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Survey on 5G and Future 6G Access Networks for IoT Applications

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Abstract: This paper comprehensively reviews the recent 5G and future 6G Internet of Things (IoT) protocols/standards, applications, and access networks used. First, most of the IoT protocols/standards and application scenarios are summarized in the form of tables, pictures, and diagrams to facilitate readers to understand and compare current and future Internet of Things technologies more easily and quickly. Second, the terrestrial and aerial radio access networks are analyzed and discussed in detail. The evolution of 5G terrestrial access networks is briefly described and its performance limitations are quantitatively analyzed and discussed. When the operating frequency reaches the sub-millimeter wave band, the terrestrial radio access network will deal with high path loss caused by weather factors, such as oxygen and water vapor absorption in the atmosphere, rainfall, and cloud/fog attenuation. The development of aerial radio access networks is preparing for 6G IoT to solve the coverage and path loss issues. In this survey, the aerial radio access architectures and infrastructure are also surveyed. This survey aims to guide readers to better understand the technical status of 5G IoT and the milestones as well as key performance indicators that need to be reached for 6G IoT in the future.

Index Terms: Internet of things (IoT), Fifth-generation (5G) wireless technology, Sixth-generation (6G) wireless technology, Long-range wide-area network (LoRaWAN), Sub-6 GHz, Millimeter wave (mmWave), Sub-millimeter wave, Radio access network (RAN)

1. Introduction

Around 2008 and 2009, the 'Internet of Things' term began to be mentioned in academia and industry. The 'Internet of Things' was normally represented by short form of 'IoT' and originally defined as [1]:

> *'A global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies'.*

In the past decade, the rapid development of wireless communication technology has indirectly driven the IoT product market. The global IoT user base are grow more than 3.4 million in 2020 [2]. By 2021, the number of IoT devices are close to 30 billion. The IoT objects is expected will exceed 50 billion by 2025 and further reach 80 billion by 2030 [3], as well as global IoT revenue will quadruple to reach 1.1 trillion US dollars. Hence, recently, more specific and explicit terms have been used in the definition of the Internet of Things [4]-[6]:

> *'A physical object that is embedded with sensors, processing ability, software, and other technologies, and that connects and exchanges data with other devices and systems over the Internet or other communications networks'.*

or

> *'A system of interrelated computing devices, mechanical, and digital machines provided with unique identifiers (UIDs) and the ability to transfer data over a network without requiring human-to-human or human-to-computer interaction'.*

or

'A device embedded with electronics, software, sensors, actuators, and network connectivity that are capable of covering a variety of protocols, domains, and applications, which include the automotive industry, public safety, emergency services, and medical field'.

At present, the Internet of Things (IoT) applications have been widely used in the industrial field and our daily lives, covering eight main areas, namely smart wearables, smart home, smart city, smart agriculture, smart vehicle, health care, industry automation, smart energy as shown in Fig. 1(a). The use of the IoT is now expanded through the evolution of 5G communication technology. At a time when 5G technology is being used, preliminary research on 6G access network has already begun, with the goal of operating at frequencies above 100 GHz to 3 THz (sub-millimeter waves or Terahertz). For instance, since 2019, a series of studies and recommendations related to 6G communications have been extensively published and up to thousand articles have been documented [7]-[33].

The first 6G research items are expected to appear in 2025, starting to roll out standardization work in 2030, while the evolution of 5G will continue in parallel with early 6G research [29]. In fact, in the last 40 years, microwave technology with operating frequencies exceeding 300 GHz to 3 THz has emerged and is in use to date, the so-called terahertz technology. The terahertz technology is widely utilized in the field of astronomy, medical, and security, such as space-based remote sensing and medical diagnostic imaging [34, 35], due to the sub-millimeter waves that are nonionizing, and it can penetrate a wide variety of non-conducting materials. Furthermore, due to the sub-millimeter waves having a short wavelength between 0.1 mm to 1 mm, and very sensitive to subtle environmental changes. Therefore, the sub-millimeter waves are very suitable for high-sensitivity sensing and imaging applications (large bandwidth cause high resolution), such as biosensors, atmospheric monitoring, personnel/baggage/package scanning, material thickness detection, and nanomaterial characterization devices, as shown in Fig. 1(b).

