AI-driven.	The quality of care will improve based on the massive amounts of medical data that can be transmitted with a high data rate, high reliability, and low latency through the 6G network. Remote surgery will become a reality based on 6G infrastructure.
[4] [8] [11], [53]-[2], [6], [7], [54]	Space-Air-Ground Integrated Network (SAGIN)	To combines terrestrial cellular systems, aerial networks, and satellite systems into one global network.	The air network is a mobile aerial system with the assistance of unmanned aerial vehicles (UAVs). The space network is comprised of satellites of different altitudes. The ground network is the actual mobile cellular system.
[5][55]	Tactile Internet (TI)	Enables human-to-machine interactions and machine-to-machine interactions.	Unlike existing communication systems, the Tactile Internet (TI) aims to support haptic media including tactile (sense of touch) and kinesthetic (muscle movement) interactions, and hence has the potential to revolutionize users' experience. The TI will enable a variety of human-type communications, such as virtual/augmented reality (VR/AR), teleoperation, online education, telesurgery, and the Internet of Skills.
[5][4][33] [56]	Industry 4.0 and beyond	The key objective in Industry 4.0 is to reduce the need for human intervention in industrial processes by using automatic control systems and communication technologies.	The industry 4.0 infrastructure is based on high reliability and extremely low latency, which can be achieved through the 6G infrastructure. Entering the 6G era, there will be a huge number of devices and equipment connected to the 6G network, so smart industries will become a reality.
[4][5][52]	Holographic Communication	This enables human communication through holographs-3D images in thin air.	Holographic communication uses cameras from different angles to create a hologram of the object. Holographic communications utilize a laser beam to produce Images. Holographic communications will demand high data rates in the order of Tbps,

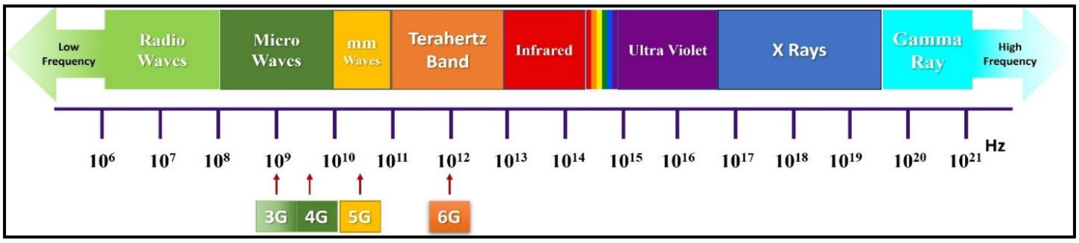


Fig. 2. Electromagnetic spectrum.

IV. TERAHERTZ BAND

Compared with 5G system, traffic in the 6G network is expected to increase by many folds, so a look for a new bandwidth becomes an urgent subject. This new band should take into consideration the following terms:

- A jump to the Terahertz bands is an optimized solution for the achievement of the necessary huge bandwidth.
- Fig. 2 shows the electromagnetic spectrum profile, where the terahertz band was situated in the range between 0.1 and 10 THz [6], [57], [58].
- Due to the saturation of the atmosphere media by oxygen and water vapor, and since these particles' dimensions are close to terahertz wavelength, atmospheric absorption becomes one of the main

challenges against the propagation of waves situated in the terahertz band [59], [60].

- FSPL becomes another challenging factor in the Terahertz band, where its value increases sharply with frequency.
- The mobile Base Station (BS) should use a high-gain antenna to overcome the above losses [61]–[63].

Some of the main characteristics of the sub-Terahertz band are illustrated below.

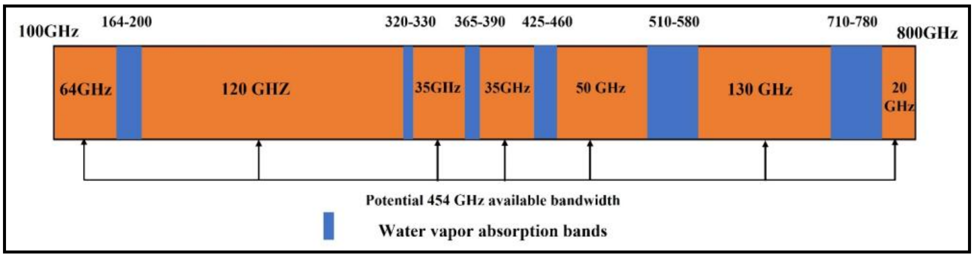


Fig. 3. Sub-Terahertz available bandwidth.

A. Potential Available THz-Band

Depending on the atmospheric absorption chart (Fig. 5), the low-Terahertz band (100 GHz to 800 GHz) was evaluated to deduce the active available bandwidth after subtraction of the highly attenuated portion of the spectrum. Based on Fig. 3, we find that the value of this active band is around 454 GHz (64 + 120 + 35 + 35 + 50 + 130 + 20), which piqued the interest of academics eager to initiate the 6G project [8], [61].

B. Sub-Terahertz Band Frequency Allocation

To encourage the development of the 6G projects that are being undertaken all over the world, the FCC voted in 2019 to locate a band of frequency above 95 GHz, making available licensing spectrum in the THz band up to 3 THz, and reserve another band for unlicensed use with an available frequency band of 21.2 GHz. In 2017, the IEEE 802.15.3d standard was formulated by the Institute of Electrical and Electronics Engineers (IEEE) to work in the Terahertz band between 252 GHz and 325 GHz and to construct a global Wi-Fi system running at an approximated data rate of 100 Gbps to achieve global coverage on an international scale. Table III shows a set of located frequencies in the sub-Terahertz band based on IEEE recommendation, FCC recommendation, and research activities [8], [64], [65].

TABLE III: SUB-TERAHERTZ LOCATED FREQUENCIES

Frequency (GHz)	Atmospheric attenuation state	Band type	Applications	Allocation reference
100, 140, 220, 410, 345, 460, 680, and 800	Acceptable	Licensed	6G Mobile cellular system	Research proposal
183, 325, 380, 450, 550, and 760	Sevier	Unlicensed	Short rang (indoor applications)	Research proposal
116 - 123 1750 – 182 185 – 190 244- 246	Acceptable	Unlicensed	Industrial, scientific, and medical (ISM) band	FCC
252 – 325	Acceptable	Unlicensed	IEEE 802.15.3d global Wi-Fi	IEEE

V. 6G MAIN TECHNOLOGICAL CHALLENGES

Due to the resonance phenomena of oxygen, hydrogen, and other gases that already exist in the atmosphere, the atmospheric absorption at the Terahertz frequency band becomes more obvious. Moreover, the wavelength in such a case approaches that of snow, dust, and rain [8], [66], [67]. By including the FSPL, the Terahertz signal can only travel a few meters. To increase this range up to 100 m, which represent the expected 6G cell radius, a new advanced technologies was needed to support the realization of the 6G system [68]–[70]. So, another important challenge will be added due to a lack of technology. Actually, some of these technologies are not on the shelf and will need many years to be commercialized. Listed below are the most significant technological challenges:

A. Free Space Path Loss (FSPL)

Considering the case of the transmission of a wireless signal between two nods separated by a distance (d) in km and modulated by a carrier frequency (f_s) in MHz, the FSPL in (dB) unit is given by (2) [1], [60], [71].

$$\mathrm{FSPL}_{\mathrm{dB}} = 32.44 + 20\log_{10}(f_s) + 20\log_{10}(d) \qquad (2)$$

Equation (2) can be formulated as:

$$\mathrm{FSPL}_{\mathrm{dB}} = 152.44 + 20\log_{10}(f_s) + 20\log_{10}(d) \qquad (3)$$

where FSPL is the free-space loss in dB, f_s is the carrier frequency in THz, and d is the LOS distance between the transmitter and receiver in km.

