

Review

# Sixth Generation (6G) Wireless Networks: Vision, Research Activities, Challenges and Potential Solutions

Mohammed H. Alsharif <sup>1</sup>, Anabi Hilary Kelechi <sup>2</sup>, Mahmoud A. Albreem <sup>3</sup>,  
Shehzad Ashraf Chaudhry <sup>4</sup>, M. Sultan Zia <sup>5</sup> and Sunghwan Kim <sup>6,\*</sup>

<sup>1</sup> Department of Electrical Engineering, College of Electronics and Information Engineering, Sejong University, 209 Neungdong-ro, Gwangjin-gu, Seoul 05006, Korea; malsharif@sejong.ac.kr

<sup>2</sup> Department of Electrical Engineering and Information Engineering, College of Engineering, Covenant University, Canaanland, Ota P.M.B 1023, Ogun State, Nigeria; kelana05@yahoo.com

<sup>3</sup> Department of Electronics and Communications Engineering, A'Sharqiyah University, Ibra 400, Oman; mahmoud.albreem@asu.edu.om

<sup>4</sup> Department of Computer Engineering, Faculty of Engineering and Architecture, Istanbul Gelisim University, Avcilar, 34310 Istanbul, Turkey; sashraf@gelisim.edu.tr

<sup>5</sup> Department of Computer Science and IT, University of Lahore, Gujrat Campus 50180, Pakistan; sultan.zia@cs.uol.edu.pk

<sup>6</sup> School of Electrical Engineering, University of Ulsan, Ulsan 44610, Korea

\* Correspondence: sungkim@ulsan.ac.kr; Tel.: +82-52-259-1401

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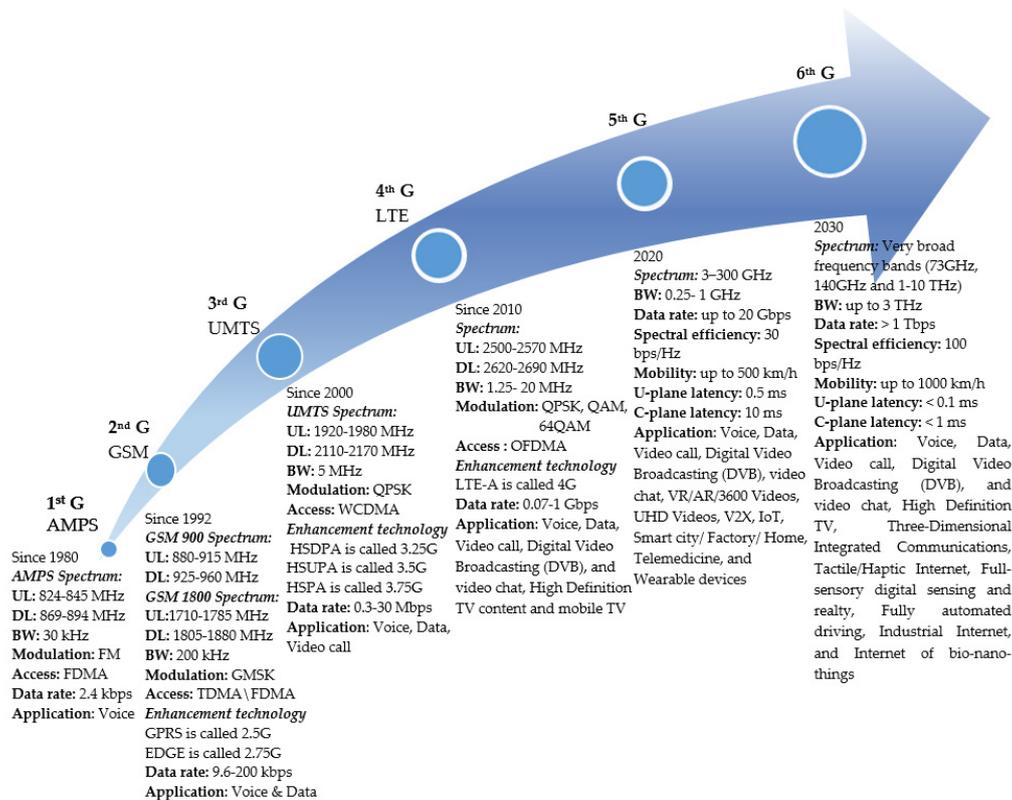
**Abstract:** The standardization activities of the fifth generation communications are clearly over and deployment has commenced globally. To sustain the competitive edge of wireless networks, industrial and academia synergy have begun to conceptualize the next generation of wireless communication systems (namely, sixth generation, (6G)) aimed at laying the foundation for the stratification of the communication needs of the 2030s. In support of this vision, this study highlights the most promising lines of research from the recent literature in common directions for the 6G project. Its core contribution involves exploring the critical issues and key potential features of 6G communications, including: (i) vision and key features; (ii) challenges and potential solutions; and (iii) research activities. These controversial research topics were profoundly examined in relation to the motivation of their various sub-domains to achieve a precise, concrete, and concise conclusion. Thus, this article will contribute significantly to opening new horizons for future research directions.

**Keywords:** wireless networks; beyond 5G; 6G; 6G mobile communication; terahertz communications; holographic communications; terahertz spectrum; visible-light communications

## 1. Introduction

Wireless communication systems are the Eureka equivalents of our time given the rapid technological innovations in the last decades and symmetry technologies for the Internet of Things. To date, five (5) generations of mobile wireless cellular communications systems exist, with the recent generation being the fifth generation (5G) wireless network. A wireless cellular communication generation emerges approximately every 10 years since 1980, including the first generation analog FM cellular systems in 1981, the second generation in 1992, the third generation (3G) in 2001, and the fourth generation (4G) (often referred to as the long-term evolution [LTE]) in 2011 [1,2]. Figure 1 presents a synopsis of the evolving wireless technologies. Generally, the last decade has witnessed a tremendous development in wireless communications which led to thriving data-hungry applications,

including multimedia, online gaming, and high-definition video streaming. The booming mobile Internet technology is the catalyst enabling and propagating various state-of-the-art user-defined services, such as mobile shopping and payment, smart homes/cities, and mobile gaming [1,3].



**Figure 1.** Major milestones for different generations of communications (1–6G).

The standardization of 5G communications has been completed, and the system is being deployed worldwide. Figure 2 shows the 5G commercial network world coverage map (5G field testing/5G trials/5G research). South Korea was the foremost nation to adopt substantial 5G deployment on a large scale for approximately 85 cities with 86,000 5G base stations as of April 2019 [4]. However, 85% of the 5G base stations were located in six cities, including Seoul, Busan, and Daegu, where a 3.5 GHz (sub-6) spectrum in distributed architecture with deployed data rate speed tested speeds in the range of 193 to 430 Mbit/s [5]. In general, close to 65% of the world's population are estimated to gain access to 5G superfast 5G Internet coverage by the end of 2025 [6].