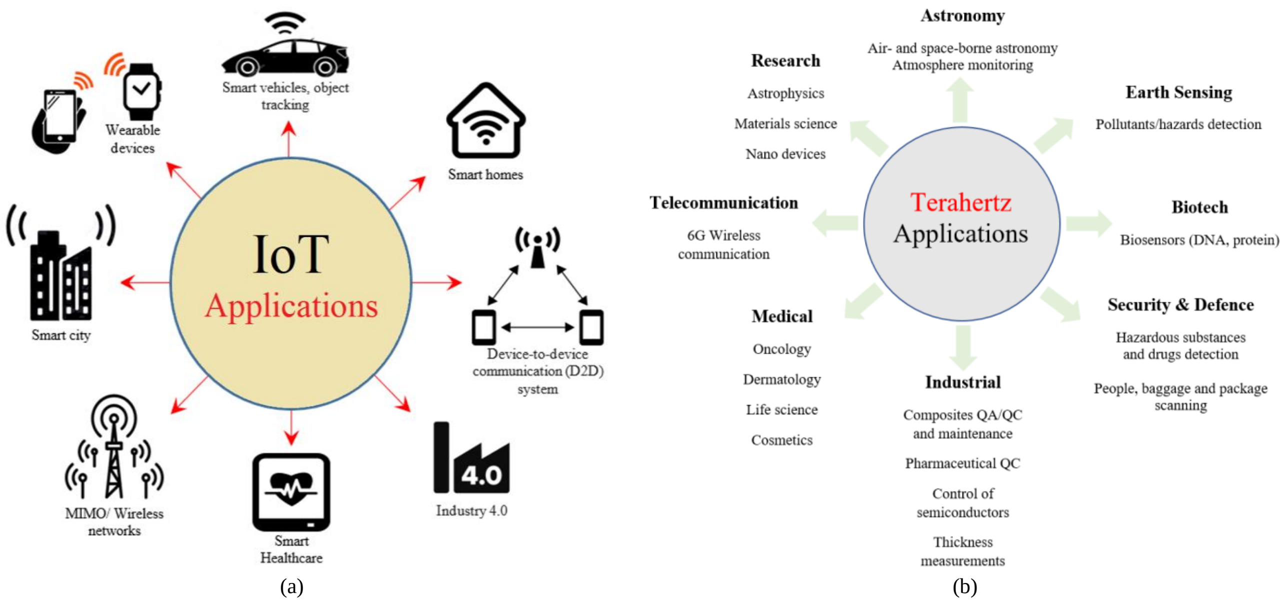


Fig.1. (a) IoT applications. (b) Terahertz applications.

When these terahertz-based devices or applications are connected to the future internet networks (operating frequency up to terahertz) assisted by artificial intelligence (AI) features, they will become the 6G Internet of Things (IoT). The 6G IoT goals to achieve data rates of 0.1–1 Tbps and spectrum efficiency of 3–60 bps/Hz, 100 GHz channel bandwidth, 1000 km/h mobility, 10^7 devices/km^2 of connectivity density, and fully automation. Hence, the coming soon 6G IoT research may involve four main technology areas [29], namely (1) increasing operating frequencies of the internet access network to sub-millimeter waves band or terahertz, (2) improving multi-antenna techniques, (3) adopting artificial intelligence (AI) and machine learning (ML) in 6G IoT, (4) integrating communications with more sensing capabilities. In fact, the progress of the 6G IoT research will be directly affected by the development of the sub-millimeter wave monolithic microwave integrated circuits (MMICs) industry. In addition to high operating frequencies (> 300 GHz), MMICs used in 6G IoT also require to have good thermal resistance, low DC power consumption, high sensitivity, high output RF power, high thermal stability, nanoscale integrated circuits, broadband, and less expensive.

In fact, 5G and 6G IoT are very extensive and broad technology research topics, such as the topic of modulation methods used, IoT architecture, IoT business models, IoT network security, and battery life/energy consumption issues. However, in this paper, only three main sub-topics of IoT are reviewed and analyzed, since the three topics are closely related, namely, IoT protocols and standards, 5G and 6G IoT application categories and their access networks, respectively. The first and second sub-topics describe the type of access network and protocol used by IoT, which depends on the type of IoT application, the complexity of IoT operation, the number of connected IoT devices, baud rate, bandwidth, operating frequency, and the coverage of the access area. Through the IoT access protocols/standards survey, entrepreneurs, engineers, and researchers can better understand the efficiencies and types of IoT that exist today, as well as provide guidance on choosing protocols/standards that are more suitable for their IoT applications. Besides, the usage scenarios of 5G and 6G are compared. The capabilities and limitations of the latest 5G IoT are discussed, then how 5G IoT can be improved and further developed using 6G wireless technology are described. By comparing the recent IoT protocols with future IoT usage requirements, readers are more aware of the direction of wireless technology development and the technical gaps that need to be caught up.

On the other hand, the third sub-topic of 5G and 6G access networks has been comprehensively emphasized and reviewed. The 6G access networks attempt to operate at frequencies up to 3 THz for future IoT efficiencies and demands. However, conventional terrestrial radio access networks (TRAN) operating at frequencies up to terahertz will face several challenges, such as high path loss issues, energy usage, and equipment costs. At this moment, the loss of the network signal up to THz in outdoor applications is a critical issue that needs to be resolved. Hence, aerial radio access networks (ARAN) have been proposed and used to replace TRAN to overcome the higher path loss of wireless signals at operating frequencies > 275 GHz.

2. IoT Access Protocols and Standards

Due to wireless technology not only used for human-to-human communication but also human-to-device or devices-to-device (D2D), as well as various types and applications of IoT has been used in the same environment at the same time. This will aggravate the interference and coupling effects between wireless signals and cause data to be lost, voice quality may degrade, and the working range and battery life of the device may be reduced. It is impossible to allocate a separate frequency spectrum to each user, device, and application. Hence, various wireless protocols and standards employ a variety of communication techniques to help the communication operation peacefully coexist despite sharing the same frequency bands.