Based on (3), Fig. 4 shows the variation of the FSPL against the separation distance d for different carrier frequencies (6GHz, 28GHz, and 800GHz) belonging to the actual 4G system, the actual 5G system, and the future 6G system, respectively.

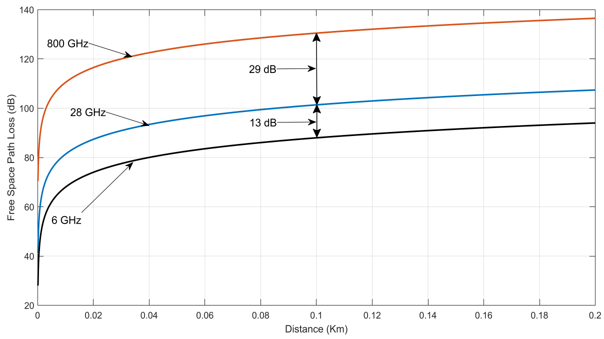


Fig. 4. Free space path loss (FSPL).

At a distance of 100m, the FSPL in the case of the Terahertz band is 29 dB more than in the case of the mmWave band. So, the 6G mobile system required an adaptive high-gain array antenna at the BS to overcome the high effect of the FSPL [66], [72].

B. Atmospheric Absorption

Due to atmospheric absorption in the Terahertz band, a number of frequencies are harmfully attenuated as depicted in Fig. 5 (see Table III) and will become suitable for certain applications such as short-range and secure communication systems [8], [73], [74].

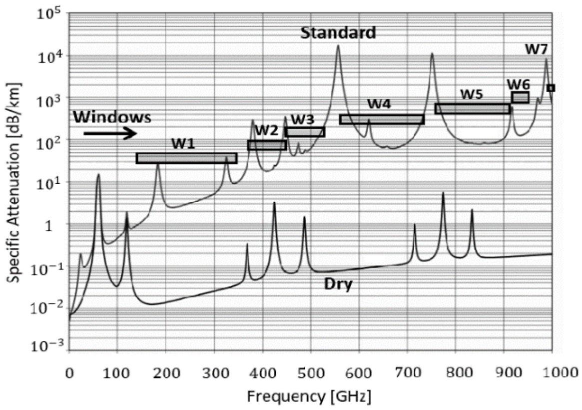


Fig. 5. Atmospheric absorption loss of electromagnetic waves [8].

The atmospheric absorption loss was nearly constant in the frequency gap between 600 GHz and 900 GHz, with an average value of around 200 dB/km. By adopting a 100m cell radius for the 6G BS, this attenuation will decay to a value of 20 dB [(200/1000) × 100]. To overcome the atmospheric attenuation in a 6G system, a high gain adaptive array antenna should be inserted at the BS level [23], [65].

C. Rain Attenuation

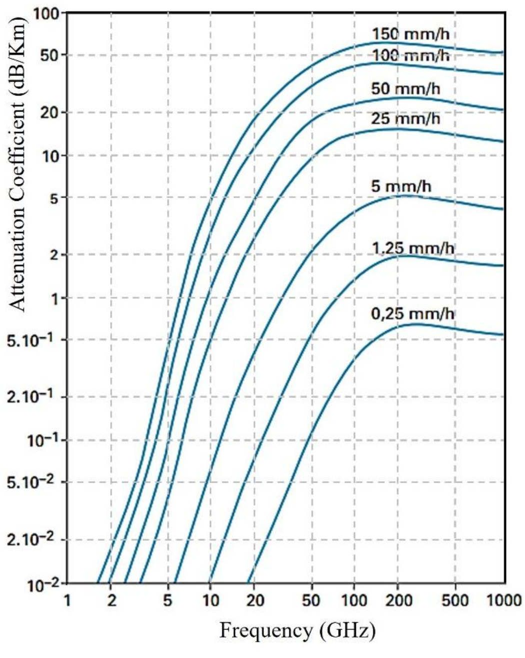


Fig. 6. Rain attenuation for sub-Terahertz band [8].

The traditional rain attenuation chart is shown in Fig. 6. It is evident that for the portion of the spectrum from 100 GHz up to 900 GHz, the rain attenuation becomes nearly flat and has an attenuation value of 20 dB/km for rain falling at a rate of 50 mm/h. By considering a 6G BS with a radius of 100m, this attenuation will be lowered to 2 dB [(20/1000) × 100], which can be easily overcome by using more gain at the BS. So, the band between 100 GHz and 900 GHz can be well allocated for the 6G cellular mobile system applications [8], [75].

D. Lack of Technology

The main challenges of THz technologies are amplifiers, antennas, MIMO systems, multiple access techniques, network management, backhaul capability, AI technologies, system security, and energy issues. This means that these elements should be met in order to construct a THz transceiver and the future wireless communication system [62]–[64]:

The main enabling technologies and the features that should be established in order to make 6G a reality are illustrated below [2], [6].

1) AI based Wireless Communication

For the implementation of the 6G communication link, AI is the most needed technology. It was first introduced partially in the 5G system, and it was expected to be fully implemented in the 6G system. Furthermore, AI will support real-time communications in 6G networks due to advances in ML. Furthermore, in a 6G mobile cellular system, tasks such as network selection and handoff procedures can be promptly established based on AI. The AI-based mobile systems will be assisted by the following behavior:

- Intelligent structures
- Meets materials
- Intelligent devices
- Intelligent cognitive radio
- ML
- Self-sustaining wireless networks

Recently, a lot of work has been initiated by academia and industry for the purpose of embedding AI, especially deep learning, in wireless communication systems in order to obtain major improvements in system performance and efficiency and to achieve what is called intelligent connectivity. Certainly, it appears that the 6G system will make extensive use of AI technology to solve the complex requirements and services needed by the future smart society [6], [76], [77]. By introducing intelligent connectivity in the 6G system, this means that we will achieve intelligently connected devices, services, and network management [6].

In March 2022, the 3GPP completed the Release-17 standard of the 5G system. Despite the role that 5G plays in supporting data-hungry applications, it is not reliable that this system will survive in supporting future applications based on IoE technologies, such as XR, BCI, and space vehicles, which prompted researchers and industrials to adopt the 6G project to be the primary leader for the IoE [3].

The strict requirements of 6G have prompted researchers to seek more advanced AI-based physical layer (PHY) techniques so that AI becomes an intrinsic element of the 6G network [30]. One of the approved definitions of an AI technique is to support the computer with a technique that makes it act like a human in terms of thinking [78]. AI will be the key leader of 6G networks, enabling an entirely new perspective for wireless networks, notably in the PHY. Devices in the physical layer, such as data links and network infrastructure, and applications in the computing layer, such as software-defined networks, network function virtualization, cloud/edge/fog computing, etc., are the two main categories to which AI technologies belong [30], [79].

The development of wireless communication technologies requires expert knowledge of communication and information theory, including coding, modulation, channel estimation, and optimum detection, in order to be reliably manipulated, where each block has been independently optimized. 6G networks will be extraordinarily complex, necessitating more implementation time, cost, and management efforts. To lower operating expenses (OPEX), mobile network operators want these networks to be intelligent, self-organizing, and cost-effective.

Adopting ML techniques for the purpose of making selective changes in the wireless communication architecture in terms of modulation, encoding, and channel estimation methods will not achieve the desired improvement [80], [81]. Otherwise, the adoption of the ML under the principle of making integrated optimization in the communication system has been applied in the 6G system and is known as End-to-End (E2E) optimization, which represents a revolution in the physical layer level and can be used under different challenging conditions [79]. Transforming the actual physical layer architecture from its current state, which is based on the principle of using scattered blocks to process various signals, by adopting the E2E principle and by introducing deep learning methods, will make a quantum leap in 6G technology and beyond.