5G networks will deliver an extensive variety of services comprising enhanced mobile broadband (eMBB), ultra-reliable and low-latency communications (uRLLC), and massive machine type communications (mMTC); for detailed information about the vision, requirements, and core features of 5G wireless cellular mobile communication networks, refer to [2,7–9]. However, wireless data traffic volume and the magnitude of connected things are expected to leap to hundredfold of equipment in a given cubic meter. Moreover, data-hungry apps such as sending holographic videos needs a spectrum bandwidth that is currently unavailable in the mm-wave spectrum. This situation presents difficult challenges on an area or a spatial spectral efficiency and the needed frequency spectrum bands for connectivity. Hence, a broader radio frequency spectrum bandwidth has become a necessity and can only be found at the sub-terahertz (THz) and THz bands. Moreover, the recent upsurge of diversified mobile applications, especially those supported by Artificial Intelligence (AI) technology, is spurring heated discussions on the future evolution of wireless communications [10]. These challenges have motivated industry and academia to start conceptualizing the next generation of wireless communication systems (6G) aimed at providing communication services for the future demands

of the 2030s [11] and maintaining the sustainability and competitiveness of wireless communication systems. Thus, the 6G communication systems are expected to provide a large coverage that allows subscribers to communicate with one another everywhere with a high data rate speed due to the unconventional technologies that will be adopted by 6G communication systems, such as an extremely large bandwidth (THz waves) and high AI that include the operational and environmental aspects as well as the services of the networks. Figure 3 presents the timeline of 6G communication.

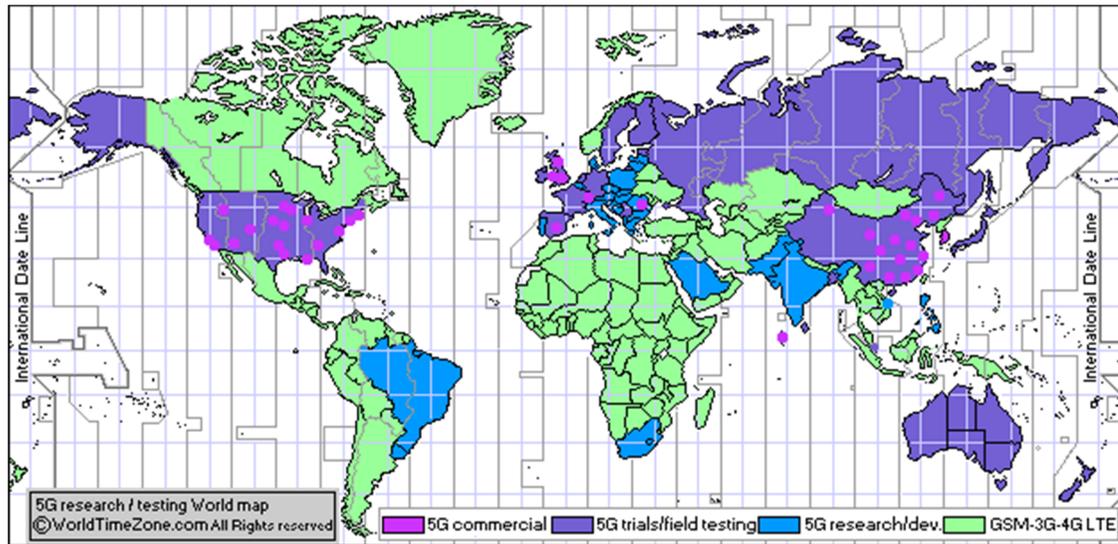


Figure 2. 5G commercial network world coverage map (December 2019) [12].

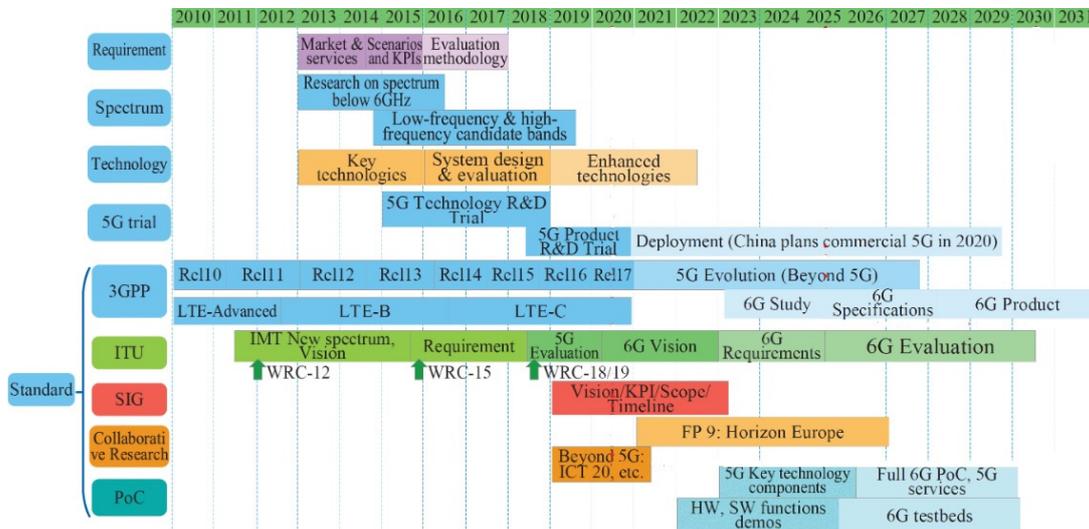


Figure 3. Timeline of 6G wireless networks [11].

The first ever 6G wireless cellular mobile communications symposium took place in March 2019 and can be framed into one big vision statement of ubiquitous wireless intelligence [13]. The 6G system is expected to witness an unparalleled revolution that would significantly distinguish it from the existing generations and will drastically re-shape the wireless evolution from “connected things” to “connected intelligence.” Specifically, 6G will transcend mobile Internet and will be required to support ubiquitous AI services from the core to the end devices of the network. Quintessentially, AI will be the driving force in designing and optimizing 6G architectures, protocols, and operations [11,14].

The current study aims to present the latest state-of-the-art developments in relation to the vision, challenges, and potential solutions as well as the research activities for 6G communications.

Accordingly, it attempts to integrate many likely solutions. Given the size constraint, this study thoroughly examined thought-provoking research areas by detailing their specific sub-domains to achieve precise, concrete, and on-the-spot deductions. The major contributions of this study are summarized as follows:

- This work presents a comprehensive overview of controversial research topics on 6G communications covering the recent industry development in the context of the main areas of services, difficulties, and major actors. We summarize the core domains of the research topics as (i) vision and key features; (ii) challenges and potential solutions; and (iii) research activities. These areas were rigorously investigated on the basis of their respective sub-domains to achieve a precise, concrete, and concise conclusion;
- The challenges associated with 6G communications stem from five key components including the provision of network security and data privacy enforcement, attaining a cost-effective approach toward rapid network deployment and expansion with emphasis on remote and stand-alone areas, reduction in the price of mobile communications' utilization, approaches to extend mobile equipment battery life longevity, and attaining a high data rate buoyed with an end-to-end, ultra-reliable, low latency regime. Notably, satisfying all features is impossible. Nonetheless, tradeoffs between these features should exist, thereby leading to a delicate balance between needs and wants. This study highlights a set of tradeoffs including the key challenges and potential solutions for 6G communications;
- For researchers, this article will contribute significantly to opening new horizons for future research directions by providing several new references that could support the pursuit of enabling 6G communication.