AI assists 6G communication to provide high Quality of Service (QoS), and the service incorporates high data rates, ultrareliable low-latency communication, further improved portable broadband, ultra-enormous machine-type interchanges, long-distance and high-mobility communications, and extremely low-power interchanges [37], [72]. The 6G vision, which is based on AI technology, can be summed up in four points, as listed below:

1) Intelligent Connectivity

The interweaving of AI and mobile communication systems has become a necessity. In this field, the work is currently underway to invest AI in the development of the B5G system [82], [83]. The current traditional improvement aims to adopt AI to improve performance and to add new applications without reaching the level of smart wireless systems. Maintaining the current traditional development of mobile communication systems will not keep up with the technological challenges facing the achievement of the strategic goals of the 6G systems. So, the 6G mobile systems will require extensive research to mature the applied side of AI technologies in a way to achieve intelligent connectivity. Intelligent connectivity is the combination of ultra-high-speed, ultra-low-latency 6G networks, cutting-edge AI, and the linking of billions of devices through the IoT [84]. The 6G communication technology will merge with full AI, and this technology will entirely transform from connected things to connected intelligence, resulting in a cloud-based architecture for everything. Together, 6G connectivity and AI can transform our technical perspective and modern way of life [85]. Thus, building a 6G network based on AI technology is a foregone conclusion, and the term "intelligent connectivity" describes this network's defining characteristic. The term "Intelligent Connectivity" refers to the fulfillment of two requirements at once: (a) all connected devices and related services inside the network itself are intelligent; and (b) the complicated and enormous network itself requires intelligent management.

2) Deep Connectivity

The term "deep coverage" is adopted in wireless communication systems, including 5G, to denote the improvement of the deep coverage of the approved access systems in order to accomplish the principle of moving from the traditional communication between one person and another to the simultaneous communication with things, which is known under the expression "connecting all things". The degree of "telepathy" is expected to become a reality with the promising growth in the field of BCI technologies, which is based on the principle of achieving direct interaction between thinking and thinking. We can conclude, in terms of linking, that the logical evolution from 1G–4G technologies' concentration on "people-to-people" linking, 5G's focus on "people-to-things," linking, and finally, 6G's focus on "things-to-things" linking [86]. Therefore, we expect that by the year 2030, the demand for access will shift from deep coverage to "Deep connectivity".

3) Holographic Connectivity

Once users are no longer restricted by their physical location when using AR/VR, this will accelerate the growth of AR/VR services and ultimately hasten the advancement and maturation of AR/VR hardware. Moreover, within the next decade (about 2030), we are expected to see a shift toward more planar multimedia engagement, high-fidelity AR/VR, and even holographic information interaction, as well as the widespread availability of wireless holographic communication. To achieve the communication vision of so-called "holographic connectivity," high-fidelity AR/VR will be ubiquitous, and holographic communication and display will be possible at any time and place. People will then be able to have fully immersive, interactive holographic experiences anywhere and at any time [6].

4) Ubiquitous Connection

The term "Ubiquitous Connectivity" describes a set of features that include the following: Integration of Space-Air-Ground-Sea-Communication for 3D coverage and connectivity to all forms of territory and space, permitting communication at any time or location. In contrast to "Deep Connectivity," which emphasizes the depth of the connected object, "Ubiquitous Connectivity" emphasizes the breadth of the connected object's distributed area [6].

5) CF Massive MIMO Communications

Massive MIMO technology is based on introducing a large number of antenna arrays in the transmitter and receiver, and this object can be suitably realized in the THz band since we deal with a very short wavelength. 5G mobile systems now use Massive MIMO and the associated BSs have more than 100 antenna components for increased antenna array gain and diversity gain [1], [87]. A new concept of massive MIMO, which is called CF massive MIMO, will be the candidate for the 6G mobile system. Instead of using a single BS packed with more than 100 antenna elements, multiple BSs, each with a few antennas, will be configured, as shown in Fig. 7 below, to create spatial variety by permitting a single user to be served by multiple BSs simultaneously, thus avoiding inter-cell interference and mitigating the problem of poor channel conditions if only one BS is connected to the user [1], [2]. However, there are some challenges for the realization of the CF massive MIMO communication which can be summarized here below:

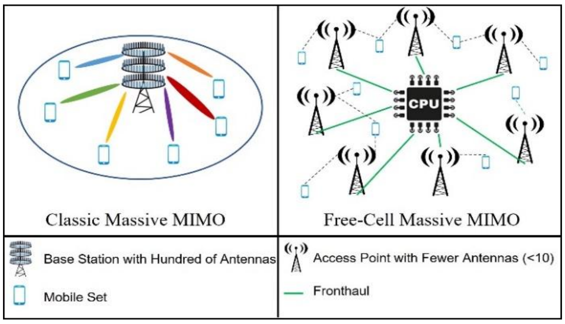


Fig. 7. CF massive MIMO in comparison with classic massive MIMO.

- Number of Access Points (APs): To provide the service to a larger number of subscribers, this requires the use of the maximum number of APs per subscriber. In the case of CF massive MIMO, obtaining excellent propagation conditions requires the adoption of a high density of access points that may reach the limits of (1000 unit/km^2) [2], [88].
- Channel estimation: Since the principle of channel estimation in wireless communication depends mainly on the Channel State Information (CSI) principle, this process will become more complicated in the case of the CF massive MIMO scenario compared with the traditional massive MIMO technique due to the huge number of signals received by different antennas in the case of CF massive MIMO [2].
- Optimization of APs locations: Conventional works in cellular networks draw heavily rely on stochastic geometry, in which the cell structure follows 2D Voronoi tessellation and geographically separated base-stations serve cell-edge users under the coordinated multipoint (CoMP) scheme to improve overall system efficiency and avoid intercell interference via scheduling. To improve network fairness, it is essential to optimize base-station location under realistic link-level limitations such as signal-to-interference ratio and success probability for individual links. Since no cell boundaries are assumed in CF massive MIMO, the system-level performance with respect to the locations of APs, random scatterers, and users' needs has to be carefully examined and improved [89]–[91].
- Hardware complexity: As a result of the huge number of antennas, APs, and associated sub-equipment that will be implemented in the CF massive MIMO system, energy consumption and equipment costs will rise. This hardware complexity represents one of the physical challenges in the way of achieving this kind of system. In order to achieve the CF massive MIMO system in a practical way, it is necessary to adopt low-energy, low-cost components, and to intensify scientific research in this aspect [92].
- Fronthaul limitation: The fronthaul links between APs and the Central Processing Unit (CPU) are another major issue in CF massive MIMO systems. An enormous amount of power (e.g., 0.25 W/Gbps) is required to transmit data between access points (APs) and the CPU through optical fiber cables because of the large number of antennas at the APs. Consequently, lowering the fronthaul load is one of the greatest obstacles in practical CF massive MIMO systems [93].

6) THz Band Antenna Technologies

Due to high path loss and atmospheric attenuation effects in the THz band, as described in Section V, a high gain array antenna is necessary to counteract these effects. Antenna arrays with high directivity are required for THz links in 6G outdoor applications [94], [95]. Until now, a lack of technology has prevented us from developing antennas in the THz range. However, Table IV shows the most related work of fabricating THz band antennas with different types, different bandwidth, different materials, and different manufacturing technologies. Meanwhile, high-precision fabrication technology for antennas to work properly in the THz band is still under development. Fig. 8 shows some fabricated THz band antennas [54], [96]–[103].

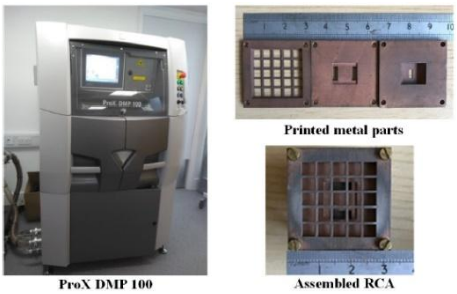
Fig. 8. Rectangular horn, cassegrain, and parabolic antennas, respectively [96].

TABLE IV: THZ BAND ANTENNA FABRICATION WORKS SUMMARY [96]

No.	Antenna Type	Freq. Range	Material	Fabrication Technology
1	Conical horn antenna	0.270-0.330 THz	Metal	Wire-cutting EDM[1]
2	16-element planar array of cavity-backed patch antenna	0.135-0.155 THz	Megatron 7N substrate	Multilayer high-frequency PCB[2] technology
3	Elliptical lens antenna	0.14-0.22 THz	Topas	HDPE[3] manufacturing antenna
4	Cassegrain antenna	0.22-0.32 THz	Brass with gold plating	CNC[4] machining
5	Lens antenna	0.24-0.32 THz	High-temperature resin is chosen as the printing material	3D printer technology
6	Vivaldi patch antenna	0.56-0.74 THz	Metallic on Rogers RT5880 substrate	Antenna scale modelling. Fabricated antenna at 0.0615 and 0.0625 THz by traditional PCB etching procedure
7	Horn antenna	0.22-0.32 THz	Metal	CNC technology
8	Horn antenna	0.09-0.140 THz	Copper	Plunge-wire EDM
9	Rectangular horn antenna Cassegrain antenna Parabolic antenna	0.3 THz		
10	Planner bow-tie antenna Horn antenna	1 THz	FR-4 substance	Antenna scale modelling. Fabricated antenna at 0.001 THz
		0.325-0.5 THz		Low-cost milling process
11	Lens antenna	0.320-0.380 THz	Teflon	No mention the fabrication technology but the prototype has made of fine copper
12	Lens antenna	0.11-0.17 THz	Metallic	Conventional milling process

[1]EDM: Electrical Discharge Machining [2]PCB: Printed Circuit Board
[3]HDPE: High Density Polyethylene [4]CNC: Computer Numerical Control

In the THz band, the main challenges for antenna realization are related to design, manufacturing, and measurement [57], [58], [104]. These challenges are based on the fact that THz band antennas require very high precision, tolerance, and very smooth surface finishing. Insertion loss, which impacts performance directly, is getting worse as surface roughness increases. In contrast, the real antenna measuring equipment, such as network analyzers, has a frequency limit of 1.1 THz [96], [105], [106]. As demonstrated by a practical case conducted by [61], nearly none of the known 3D printing processes are capable of producing such small structures for 300 GHz band antenna design. As indicated in Fig. 9, a scaled model working at 30 GHz was simulated and printed using the 3D printer ProX DMP 100 based on the 300 GHz design.



(a) (b)

Fig. 9. (a) The printer and (b) printed antenna [61].

7) Non-orthogonal Multiple Access (NOMA)

All mobile cellular systems starting from G1 up to the first release of 5G are based on orthogonal multiple access (OMA) techniques, where the mobile channels are orthogonally allocated to different users in the time, frequency, code, and subcarrier domain, according to the following classifications [1]:

- G1 allocates channels in the frequency domain using frequency division multiple access (FDMA).
- G2 allocates channels in the time domain using time division multiple access (TDMA).
- G3 allocates channels in the code domain using code division multiple access (CDMA).
- G4 allocates channels in the subcarrier domain using orthogonal frequency division multiple access (OFDMA).
- G5, as a first release, allocates channels in the subcarrier domain using filtered-bank orthogonal frequency division multiple access (FB-OFDMA).

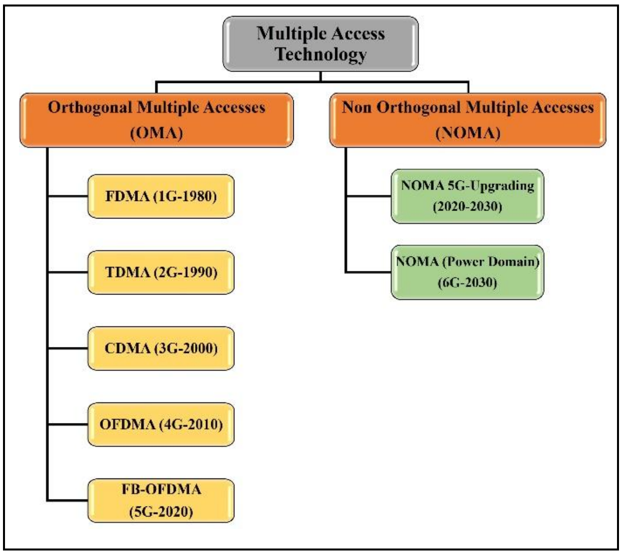


Fig. 10. The milestones of the multiple access technology.

The increased demand for new services, as well as the rapid increase in the number of connected devices, have resulted in massive amounts of data traffic that must be transferred by mobile networks at ultra-high bit rates and ultra-low latency. Therefore, the utilization of OMA methods will no longer be supported in the 6G system. Due to its great spectrum efficiency and high connectivity, NOMA has been recognized as an option for B5G and 6G cellular networks. NOMA, unlike OMA, permits many users to multiplex on the same frequency by allocating power to various channels. Fig. 10 highlights the numerous access technology milestones [7], [53], [107], [108].

In NOMA, all channels can be used by each user. Fig. 11 illustrates the spectrum sharing for OFDMA and NOMA for two users' cases. In NOMA, superposition coding at the transmitter and Successive Interference Cancellation (SIC) at the receiver make it possible to utilize the same spectrum for all users.

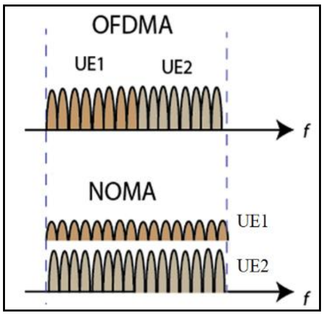


Fig. 11. Spectrum sharing for OFDM and NOMA for two users [109]

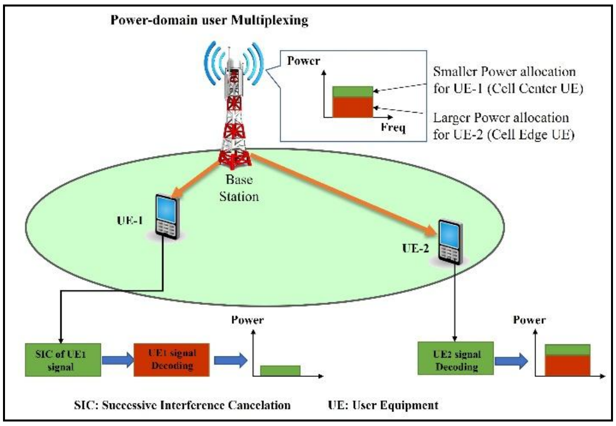


Fig. 12. Illustration of downlink NOMA with SIC.

In Fig. 12, the NOMA downlink channel was depicted with SIC for the case of one BS and two user equipment (UEs). More power is allocated to the UE located farther from the BS and the least power to the UE closest to the BS. All UEs receive the same signal that contains the information for all users. Each UE decodes the strongest signal first, and then subtracts the decoded signal from the received signal. SIC receiver iterates the subtraction until it finds its own signal.