Figure 4 illustrates the outline of the paper. Section 2 presents a detailed vision of 6G communication with a focus on key features. Section 3 provides a detailed discussion of a set of tradeoffs, including key challenges and potential solutions for 6G communications. Section 4 highlights the current progress of research activities. Finally, Section 5 concludes the work.

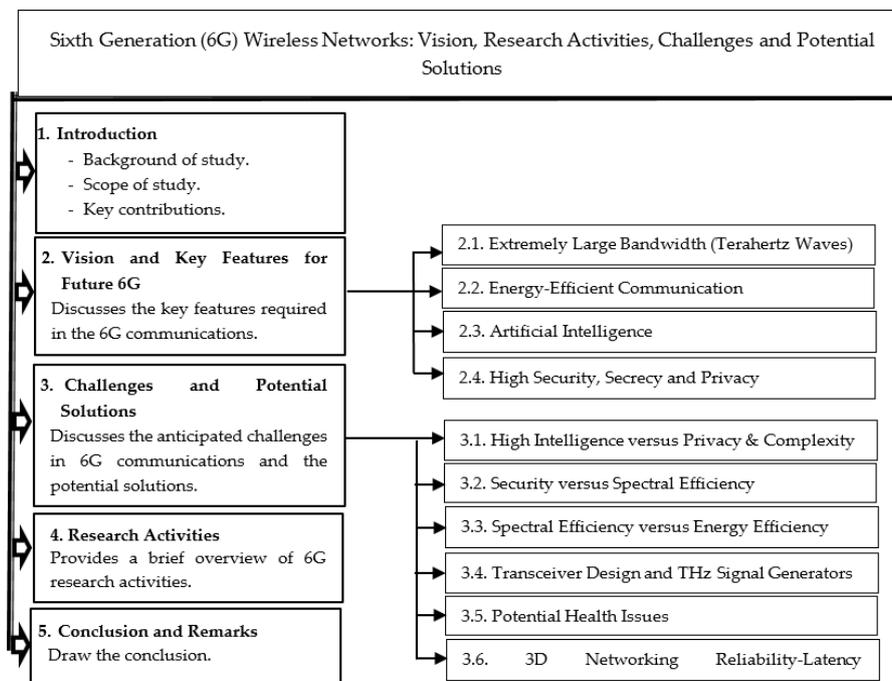


Figure 4. Schematic map of the structure of this paper.

## 2. Vision and Key Features for Future 6G Networks

Given the massive capabilities of 5G cellular mobile wireless communications networks and their likely evolution, is there any tangible rationale for 6G networks? If yes, then, what are the missing units from LTE and 5G that 6G must integrate? Academicians, industries, and research communities have set out research modalities on the formulation, definition, design, and identification of important core-enabling technologies driving the initiation toward a “beyond 5G” or 6G system [15,16]. This section will cover a large range of topics discussed in recently published works about the vision and key features of 6G communications. First, this section starts with a brief view of the expected applications that will be supported by 6G communications and which will lead to identifying the key features that are required in such communications.

The following are five expected scenarios of applications that will be supported by 6G communications:

- eMBB-Plus

eMBB-Plus [17,18] in 6G will replace its 5G counterpart of eMBB and provide a high-quality experience (QoE) in data utilization and standards. Notably, other integral components of the wireless communication of network optimization, handover, and interference should be able to exploit the concepts of big data to facilitate these operations. Providing other add-ons such as accurate indoor positioning and a globally compatible connection among diverse mobile operating networks is expected, at an affordable rate for network subscribers. A strategy should be designed for eMBB-Plus communication services without compromising the security, secrecy, and privacy of network subscribers;

- Big communications (BigCom)

BigCom [19] in 6G aims to provide a large coverage of urban and remote areas by maintaining resource balance, thereby allowing subscribers to communicate with one another everywhere with a high data rate speed due to the unconventional technologies adopted by 6G communication systems, such as an extremely large bandwidth (THz waves) and a high AI that will include operational and environmental aspects as well as the services of the networks;

- Secure ultra-reliable low-latency communications (SURLLC)

Vehicular communications in 6G could also largely benefit from SURLLC [19,20]. SURLLC in 6G is an advancement of the URLLC and the mMTC in 5G and has more stringent demands on reliability (higher than 99.999999%) and latency (less than 0.1 ms) coupled in a security framework;

- Three-dimensional integrated communications (3D-InteCom)

Before the evolution of 6G networks, device communication heights were inconsequential, as could be seen from the established propagation empirical models. This situation anticipates change in the 6G 3D-InteCom model [19–22], which highlights the need for a radical change from two to three dimensions, through which the heights of communications nodes must be considered. Some of the notable technologies that have already incorporated this dimension are satellite, unmanned aerial vehicle (UAV), and underwater communications. Thus, the analytical framework designed for 2D wireless communications that stemmed from stochastic geometry and graph theory needs re-adjustment in the 6G environment. Considering the device height leads to the actualization of elevation beamforming with full dimensional MIMO architectures, thereby preventing the need for a different approach for attaining network optimization;

- Unconventional data communications (UCDC)

Currently, the actual meaning and composition of UCDC [19] lack proper definition. Nevertheless, some of the following facets should be addressed: holographic, tactile, and human-bond communications.

- *Holographic communications:* Holographic communications are one aspect that will add glamor to the 6G era. A hologram is a 3D technology that manipulates light rays beamed to an object and subsequently captures the resulting interference pattern using a recording device. In fact, transmitting 3D images without a stereo voice is insufficient to depict the in-person presence characteristics. In the 6G era, reconfigurable stereo audio will motivate the development of a platform for use in capturing several physical presences in each configuration. In other words, ample freedom for entities exists to interact with and modify received holographic data and video if the need arises. Holographic data are expected to consume a high bandwidth and must be delivered over reliable network links [23];
- *Tactile communications:* Holographic communication makes it possible to transmit a virtual vision of close-to-real sights of people, events, and environments. The cinematic experience will be incomplete without deploying a tactile Internet that would allow the real-time conveyance of an image [24]. Some of the expected beneficiaries of this technology are teleoperation, cooperative automated driving, and interpersonal communication. For these technologies, a haptic touch could be easily implemented using communication networks. Realizing this technology may lead to the abolition of the open systems interconnection network model and the adoption of a cross-layer communication-system design. The cross-layer architecture should meet the stringent needs of these technologies. This circumstance may trigger the design of novel physical layer (PHY) schemes that will enhance the implementation of the signaling system designs and waveform multiplexing. Another aspect that requires attention is how to design procedures such as buffering, queuing, scheduling, handover, and protocols that will meet the needs of 6G networks. Obviously, the existing wireless communication systems are incapable of satisfying these needs; hence, over-the-air fiber communication systems require analysis [25];
- *Human-bond communications:* Human-centric communication is expected to be one of the main drivers of 6G communication. With this technology, humans are expected to access and/or share physical features or express physical phenomenon as it is. Invariably, the five human senses will be involved in this project. An example of this technology is the “communication through breath” project, which makes it feasible to read a human bio-profile using exhaled breath, even the interaction with the human body by inhalation using volatile organic compounds [26]. Consequently, such technology facilitates disease diagnosis, emotion detection, collection of biological features, and remote interaction with the human body. Designing a communication system capable of mimicking the five human senses demands interdisciplinary research collaborations. Such research efforts would naturally result in hybrid communication technologies capable of extracting various physical quantities and then distribute them to the intended receiver via secured channels.