8) Energy Harvesting (EH) Technology

Prospective 6G applications, which are presented in Table II, have significant energy consumption since in the THz band, data is transmitted at a very high bit rate and sophisticated signal processing is required. In addition, the structure of the 6G node will be reliant on AI, which requires more energy. Consequently, 6G systems must implement the energy harvesting (EH) principle to sustain charging and energy saving [7], [110], [111]. Prolonging the battery life of the mobile set is another subject to be achieved by using EH. The main aspects which can contribute to achieving the EH goal are illustrated below and depicted in Fig. 13:

- A low peak to average power ratio (PAPR) modulator.
- Terrestrial and drone communications can be supported by solar energy.
- Vibration and kinetic energy can power human body wearables.
- Industrial IoT devices can be powered by thermal energy that is produced from industrial manufacturing and production processes.
- Ground BSs can be powered by RF energy emitted from other BSs.

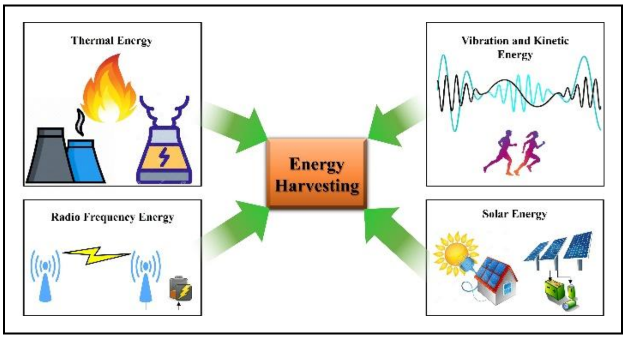


Fig. 13. Energy harvesting scenarios in future 6G network.

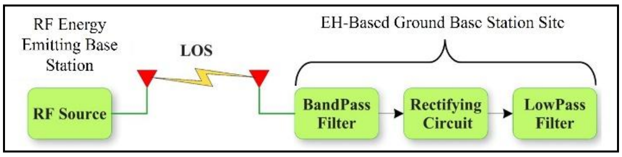


Fig. 14. Energy harvesting-based mobile base station site.

As an example of one of the aforementioned EH resources, the RF EH fitted with an energy conversion circuit as indicated in Fig. 14. The rectifier will be injected with maximum signal power thanks to the bandpass filter, which includes a resonant circuit with a resonance frequency equal to the received carrier frequency. For maximal EH, a line of sight (LOS) must be established between the energy donor BS and the EH node [112], [113].

9) FSO backhaul technologies

Backhaul is the connection of the cellular system to the core network or to the Internet through the following facilities:

- Microwave links.
- Fiber optic connection.
- VSAT satellite terminal.
- FSO link.

One of the key benefits of 6G is the exploiting of the enormous bandwidth that exists in the sub-THZ spectrum. However, sub-THZ implementations are limited in coverage and require a higher density of tiny BSs, as indicated in Fig. 15, which can greatly raise the cost. The deployment of backhaul fiber is one of the primary ways to decrease this cost. FSO wireless backhauling is the preferred alternative for 6G networks over fiber optic since it has a reasonable installation cost and can be deployed in a shorter amount of time than standard fiber optic. Below, we list the primary factors that make FSO more desirable than fiber optic links [114], [115].

- In order to lay optical cable underground, it necessitates enormous expenditures, and obtaining approval from a variety of authorities is costly and time-consuming.
- In urban areas, the fiber optic network is projected to cost between 100,000 and 200,000 USD per kilometer. Trenching and installation procedures account for nearly 85 percent of total expenditures.

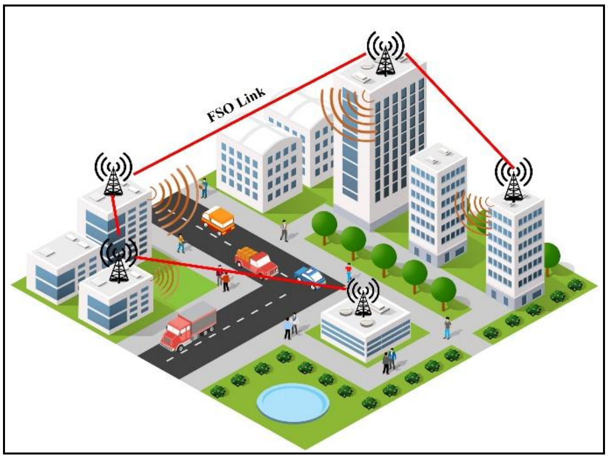


Fig. 15. 6G small cell configuration.

- Trenching and excavating streets are not only costly but also generate traffic congestion (which increases air pollution), uproot trees, and sometimes demolish historical sites.
- The FSO technology using eye-safe infrared lasers provides fiber cable-like speed, does not require authorization, and can be rapidly installed and configured.
- FSO is an unlicensed band that does not require a fee to use.

Unfortunately, the primary drawbacks of the FSO connection include fading caused by fog, rain, and dust [116], [117].

FSO is a line-of-sight technique that replaces the labor-intensive installation of optical fiber or wireless micro/mmWave RF lines with a light beam from semiconductor lasers for data transfer. FSO has become an adequate complementary technology for 6G future communication networks. Due to its many benefits, including its unregulated bandwidth, no electromagnetic energy effect, high level of security, and frequency in THz, as shown in Fig. 16, FSO can be spectacularly employed as a back-hall communication link to connect various data communication terminals [118].

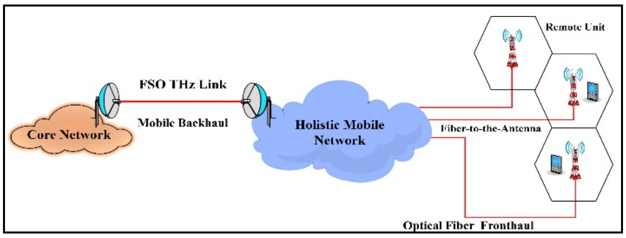


Fig. 16. FSO backhaul link for 6G mobile system.

FSO technology transmits data through the air using safe, low-power infrared. An FSO link can be easily mounted behind windows or on rooftops. It can achieve transmission distances of up to a few kilometers, depending on atmospheric conditions. Although FSO is an unlicensed transmission, the radiation power cannot exceed the International Electrotechnical Commission's standards (Standard IEC60825-1) [115], [119].

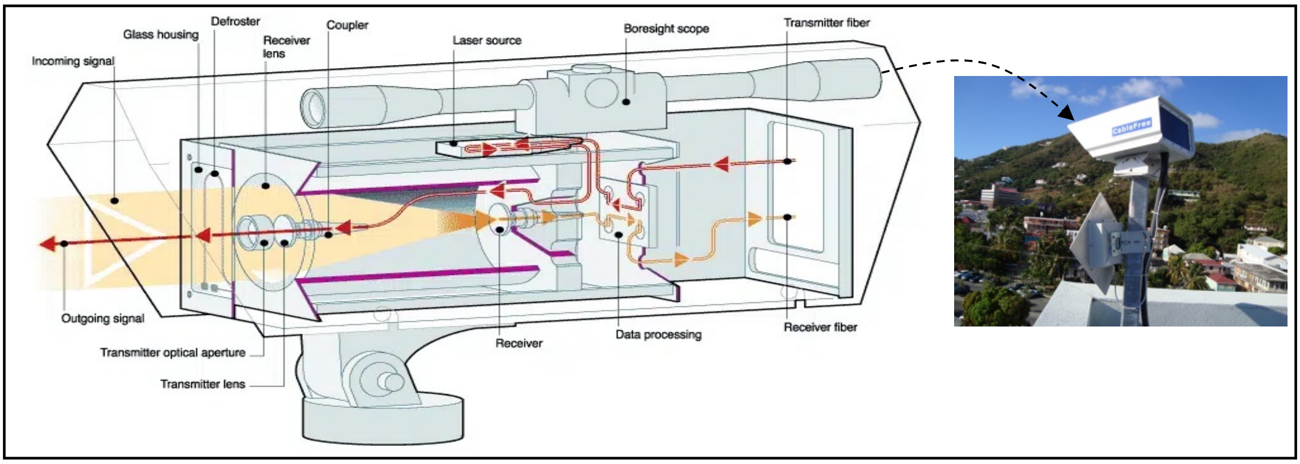


Fig. 17. FSO transceiver for outdoor application [115], [120].