Thus, 6G communications are expected to raise the bar currently set by 5G communications with the provision of enhanced services from the perspectives of network data availability, mobile data rate, and seamless ubiquitous connection. In addition, 6G communications will utilize an unusual communication approach to gain acceptance to various mobile data categories and send them via traditional enhanced radio-frequency networks. Such process will allow the novel wireless transmission of feelings with virtual presence and participation. A host of futuristic currently non-existent wireless communication scenarios of the 2030s are predicted in [27], comprising holographic calls and a tactile Internet. 6G will usher in the same reliability as wired networks with a low bit-error-rate considering the type of applications that will be supported. Figure 5 summarizes the key features for future 6G. the THz wireless communications system, AI, and programmable intelligent surfaces are the outstanding concepts among all the blocks listed in Figure 5 [28]. These innovations welcome a radical departure from the traditional design principles and implementation norms practiced in mobile wireless telecommunication industries.

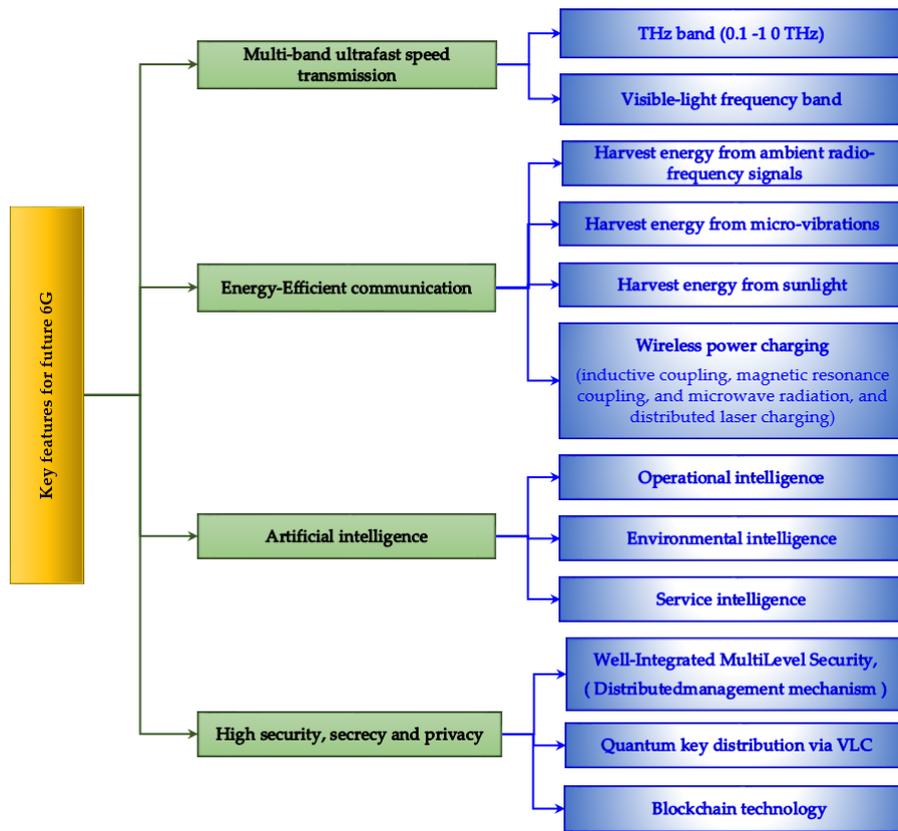


Figure 5. Key features for future 6G.

2.1. Extremely Large Bandwidth (THz Waves)

The wireless data traffic volume and magnitude of connected things are expected to leap by many folds in 6G, specifically in the region of hundred(s) of equipment in a given cubic meter. Moreover, data-hungry apps such as sending holographic videos need a spectrum bandwidth that is currently unavailable in the millimeter-wave spectrum. This situation presents difficult challenges related to area or spatial spectral efficiency and the needed frequency spectrum bands for connectivity. Hence, a bigger radio frequency spectrum bandwidth has become necessary and can only be found at the sub-THz and THz bands, often referred to as the gap band between the microwave and optical spectra (Figure 6) [29].

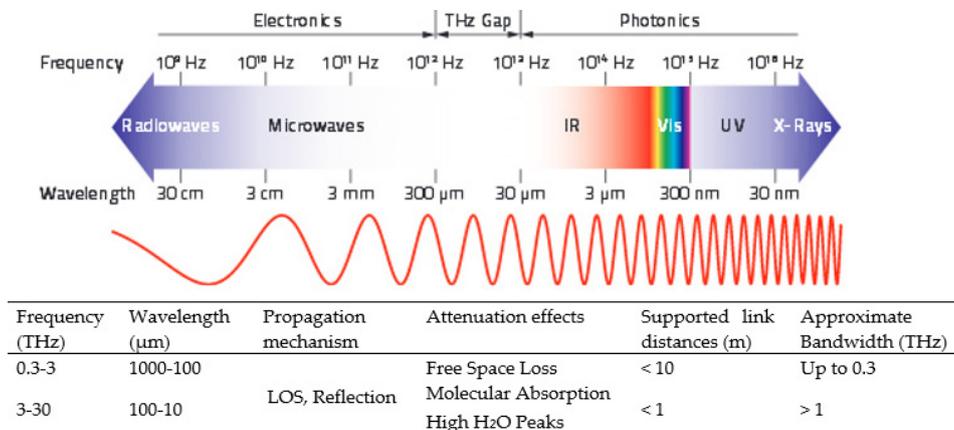


Figure 6. Electromagnetic spectrum and wavelength of terahertz and millimeter waves [29].

Using basic wave equations, the THz waves are denoted as having small wavelengths and radio frequencies higher than millimeter waves. Thus, THz waves principally convey more data faster, but a strategy must be devised to overcome the inherent short propagation capabilities. Therefore, the advent of THz waves into a mobile network portfolio could provide solutions for those applications where 5G technology failed to meet the high data throughput requirement or ultra-reliable low latency regimes [30]. Accordingly, service providers harnessing THz waves are expected for communications in areas with many devices or large amounts of data. Especially with the increasing adoption of smart homes, buildings, cities, and societies, 6G will fulfil the need for human-to-machine and M2M communications that will arise, particularly with the development of robotic and self-directed, unmanned aerial vehicle systems. This technology is enshrined in the concept of the Internet of Everything (IoE). One can infer that 6G will convey an ultra-dense network capability encouraging super network flexibility with the capacity to cleverly assimilate divergent techniques to instantaneously meet the numerous applications conditions. Conversely, an extended THz band communication technology is equipped with the capability to concurrently assist macro-scale and micro-scale services, such as terabit WLAN and nano-sensor networks [31]. References [28,32] present an extensive and exhaustive review of THz band within the range of 0.1–10 THz for assisting Tbps high-speed communications.

However, utilizing that spectrum presents many challenges that must be addressed. One of the possible techniques entails the arrangement of the THz spectrum bandwidth based on the absorption and reflection attributes of its sub-bands to optimize and reuse for communications and provide support for many other services. For instance, in scenarios assisting various divergent applications, extending harmonic attributes should be allowed, and this condition can be met by meticulous frequency planning. Detecting weak signals as sensitivity decreases is extremely difficult in the THz regions. Consequently, the THz radio spectrum can be boldly partitioned into favorable spectrum windows between atmospheric absorption peaks above 500 GHz (Figure 7) and below the 500 GHz bands [33]. Figure 6 indicates that the rise in free space loss is negligible when moving into the THz region from 30 GHz onwards. If we assume that the transmitting and receiving antenna area is maintained, the free space loss can be reduced by deploying an antenna with high gain. Apart from the free space loss, another issue in the higher frequencies that must be tackled is the increased complexity and parallelism in RF hardware and the reduced beam width that creates problems with signal acquisition and beam tracking in mobile applications [34]. Moreover, the signal penetration and reflection capability of various surfaces are two of the essential parameters that require further consideration when categorizing the radio spectrum in the presence of technological boundaries.

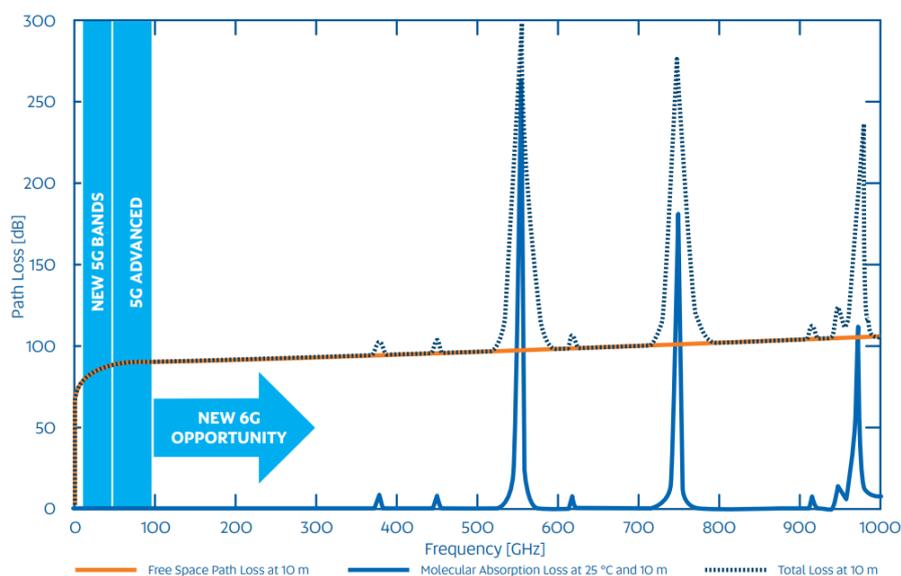


Figure 7. Effect of free space loss and water vapor absorption at a distance of 10 m [35].

The consensus among wireless communication researchers is that the high-frequency spectrum must be further exploited with the adoption of multi-cellular topology for achieving improved wireless communication systems [1]. The former approach is in line with the global trend of migrating from the cellular RF spectrum to the mm wave, THz radio spectrum, and visible-light spectrum. To fully exploit the high-frequency spectrum domains, the electronic components such as the drivers must be readily available. Recent advances in the microwave communications leading to the design of THz electronic, photonic, and hybrid electronic–photonic technologies are encouraging. Most likely, 6G will witness the evolution of a THz/free-space-optical hybrid deployed in hybrid electronic–photonic transceivers. In this configuration, the optical laser can either produce a THz signal or transmit an optical signal [36]. Some of the advantages of using a hybrid link include exploiting the THz-wide bandwidth for signal transmission and immunity against unfavorable weather climates [37]. Furthermore, THz transmission has a crucial function to perform in the uplink, as a line-of-sight link is not a prerequisite. From the channel model perspective, this condition will tilt the 6G technology into the Rayleigh channel model and drastically reduce the need for the Rician channel model. With the adoption of the THz, a reliable uplink communication link in the visible-light communication (VLC) networks is assured in contrast to the infrared solution that requires a tracking and positioning system. A system consisting of hybrid VLC/terahertz system ushers in a rugged communication technology that can withstand ambient light, thereby ultimately leading to a reduction in the signal-to-noise ratio of the VLC system. Moreover, super-efficient, short-range connectivity solutions will be the driving force for 6G, a domain in which the higher-frequency bands will play a significant role in the future. Molecular absorption has a substantial impact on the path loss, especially at longer distances ( $\sim 1 \dots 10$  dB/km at frequencies up to 400 GHz) [38]. A photonic solution is a viable approach for providing high data rates at low propagation losses, but the component size is two orders of magnitude larger than the counterpart required for the THz band case. By contrast, plasmon-based THz link components present a promising solution for THz communications due to their extremely small size and ability to operate at ultra-high data rates. Moreover, they could be perfectly combined with photonic technology, particularly with dielectric wave guiding, as plasmonic waveguiding is quite lossy concerning relatively long interconnect distances. *Lallas* [39] thoroughly investigated the in-depth reference material of the current fundamental aspects of plasmonic technology and hybrid combinations, and highlighted the future roles of plasmon in THz band wireless communication and wireless THz nano-applications.

## 2.2. Energy-Efficient Communication

6G will meet and fulfil many expectations, including the delivery of a high-energy performance, most especially from the perspective of pervasive utilization of the Internet-of-Things (IoTs) and with an eco-system of many minute sensors. Furthermore, extending the battery-recharge capacity of smartphones must be addressed, in line with the notion that their capabilities and abilities to deal with sophisticated multimedia signal processing leap in quantum rises as their power consumption increases [40]. Thus, low energy utilization and elongated battery charge life duration are two research topics in 6G to overcome the daily re-charging difficulties for most communication equipment and enhance communication needs. Accordingly, 6G must evoke a comprehensive energy-efficient wireless communication strategy. A fundamental goal of 6G communication is to perform whenever and wherever possible with battery-free communications, aiming at 1 pico-Joules per bit communication efficiency [16]. 6G communication has the advantages of high-power THz-waves, apart from directional beam communication with MIMO antenna arrays, thereby enabling devices to send power beams in a certain direction. This technique can potentially supply sufficient energy to devices under the network coverage. The 6G vision and directions, as published in [41], indicate that research attention should prioritize battery lifetime and service classes in 6G rather than data rate and latency. To reduce energy utilization, the computing functions of user nodes must be transferred to smart base stations equipped with a dependable power supply or universal smart radio space [42]. Cooperative relay communications and network densification can also have utmost importance in a bid to reduce the

transmitting power of mobile nodes by reducing the per-hop signal propagation gap [43,44]. Achieving long battery longevity in 6G requires an accumulation of divergent energy-harvesting strategies which not only harvest energy from ambient RF signals but also extract energy from micro-vibrations and sunlight [45,46]. Long-range wireless power charging would also be a promising candidate to prolong battery longevity [47,48]. In addition, distributed laser charging is a technology that may be capable of safely providing 2-W power and reach a distance of 10 m for mobile devices [16]. Table 1 presents a comparison of the major wireless charging techniques (i.e., inductive coupling, magnetic resonance coupling, microwave radiation, and distributed laser charging).