Typically, FSO equipment operates at either 850 nm or 1550 nm wavelengths. Lasers with a wavelength of 850 nm are significantly less costly than those with a wavelength of 1550 nm (about $30 versus over $1000 for a 1550 nm laser) and are thus preferred for applications at moderate distances. In actuality, the 1550-nm laser is preferable to the 850-nm laser for reasons pertaining to power, distance, and eye safety. The cornea absorbs the vast majority of the 1550 nm infrared light, preventing it from reaching the retina. Accordingly, regulations permit these longer-wavelength beams to operate with around two orders of magnitude more power than 850-nm beams, which may increase the link range by a factor of at least five. Alternately, the data rate might be significantly increased throughout the same range. An 850-nm unit with a bit rate of around 100 Mbps and a connection distance of a few hundred meters costs approximately $5000, while a 1550-nm unit with a bit rate in the Gbps range and a link distance of up to 2 km costs approximately $50,000. Fig. 17 depicts an FSO transceiver with the outdoor unit. It demonstrates that the received laser beam (orange) is significantly wider than the transmitted beam (red). Consequently, the receiver lens is significantly bigger than the transmitter lens. Both lenses, which share a common axis, are housed in a glass case with an inbuilt defroster for use in cold settings [115], [120].

10) 6G Security Issue

By the years 2030 and beyond, 6G networks will be indispensable in order to satisfy the demands of a highly interconnected human civilization. 6G is expected to pave the way for the development of numerous new technologies, including advanced AI techniques, AI-driven air interfaces, AI-powered automated devices, humanoid robots, quantum computing systems, self-sustained networks, and smart surfaces [11], [121]. On the other hand, there are significant worries that the level of security provided by 6G as well as privacy may be worse than that of earlier mobile generations. For instance, the integration of connected devices into every aspect of the human body (e.g., implants/cyborgs) raises grave concerns about the possibility of data breaches (e.g., health records). In addition to wealth and reputation, life itself may be at risk in the event of a security breach (e.g., a tragic collision resulting from cyberattacks against autonomous driving systems) [122].

The security framework of the 6G system was created with transparency in mind. Due to 6G's intention to be an even more open network than 5G, the boundary between inside and outside the network will gradually blur. This means that standard precautions against network intrusion, such as IPsec and firewalls, will be ineffective. To solve this problem, the 6G security framework must support the core security principle of Zero Trust (ZT) in the network of mobile communications [123].

Wireless communications performance relies heavily on its ability to secure users' personal information; hence, this is a feature that must be present at all times [11], [124]. Numerous initiatives and ideas have been made to address security and privacy concerns in the 6G era by integrating emerging technologies like blockchain, Visible Light Communication (VLC), THz band, and quantum computing and communication characteristics into 6G intelligent networking paradigms [11], [124]. Many existing approaches focus on providing security against threats, but AI improves upon this by making defenses more robust and proactive [122]. And with all this focus comes a slew of new privacy and security concerns, where security risks evolve as time goes on, and so do the adversaries who pose them. As a result, it will be more important than ever to build 6G networks with intelligent and adaptable security systems that can predict, detect, mitigate, and prevent security threats as well as limit the propagation of such vulnerabilities [125].

In addition, quantum computing and networking will also be used in future computing and 6G communication systems. The use of quantum computing based on quantum cryptography provides an additional layer of security for stored information, surpassing that of traditional cryptography [126]. In this article, the top security solutions related to the 6G system will be discussed:

i) Physical layer security

Since security techniques are distributed across a network's layers, they may work in combination to provide robustness in protection, or they can be employed in subsets of layers for applications with limited resources. Due to its central role in wireless communications, the physical layer must be safeguarded from common attacks on radio signals, including eavesdropping and jamming, which can have far-reaching consequences for practically any application [122]. Physical Layer Security techniques will be developed by 6G to give an adaptable extra layer of security within the context of emerging enabling technologies, as seen below [11].

Terahertz technology (THz): Compared to the mmWave range, the THz band provides more available spectrum for communication. Furthermore, it makes use of electromagnetic waves as well as light waves. THz communication's narrow beam and short pulse duration would make eavesdropping more difficult, making it a more secure communication [123], [124]. However, it has been demonstrated that a signal may be intercepted in a Line-of-Sight (LoS) transmission by scattering radiation towards the eavesdropper. The anti-eavesdropping method, based on backscatter characterization, can be used to identify some eavesdroppers but not all [127], [128]. According to another study, eavesdroppers might intercept THz transmissions using narrow beams. This study developed several resistant security solutions against such narrow beam attacks [129]. Undoubtedly, THz communications are susceptible to access control threats, illegal activity, and unsecured data transfer. Therefore, to secure THz communications, new Physical Layer Security solutions are necessary, such as electromagnetic signatures of materials and devices at THz frequencies for authentication techniques [124].

Visible Light Communication (VLC) Technology: VLC (also known as FSO) is an optical wireless technology whose benefits over Radio Frequency (RF) systems have generated considerable interest. VLC systems can provide a better level of security than RF systems since light cannot pass through barriers. Nevertheless, VLC systems are susceptible to eavesdropping by unauthorizable nodes positioned inside the coverage area of transmitters because of their nature in broadcast and LoS propagation. The privacy of VLC systems is an important factor for making them work in the real world, and Physical Layer Security techniques can help with this. For example, VLC's accurate localization capabilities combined with ML approaches may be employed for anomaly detection [121], [130].

Reconfigurable Intelligent Surface (RIS): With the development of metamaterials and micro electromechanical systems, RIS has emerged as a promising choice for addressing the challenges of intelligent environments in terms of security, energy efficiency, and spectral efficiency. RIS is a software-controlled metasurface that consists of a planar array antenna composed of a huge number of passive and low-cost reflecting elements that are capable of dynamically adjusting their reflective coefficients, thereby controlling the amplitude and/or phase shift of reflected signals to improve the wireless propagation performance, including security [125].

Molecular Communication (MC): MC is a potential technology for 6G in a range of healthcare applications since it allows bio nano-machines to connect in an aqueous environment utilizing molecules or chemical signals. Safe MC is essential since it handles highly sensitive data, which raises several security and privacy concerns in the areas of authentication, communication, and encryption. Consequently, the concept of biochemical cryptography was presented, where the composition and structure of a biological macro-molecule might be employed to secure data [125].

ii) Quantum Computing

The transfer of quantum bits is closely linked to quantum networks and quantum computers. Quantum bits, also known as qubits, are the basic units of data transmission in a quantum computing network. When compared to traditional bits in computers, which can only ever be either 1 or 0, qubits have the unique ability to hold both states at once [126]. In addition, the same computational problems that can be performed on a modern computer could also be performed on a quantum computer, and vice versa. On the other hand, superposition of entangled qubits allows for an exponential speedup in performing certain sorts of problems compared to the conventional method of computation.