**Table 1.** Different wireless charging techniques.

Technique	Advantage	Disadvantage	Effective Charging Distance	Applications
Magnetic inductive coupling	<ul style="list-style-type: none"> <li>Simple implementation.</li> <li>Safe for human.</li> </ul>	<ul style="list-style-type: none"> <li>Short charging distance.</li> <li>Needs tight alignment between chargers and charging devices.</li> <li>Heating effect.</li> </ul>	From a few millimetres to a few centimeters.	<ul style="list-style-type: none"> <li>Mobile electronics (e.g., smartphones and tablets).</li> <li>RFID tags, contactless.</li> <li>Smartcards.</li> </ul>
Magnetic resonance coupling	<ul style="list-style-type: none"> <li>Loose alignment.</li> <li>Nonline-of-sight charging.</li> <li>Charging multiple devices simultaneously on different power.</li> <li>High charging efficiency.</li> </ul>	<ul style="list-style-type: none"> <li>Limited charging distance.</li> <li>Complex implementation.</li> </ul>	From a few centimeters to a few meters.	<ul style="list-style-type: none"> <li>Mobile electronics.</li> <li>Home appliances (e.g., TV and desktop).</li> <li>Electric vehicle charging.</li> </ul>
Microwave radiation (Non-directive RF radiation)	<ul style="list-style-type: none"> <li>Long effective charging distance.</li> <li>Suitable for mobile applications.</li> </ul>	<ul style="list-style-type: none"> <li>Line of-sight charging.</li> <li>Low charging efficiency.</li> <li>Not safe when the RF density exposure is high.</li> </ul>	Typically, within several tens of meters, up to several kilometers. Suitable for mobile applications.	<ul style="list-style-type: none"> <li>RFID cards.</li> <li>Wireless sensors, implanted body devices.</li> <li>LEDs</li> </ul>
Distributed laser charging	<ul style="list-style-type: none"> <li>High power, safe.</li> <li>Multiple-Rx charging.</li> <li>Compact size.</li> <li>EMI-free.</li> <li>SWIPT-ready.</li> <li>Suitable for mobile applications.</li> </ul>	<ul style="list-style-type: none"> <li>Line of-sight required.</li> <li>Low charging efficiency.</li> </ul>	Up to 10 m.	<ul style="list-style-type: none"> <li>Mobile devices (e.g., cell phone, laptop, tablet, wearable devices, drone).</li> <li>Consumer electronics (e.g., projector, speaker).</li> <li>Wireless sensors.</li> <li>LEDs.</li> </ul>

### 2.3. Artificial Intelligence

Machine learning (ML), along with AI and deep neural networks (DNNs), are revolutionizing technology that drives new research opportunities in various areas, including 6G communications and IoTs [10]. The link and system-level solutions for 6G communication are being built using AI and ML. AI-empowered 6G is expected to extend several features including self-configuration, aggregation, opportunistic set-up, and context awareness [15]. The potential of radio signaling and maximum cognitive to intelligent radio transmission can be realized fully through AI-empowered 6G with an aid from ML algorithms [11,49]. Additionally, building the hardware foundations for wireless technologies is expected through intelligent and reconfigurable materials [50]; they are predicted as the MIMO 2.0 and explored in detail in [51,52].

The summaries of ML methods for device-to-device (D2D) communication, massive MIMO optimization, and the design of heterogeneous networks are provided in [53,54]. Furthermore, [55] proposed a new network architecture for mobile communication for evaluating the analytics related

to big data, and such analysis can facilitate optimizations on the physical layer. The authors in [56] suggested the incorporation of an index modulation, which can serve as an aid to enhance 6G network efficiency. Notably, high intelligence and ML techniques may not only increase performance but may also change the configuration and design of 6G networks. The advantages of intelligent 6G functions in wireless and non-wireless communication services are detailed in the following three classifications:

- *Operational intelligence (OI)*: This technology allocates resources (i.e., bands and power) efficiently to achieve satisfactory network-operations instead of involving traditional methods, using multi objective optimizations that can work in the highly complex and dynamic nature of 6G owing to its heterogeneity, density, and scalability. Such optimizations that measure prioritizing multi-objective performance are typically NP hard problems and are difficult to measure in real time [57]. Today, advances in AI technologies and ML techniques including deep reinforcement learning (DRL) can aid the decision maker in iteratively refining and eventually optimizing their decisions using the feedback generated through a loop established by DRL, which can be termed AI's major application in 6G [11]. By aiding optimization, such learning algorithms can be utilized for efficient resource allocation [58]. Quite recently, Luong et al. [59] addressed many emerging issues including data offloading, caching, and adaptive modulation;
- *Environmental intelligence (EI)*: The pervasive and distributed intelligence may become a reality in holistic technology, including wireless communication environments with the advancements in smart radio spaces and materials [50]. The services based on intelligence could realize many application scenarios including data centers, IoT devices such as unmanned aerial and road vehicles and auto-robots [60] with self-organizing and self-healing properties, while increasing the reliability in D2D communication for a 6G network using intelligent frameworks [17]. In [50,61], some of the latest developments described involve adaptive manners on the bases of sensing for the radio wave customized transformations using reconfigurable intelligent surfaces. These developments set the foundation for specialized hardware that is usable for EI. For DNNs, the extracted initial features are passed to the edge and/or cloud devices; however, the processing of these features is a challenging task due to the computation and communication capabilities and heterogeneity of the devices [11];
- *Service intelligence (SI)*: Communication services including e-health, positioning (indoor and outdoor), management of multi-devices, information search, and security are the main beneficiary platforms for 6G intelligence deployments in a human-centric network [62,63]. SI can help in extending all such human-centric applications in an intelligent and personalized manner to enhance user satisfaction, such as the deep learning techniques that can enhance position accuracy, especially for indoor cases [64]. Similarly, the intelligent IoT and data collection using a multi-model-based infrastructure can help in the personalization of e-health [65]. The improvement in SI can be realized through the high-performance core networks underneath 6G [66,67].

#### 2.4. High Security, Secrecy, and Privacy

To date, research attention in 4G and 5G communications have been concentrated on the core network metrics of throughput, reliability, latency, and the number of served users with little attention to security, secrecy, and privacy issues. As acknowledged and assimilated, the two most efficient schemes to enhance these parameters involve increasing the density of the network and deploying a higher frequency to send modulated symbols. In 5G networks, traditional encryption algorithms based on the Rivest Shamir–Adleman (RSA) public-key cryptosystems are still in use to provide transmission security and secrecy [19]. RSA cryptosystems have become insecure under the pressure of Big Data and AI technologies, but novel privacy protection mechanisms remain far from being full-fledged in the 5G era. Thus, improvements in security, secrecy, and privacy in 6G networks are expected through these novel technologies.