Consideration is being given to quantum computing as a viable solution for detecting, mitigating, and preventing security issues in 6G networks. Safe 6G communications may be achieved by the integration of post-quantum encryption and physical layer security schemes. Furthermore, in order to reach the highest level of reliability in 6G networks, researchers are investigating the possibility of using noiseless classical communication channels to replace quantum channels. Quantum communication may greatly improve the security and reliability of data transfer in 6G networks, which is one of its principal advantages. In quantum communication, if an attacker eavesdrops, measures, or duplicates anything, the quantum state will be changed. Thus, the recipient cannot be oblivious to the interference [30], [131]. As quantum computing continues to advance at a rapid pace, cryptography that is quantum-safe is expected to become standard practice in the era of post-quantum. Current asymmetric cryptography depends on solving the discrete logarithmic problem, which may be possible with quantum computers in polynomial time [11], [132]. Quantum cryptography and quantum key distribution (QKD) have promising future uses in a wide variety of 6G applications, including ocean communication, satellite communication, terrestrial wireless networks, and THz communications systems. Standard key distribution techniques can use QKD, which uses quantum physics to generate a shared secret key between trusted parties [133].

iii) Blockchain

It might be said that blockchain technology is the most-hyped breakthrough of the 21st century, as it was developed to support bitcoin and now powers several globalist applications and is reported to be the dominant technology for supporting 6G technologies. Blockchains are a type of digital ledger of transactions (DLT), a special kind of database that can record encrypted transaction data in chronological order, and these records, or "blocks," are linked together to form the entire ledger, each of which contains a small list of transactions and is chained together [134], [135].

Future 6G networks will rely heavily on blockchain technology to build trust. Since it has numerous possible applications within a 6G network, it is expected to be one of the primary supporting technologies that guarantees privacy and uniqueness for all 6G-enabled devices, services, and applications. Recently, the telecommunications sector has paid close attention to it [135]. The 6G networks, with their unparalleled speed and capacity, vast connectivity, and unique services, are expected to significantly improve the efficiency of blockchain-based applications. Blockchain's benefits include the following: (i) decentralization by eliminating centralized trusted third parties and intermediaries; (ii) transparency with confidentiality; (iii) transaction authenticity and non-repudiation; (iv) immutability and tamper-proofing of distributed ledger content; (v) elimination of a single point of failure (improved resilience and resistance to attacks such as DDoS); and (vi) reduced processing times and costs [136]. These blockchain benefits are essential to enabling trusted and secure 6G network services.

The fundamental concept of a blockchain relies on a decentralized, peer-to-peer network architecture in which all peers process and verify transactions independently [137]. So, the blockchain doesn't keep track of its data in a central location. Instead, people in the network copy and share the blockchain (i.e., computers). When the blockchain receives a new block, all computers in the network will update their copies of the blockchain. Because it is distributed (decentralized), blockchain operations are strong and safe, and they can run reliably without the risk of a single point of failure. A blockchain is not owned by any network authority, therefore it may be accessed by anybody. The consensus protocol makes this feasible by establishing ground rules for achieving widespread unanimity on the blockchain ledger's state. Fig. 18 depicts the general blockchain operation concept [137].

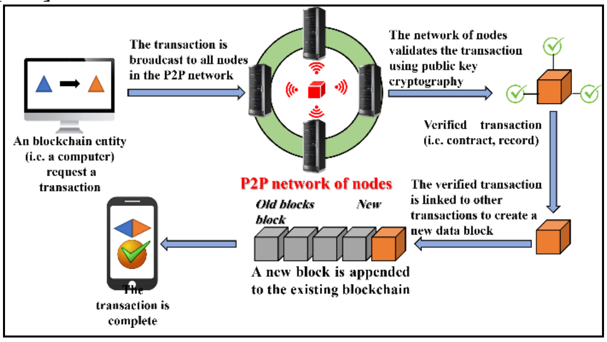


Fig. 18. The concept of blockchain operation.

There are certain obstacles to overcome in order to successfully incorporate blockchain technology into 6G mobile networks. Blockchain's built-in transparency improves confidence and makes it simple to verify and trace transactions, but it may have unintended consequences for users' privacy [138]. Nevertheless, there has not been much research done into how blockchain integration and multifactor authentication might be used in a 6G network. Multifactor authentication mechanisms developed for 5G and previous networks may be improved for the 6G system in the future. The fact that 6G network technology is still mostly theoretical is a potential issue for this field. Hence, researchers will need to put the actual methods to the test on real networks and in simulated settings [135], [139].

iv) Cryptography and the Development Towards 6G

Scientists have already begun looking into quantum resistant technology and encryption options in order to be prepared for the threat posed by quantum computing in the next 6G era. Lattice-based, code-based, hash-based, and multivariate-based cryptography are some of the few post-quantum cryptographic primitives [125], [140]. There are two categories of cryptography [141]:

- Symmetric cryptography, both parties must use the same secret key in their communication. Stream ciphers, block ciphers, cryptographic hash functions, and message authentication codes are all examples of conventional cryptographic primitives. A secure channel is still required for symmetric cryptography to generate the shared secret key.
- Asymmetric cryptography, also known as public-key cryptography, eliminates the need for a shared secret key. A set of keys, one private and one public, is utilized instead. This category includes things like key exchange protocols used to set up public-key encryption, digital signatures, and symmetric-primitive-based key exchanges. The private key is the only one of the two keys that is protected. For instance, to encrypt a message to the key's owner or verify digital signatures, the public key is required. For tasks like decrypting or creating signatures, for instance, a private key is required.

Symmetric cryptography has been the basis of authentication up to 4G and into the recently deployed 5G. A Subscriber Identity Module (SIM) card stores the shared key. In 4G, authentication takes place only between the user equipment (UE) and the mobility management entity, and the Authentication and Key Agreement (AKA) protocol uses symmetric primitives for this purpose. Authentication in 5G must also include service providers and other third parties, hence a more flexible authentication system is required. Furthermore, the SIM card approach is not optimal for IoT devices, so other strategies have been developed. Three authentication protocols, which are (5G AKA), Extensible Authentication Protocol-authentication and Key Agreement (EAP-AKA), and Extensible Authentication Protocol-Transport Layer Security (EAP-TLS), are presently defined by the 5G standard. The first two use symmetric cryptography. The third, on the other hand, is based on asymmetric cryptography and was introduced specifically to enable IoT applications. At the data link layer, the EAP is compatible with a wide variety of authentication methods, while TLS is a group of cryptographic protocols that ensure the authenticity, privacy, and integrity of transmitted messages [142].

It is expected that 6G will serve as the primary link between the digital and physical worlds. The trend toward cloud and edge native infrastructures, which began in 5G, is going to continue in 6G. Virtualization and software-defined capabilities will grow in popularity. To decrease latency, computations will be conducted both in the cloud and on the network's edge. As cyber-attacks threaten individuals' physical safety, the robustness of systems will become increasingly important. Nonetheless, efforts are being made to standardize post-quantum secure quantum cryptography. Quantum cryptography is an encryption technique that utilizes the inherent features of quantum physics to protect and transmit data in an unbreakable manner. Quantum cryptography, or QKD, employs photons (light particles) to send data across a fiber optic cable or FSO link. By comparing measurements of the characteristics of a small number of these photons, the two terminals may determine what the key is and if it is secure to utilize according to the procedure below [143], [144].

- The transmitter sends photons via a filter (or polarizer) that assigns them randomly to one of four polarizations and bit designations: vertical (one bit), horizontal (zero bit), 45 degree right (one bit), or 45 degree left (zero bit).
- The photons proceed to a receiver, which utilizes two beam splitters (horizontal/vertical and diagonal) to "read" each photon's polarization. Because it doesn't know which beam splitter to use, the receiver has to guess which one to use for each photon.
- Once the photon stream has been transmitted, the receiver informs the sender which beam splitter was used to deliver each photon, and the sender verifies this information with the sequence of polarizers used to transmit the key. The photons that were read with the incorrect beam splitter are eliminated, and the key is made from the remaining bit sequence.