PHY security techniques and quantum key circulation through VLC should address the data security issues in 6G networks [68,69]. Sophisticated quantum computing and quantum communication schemes may be effective in the provisioning of a comprehensive shield against different cyber-attacks [70]. Nevertheless, communication/data service providers have legally amassed a huge cache of user information, and private data leakage occurrences happened sporadically. As expected, this aspect will become a soft spot in the human-centric 6G technology and might produce a calamitous outcome without appropriate countermeasures. To address this issue, attaining total anonymization, non-distributed, and untraceability is expected in 6G systems via the use of blockchain technology [71].

Conversely, recent research efforts have focused on real-life practical deployments, including multiple access schemes [72], physical air interfaces [73], and 6G data centers [74]. 6G network configurations are outlined in [75,76], in which deploying cell-less topology, distributed resource distribution, and 3D super-connectivity are highly envisioned in 6G networks. Machine-type communications (MTCs) and vertical-specific wireless network results for 6G are examined in [77]; the work suggests that 6G could hasten the development of the first-ever barrier-breaking standard to fully substitute prevailing industry explicit communication protocols and offer an integrated solution permitting effortless connectivity of all needs in vertical industries.

### 3. Challenges and Potential Solutions

The challenges regarding 6G communications stem from five key components: provision of network security and data privacy enforcement, attainment of a cost-effective approach towards rapid network deployment and expansion with an emphasis on remote and stand-alone areas, reduction in the price of mobile communications utilization, approaches to extend mobile equipment battery life longevity, and attainment of a higher data rate buoyed with end-to-end, ultra-reliable low latency regime. Notably, satisfying all features is impossible, but a scheme must be devised to balance these features adeptly. This section highlights some of the anticipated challenges in 6G communications and the potential solutions.

#### 3.1. High Intelligence versus Privacy and Complexity

The balance between privacy and intelligence would be significant in 6G networks, as they are humanoid networks. Conversely, AI algorithms must interact with private data and refine them to improve network functionality, alter network figures, and deliver superior quality services [10]. Therefore, privacy would be foregone to the detriment of superior intelligence. A candidate solution is to utilize an intermediary negotiator between the end-user data and AI algorithms. Such a negotiator should be a third party, independent if possible, and operate on a distributed fashion. All personal and sensitive data will be anonymized by an intermediary negotiator agent. Similarly, the superior intelligence offered by AI algorithms and smart nodes lowers the freedom offered to human beings. Most likely, the user inclination will not be constantly tuned with the improved alternative generated by AI algorithms. The conflicting condition becomes more complicated when numerous users are considered. This issue can be modelled as locating the mid-point between customization and intelligence in 6G communications [11]. Definitely, customization attracts increased attention, and Intelligence versus exorbitant routines and Intelligence versus sub-routines are needed for AI algorithms and smart nodes. Such routines and sub-routines should be specified in the most fundamental procedures of 6G networks. By using this approach, intelligent portfolios can simply be delivered inside the permitted boundary.

High intelligence comes at a cost in terms of network complexity [19] and could translate to higher network operators and gadget producer budgets. Such developments would lead to a higher device cost for consumers and negate the dream of providing affordable gadgets. To tackle this issue, technological innovations in intelligent structures are essential. More significantly, novel business plans are vital. Once the security, secrecy, and privacy are guaranteed, consumers are permitted to

exchange the available anonymized data for a reduced data price. Analogous to this scheme is the smart grid concept, through which electricity consumers trade their own-produced electricity with electricity power firms, and which would be borrowed by 6G communication networks.

### 3.2. Security versus Spectral Efficiency

Achieving end-to-end, attack-proof wireless data communication requires many spectrum bandwidth preventive measures which results in a reduction in the available spectrum data available for data transmission [78]. Finding an acceptable scheme to address the security and spectral efficiency concerns of wireless communications would entail complex computations but can be addressed via three possible strategies. First, encryption algorithms designed by security experts are expected to be highly successful. With the encryption algorithm reaching the maturity stage, realizing such algorithms might be slightly cumbersome. Second, security experts should identify a strategy to implement PHY security technologies with a loss in spectrum spectral. Third, AI algorithms are equipped with the capacity to expertly discover network shortcomings and would become handy in 6G networks for designing an early warning strategy for security fortification.

### 3.3. Spectral Efficiency versus Energy Efficiency

Several studies in wireless communication have all attempted to ascertain an acceptable point between spectral efficiency and energy efficiency, and one which is not detrimental to both features. As we witnessed in the literature, this optimization topic has dominated the various wireless generations and shall continue to attract considerable research attention in 6G communications [79]. Unlike the 1–5G communications, the 6G counterpart can present an innovative route-breaking, energy-harvesting technology to significantly ease this tradeoff. By energy harvesting, consumer nodes will have the capacity to harvest radio, vibratory, and solar energy from the ambient environment, thereby addressing the complications of energy utilization. The environmental advantages obtained via ubiquitous intelligent surfaces would be crucial in reducing the spectrum-energy tradeoff by responding to the ever-changing radio propagation conditions.

### 3.4. Transceiver Design and THz Signal Generators

The current transceiver structure is considered as one of the main challenges in utilizing the THz band. In other words, the available transceivers remain incapable to operate at the THz spectrum [80]. For instance, sophisticated signal processing is required to handle the massive propagation loss at THz band frequencies. Other parameters, such as the high power, high sensitivity, and level of noise figure must be handled. Furthermore, transmission power and distance require careful investigation. In THz frequency bands, utilizing silicon germanium-, gallium nitride-, gallium arsenide-, and indium phosphide-based technologies is highly possible, but designers must consider the limited power gains in mobile networks [80]. Transmission distance is also limited in such technologies. Therefore, a novel transceiver architecture that considers the nonlinear amplifier, phase noise, and modulation index is necessary. To conclude, the current transceiver architectures are inadequate to deal with the THz sources, and new architectures are required, especially for the medium-to-high part of the THz bands (> 300 GHz) [80,81]. The conventional complementary metal oxide semiconductor technologies and the recently introduced nanomaterials, such as graphene, can be utilized for novel transceiver architectures for THz-enabled equipment [82].

### 3.5. Potential Health Issues

The massive data rate (terabit/seconds) in the THz band and available bandwidth can be exploited in fast communication networks. Although experts projected that the 6G networks and applications are still inchoate, 6G could benefit from the very high-frequency bands (100 GHz to 1 THz). Thus, considering human safety, which could be affected by the propagation of THz waves, is necessary.

Notably, THz radiation is nonionizing because the photon energy is insufficient (0.1 to 12.4 meV). In other words, the magnitude of an ionizing photon's energy levels is three times higher than that of the nonionizing photon [83,84]. The Federal Communications Commission (FCC) [85] and the International Commission on Non-Ionizing Radiation Protection standards [86] are utilized to protect humans from potential hazards such as those to the eyes and skin tissues, which are highly sensitive to heat due to the low level of blood flow. In addition, the biological and molecular impact of THz radiation on the environment requires careful consideration. Electromotive force transmission is another novel concept which will be presented in 6G to mitigate health issues [87].