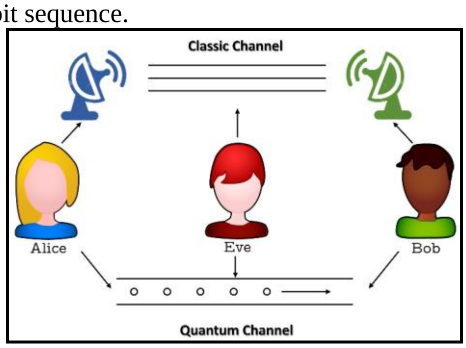


Fig. 19. Quantum cryptography model.

The photon's status will be affected if an eavesdropper reads or copies it in any way. Endpoints will detect the modification. In other words, it would be impossible to read the photon, send it, or duplicate it without being noticed. The core model for QKD protocols is depicted in Fig. 19. Alice and Bob are the two people involved in this scenario, and they want to exchange a key via both a regular public channel and a quantum channel. It is presumed that Eve, the eavesdropper, has access to both channels, but no other assumptions regarding her capabilities are made.

If Alice and Bob want to communicate privately via a public channel (like the Internet), they'll need to encrypt their message. Thanks to their shared secret key, Alice and Bob can use symmetric-key cryptography to exchange messages securely. If Alice and Bob want to utilize Eve's traditional communication channel to trade their key, they must have complete confidence in Eve that she is not listening. Whether they want to use Eve's channel, though, it is not easy to tell if she has not created a copy of the key for herself. To the contrary, if Eve provides a quantum communication channel, Alice and Bob do not have to trust her since they will be alerted if she tries to read Bob's message before it reaches Alice. A fiber optic cable is one candidate for use as a quantum communication channel, as it may be used to transmit individual photons (particles of light). The polarization of a photon is a characteristic that can have a value of 0 or 1. Alice and Bob employ polarized photons as the basis for their secure key. Alice sets up the polarization of each photon in one of two bases, H/V (horizontal/vertical) or +45/-45, by positioning a polarizer in one of these four orientations. The vertical and -45 degree orientations receive the number 1, whereas the horizontal and +45 degree orientations receive the value 0. The states |H>, |V>, |+45>, and |-45> correspond to photon polarization orientations in this scenario. In this protocol, the state of a qubit may be changed by measuring it. Alice could give Bob a qubit in one state, but if Eve measures it before Bob does, the state may be altered, and Bob would not receive the qubit Alice intended. Eventually, Alice will figure out that there is an issue with their transmission. Multiple iterations of this process are included in the QKD protocol to prevent an eavesdropper from successfully exploiting a vulnerability in the system [126].

Lastly, the National Institute of Standards and Technology (NIST) of the US launched a multi-year project in 2016 to find a standard suite of quantum-resistant cryptographic systems by 2024 [145].

VI. 6G Main Non-Technological Challenges

In addition to the technical challenges listed in Section V, the realization of the 6G system has "non-technological challenges" linked to a variety of domains, including battery-recharge time, economic and environmental concerns, and health issues. Below is a basic description of the various categories of non-technological challenges:

A. Battery-Recharge Period Challenge

Battery-recharge period becomes one of the challenges in the domain of smartphone device manufacturing since their power consumption is increased as a result of enhanced functions that require sophisticated multimedia signal processing. At the 6G system level, we talk about 257 GB of traffic volume per month per subscription, so the charging period will become shorter if we keep the traditional wire charging method and even if we use the most up-to-date manufacturing process in the battery manufacturing domain. An attractive solution for the durability of battery power for mobile phones is to recharging the battery over the ether by adopting wireless communication techniques. Wireless power transmission, or wireless charging, is the technology of transmitting electrical power from a power source to electronic devices or batteries without using wires. The benefits of wireless charging have been summarized in terms of user convenience, product durability, usage flexibility, and on-demand availability. Therefore, with the advent of 6G, it is believed that energy harvesting via radio waves or laser beams will be widely adopted to enable wireless charging of mobile phones [146]–[148].

B. Economic and Environmental Challenges

The actual chemical materials used in mobile phone batteries are not environmentally friendly, especially when they accumulate in large quantities and for long periods in nature, and this important factor has prompted specialists to plan to secure the charging power of the 6G phone system by harvesting the energy emitted by radio waves in order to achieve in the future what we call free battery devices [146]. There is still a kind of disregard for the impact of communication equipment on environmental and economic factors, especially what is emitted from toxic waste resulting from electronic materials that enter into the manufacture of such systems when they disappear. In addition, the excessive number of equipment connected to the internet constitutes an important proportion of electronic waste that may reach tens of millions of tons [146], [149]. What is worrying is the increase in these numbers and their effects on environmental health due to the presence of toxic substances such as chromium, mercury, and arsenic in computers and mobile phones, which requires a focus in the future technology of 6G on the issue of recycling electronic materials according to international standards and to increase the performance of disposing of this waste with a focus on spreading awareness among consumers in this field. The future use of environmentally friendly biological materials in the field of electronic materials industry is one of the most effective ways to reduce the impact of electronic waste and to facilitate the electronic recycling process while saving the energy needed for production processes, which is directly reflected in the economic field [150].

C. Health Challenges

Related to electromagnetic radiation, the electromagnetic spectrum consists of two regions: the lower one is the non-ionized region, which represents the source of the "nonionizing radiation", while the upper one is the ionized region, which represents the source of the "ionizing radiation", as depicted in Fig. 20 [8], [73], [74].

Unlike nonionizing radiation, ionizing radiation has sufficient energy to destroy the atom by removing the electrons from its orbit, causing the atom to move to the ionization state, which causes a health risk by damaging tissue and DNA. Since the Terahertz band is situated in the nonionized region, then by logic, its radiation is insufficient to destroy the atom [151]. The World Health Organization (WHO) has taken steps to safeguard the public from the harmful effects of radiation by launching a radiation protection program. In order to manage the amount of radiation that people are exposed to.

As we have plenty of time to enter the 6G area, now is the time to achieve sufficient research to establish with absolute certainty that Terahertz radiation poses no health risks other than heating [8], [71], [73], [74].

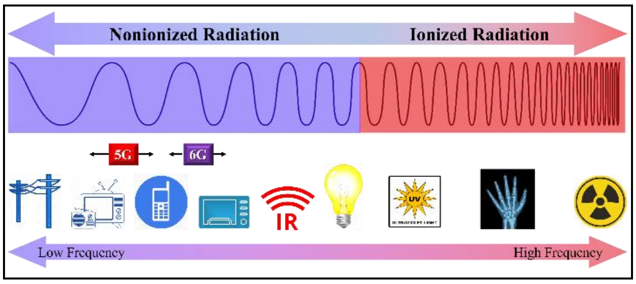


Fig. 20. Ionized and nonionized bands.

VII. Conclusion

In conjunction with the actual 5G updating process, researchers have already begun designing a new core for the 6G system. As expected, by 2030, the 6G mobile system, operating in the THz band and AI-based, will be employed internationally. The FSPL, the atmospheric absorption loss, the lack of technology, and security are the biggest challenges that need to be solved so as to guarantee the propagation of waves in the new Terahertz band up to the desired distance. To overcome the main 6G challenges, an evaluation of the most significant 6G enabling technologies was conducted. For the future 6G mobile system, a highly efficient beam-forming technique should be used at the BS level to achieve the required high gain. In addition to the technical challenges, non-technological challenges linked to a variety of domains, including battery-recharge time, economic and environmental concerns, and health issues, were also considered.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

All the authors had written the paper and approved the final version.

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