### 3.6. 3D Networking Reliability-Latency Fundamentals

The 6G is expected to support 3G applications and deployment. For instance, 3D base stations will be presented. Research into measurement and data-driven modeling of the propagation environment is essential. Network planning and 3D frequency utilization should also be developed where 3D networks are significantly different from the conventional 2D networks because of the new altitude dimension and degrees of freedom. Moreover, the fundamental 3D performances of 6G systems, i.e., the rate-reliability-latency tradeoffs and SE, are required. Such analysis must quantify the spectrum, energy, and communication requirements that 6G must support the identified driving applications. Recent research in [88,89] provides the related fundamental information in that direction.

Sequentially, the Poisson point process (PPP) has a major benefit in the mathematical tractability and is used in modeling network deployment and coverage probability. However, the mathematical objects are randomly distributed in the space. In real applications, multi-tier heterogeneous applications have random distributions. Actual interactions between base station locations could appear in terms of repulsion and attraction. Small cell networks tend to involve attraction reflecting user-centric hotspot areas, whereas repulsion is observed at the macro cell level to represent rural and urban deployments. This distinction will be more emphatic in very small cell environments. However, the 6G networking environment will not be presented by the trusted PPP because the latter is mostly limited to the 2D plane. In the future, emerging deployment scenarios will be conducted in 3D. However, such scenario is complicated at the THz frequency band because of the blockages and the highly directional beam patterns.

## 4. Research Activities

This section provides a brief overview of 6G research activities. Several 6G activities have been commenced globally by industrial organizations and governments whose objectives include formulating and defining 6G technology and then re-adjusting the outline in addition to the business model of wireless systems. The United States FCC has proposed allocating the 95 GHz to 3 THz spectrum to be used for 6G research, thereby setting the US as the pacesetter in the 6G research race. Other entities have begun concrete research efforts in 6G networks. Some of the notable names include the Finnish consortium through their 6Genesis Flagship Program and the Terabit Bidirectional Multi-user Optical Wireless System (MU-OWS) for 6G LiFi which commenced in early 2019. The 6G research race from academia can be said to have started in March 2019, when the first 6G Wireless Summit was held in Levi, Finland [13]. Apart from the aforementioned efforts, other mini workshops and conferences have been conducted globally to examine the prospect of 6G, including the Huawei 6G Workshop, the Wi-UAV Workshop of Globecom 2018, and the Carleton 6G Workshop. A research group based on the EU's Terranova project is now working toward a reliable 6G connection with 400 Gbit per second transmission capability in the THz spectrum [19]. LG Electronics also announced the foundation of a 6G research center at the Korea Advanced Institute of Science and Technology, Daejeon, South Korea. Samsung launched its 6G research in June 2019. SK Telecom announced a collaboration with Nokia and Ericsson for 6G research in 2019. In late 2018, China's Ministry of Industry and Information Technology declared its goal of leading the wireless communication market in the 2030s by expanding research investment in 6G. In addition, an EU-Japan project under Horizon

2020 ICT-09-2017 funding called “Networking Research beyond 5G” also investigated the possibility of using the THz spectrum from 100 to 450 GHz. Table 2 summarizes the research initiatives into 6G communications. Moreover, IEEE launched the IEEE Future Network with the tagline “Enabling 5G and beyond” in August 2018. The ITU-T Study Group 13 also established the ITU-T Focus Group Technologies for Network 2030 in its aim to understand the service requirements for future networks by 2030 [19].

**Table 2.** Research initiatives into 6G communications.

Country	Research Initiatives
<i>Finland (2018)</i>	Finnish 6G research activity is coordinated by the University of Oulu, where a 6G initiative was launched.
<i>United States (2019)</i>	<ul style="list-style-type: none"> <li>• The Federal Communications Commission opened the spectrum between 95 GHz and 3 THz to create a new category of experimental licenses.</li> <li>• IEEE launched IEEE Future Network with the tagline ‘Enabling 5G and beyond’.</li> <li>• ITU-T Study Group 13 also established the ITU-T Focus Group Technologies for Network 2030 intending to understand the service requirements for future networks round 2030.</li> </ul>
<i>EU (2019)</i>	<ul style="list-style-type: none"> <li>• A research group based on the EU’s Terranova project is now working toward the reliable 6G connection with 400 Gbit per second transmission capability in the terahertz spectrum.</li> <li>• An EU–Japan project under Horizon 2020 ICT-09-2017 funding, called ‘Networking Research beyond 5G’, also investigates the possibility of using the terahertz spectrum from 100 GHz to 450 GHz.</li> </ul>
<i>South Korea (2019)</i>	<ul style="list-style-type: none"> <li>• LG Electronics established a 6G research centre in collaboration with the Korea Advanced Institute of Science and Technology.</li> <li>• The Electronics and Telecommunications Research Institute has signed a memorandum of understanding with the University of Oulu in Finland to develop 6G network technology.</li> <li>• Samsung Electronics and SK Telecom work together to develop technologies and business models related to 6G.</li> <li>• SK Telecom signed agreements with Finnish firm Nokia and Sweden’s Ericsson to step up collaboration on 6G network research and development.</li> </ul>

Table 2. Cont.

Country	Research Initiatives
<i>China (2019)</i>	The Ministry of Science and Technology planned to set up two working groups to carry out the 6G research activities; the first is from government departments to promote 6G research and development, the second is made up of 37 universities, research institutes and companies, focusing on the technical side of 6G.
<i>Japan</i>	<ul style="list-style-type: none"> <li>• Japan readies US\$2 billion to support industry research on 6G technology.</li> <li>• NTT and Intel have decided to form a partnership to work on 6G mobile network technology.</li> </ul>

## 5. Conclusions

During the worldwide deployment of 5G networks, industrial and academia synergy have commenced to conceptualize the next generation of wireless communication systems (6G) to address the coming challenges of the drastic increase in wireless data traffic. 6G technology allows bitrates of up to Tbps with a latency less than 1 ms, apart from introducing a group of new services. This study started by highlighting a vision and the key features aimed at fostering future 6G in the following dimensions: energy efficiency; intelligence; spectral efficiency; security, secrecy, and privacy; affordability; and customization. Then, we discussed the several potential challenges associated with 6G technology and the potential solutions to fostering future 6G. Finally, this work concludes with international research activities that aim to create a vision for future 6G.

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## Abbreviations

The following abbreviations and symbols are used in this manuscript:

1G	First Generation
2G	Second Generation
3G	Third Generation
4G	Fourth Generation
5G	Fifth Generation
6G	Sixth Generation
AI	Artificial Intelligence
B5G	Beyond 5G
BigCom	Big Communications
DRL	Deep Reinforcement Learning
DNN	Deep Neural Network
eMBB	enhanced Mobile BroadBand
IoE	Internet of Everything
ML	Machine Learning

mMTC	massive Machine Type Communication
MIMO	Multiple-Input and Multiple-Output
PHY	Physical Layer
RFID	Radio-Frequency Identification
RSA	Rivest Shamir–Adleman
SURLLC	Secure Ultra-Reliable Low-Latency Communication
THz	Terahertz
3D-InteCom	Three-Dimensional Integrated Communication
VLC	Visible-Light Communication
WLAN	Wireless Local Area Network
UCDC	Unconventional Data Communication
UAV	Unmanned Aerial Vehicle
uRLLC	ultra-Reliable and Low-Latency Communication

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