The IoT technologies can be categorized into three groups of coverage distance range applications as tabulated in Table 1. In addition to the coverage distance, IoT users can also select an appropriate wireless access protocol based on its baud rate, energy consumption, and cost required for particular IoT applications. Recently, these are two common unlicensed technologies used in IoT, namely Wireless Fidelity (Wi-Fi) and LoRaWAN (Long-range wide-area network) [36]. In fact, Wi-Fi is the unprecedented leader in broadband connectivity and its generations/protocols are shown in Table 2. Recently, the new generation of WiFi protocol (Wi-Fi 6) can benefit IoT hardware by improving battery performance, better outdoor operation, and expanding range [36]. On the other hand, LoRaWAN is used for long-range and low-energy connectivity. However, still a lot of IoT connectivity technologies use cellular networks and licensed spectrum under 3rd Generation Partnership Project (3GPP) access standards, such as Extended Coverage GSM IoT (EC-GSM-IoT), Long Term Evolution-Machine Type Communication (LTE-M), Narrowband Internet of Things (NB-IoT), 4G LTE, and 5G New Radio (NR). Compared with non-3GPP standards (LoraWAN and SixFog), 3GPP standards are mainly used for long-range high-quality mobile voice and data services.

As more and more IoT devices are connected to 3GPP standards, for instance, the china's government announced a policy that aims to reach 600 million NB-IoT nodes by 2020 compared to only 20 million NB-IoT based connections in 2017 [37]. In July 2016, the first 3 GPP standards (part of Release 13) specifically for IoT applications were released, which is known as NB-IoT [37, 38]. Subsequently, 3GPP release 14 (initial) and release 15 (5G New Radio) were defined as the first phase of the 5G technology standards, which were approved in 2017 and June 2018, respectively. Then, the 3GPP Release 16 for second phase of the 5G standards are approved in 2018 and ended in July 2020. Recently, 3GPP release 17 is approved for enhanced support of industrial IoT in the 5G system. Starting in 2020, 5G has been widely deployed worldwide. For example, the first full 5G smartphone Samsung Galaxy S20 and the Nokia 8.3 5G with wider 5G compatibility were released in March 2020. While, the Apple iPhone 12 with 5G connectivity was released in October 2020.

In future, the 3GPP standardization for 6G is expected to be started in 2025 [29]. The brief 5G, 6G, and corresponding 3GPP standards roadmap is shown in Fig. 2. In addition to the 5G specifications defined by 3GPP, there are two other important international committees, namely International Telecommunication Union (ITU) and International Mobile Communications (IMT-2020), which define 5G technical goals [39]. Besides, for short- and medium-ranges applications, the Institute of Electrical and Electronics Engineers (IEEE) uses millimetre-wave (mmWave) unlicensed bands (45 GHz and 60 GHz) as the 5G technical standards, such as IEEE 802.11ad/aj/ay and IEEE 802.15.3c standards, to achieve data rates from 6.7 Gbps to 20 Gbps as shown in Tables 1 and 2 [36], [40]-[45].

In fact, most industrial IoT applications do not require a high baud rate (high transfer data rate), but the main factors considered are the cost of sensors and devices, as well as battery life. For instance, agricultural remote sensing systems used for large-scale agricultural management and monitoring do not need to transmit data every second (data only needs to be sent once every half an hour), hence the access protocol of the IoT system is usually Low-Power Wide-Area Network (LPWAN), such as Sigfox, LoRaWAN, and LoWPAN, the protocol provides low power consumption and low baud rate, but long coverage distance (> 5 km). On the other hand, for the automation industry and vehicle-to-infrastructure communication, the IoT system provides intelligent, interconnected, and roboticized industrial production.

Therefore, real-time data exchange is required to ensure the real-time response and precision of robot movement during factory production. In this case, Wi-Fi is usually selected for wireless interaction between IoT systems to achieve a high data transfer rate within 1 km coverage.

The relationship between baud rate, operating frequency, and coverage is shown in Fig. 3 (a). High operating frequency will provide a high baud rate, but the high operating frequency will reduce coverage. Vice versa, the high operating frequency has a low wavelength causing low penetration and high path loss. On the other hand, the relationship between energy consumption, baud rate, and coverage are illustrated in Fig. 3 (b) and Fig. 3 (c). In general, high baud rate has high energy consumption (will discuss in the next sub-section). Non-3 GPP standards (Sigfox, LoRaWAN, LoWPAN) have low energy consumption and low baud rate, but have high coverage. Here, IoT users can choose the appropriate access protocol or standard according to the required application specifications. The specification and performance comparisons between 802.15.4-based protocol (short range) and LPWAN technologies (Long range) are tabulated in the Table 1. Besides, other IoT wireless protocols are also compared in terms of coverage distance, power consumption, number of IoT device connections, bandwidth, operating frequency, and baud rate as illustrated in Table 1.

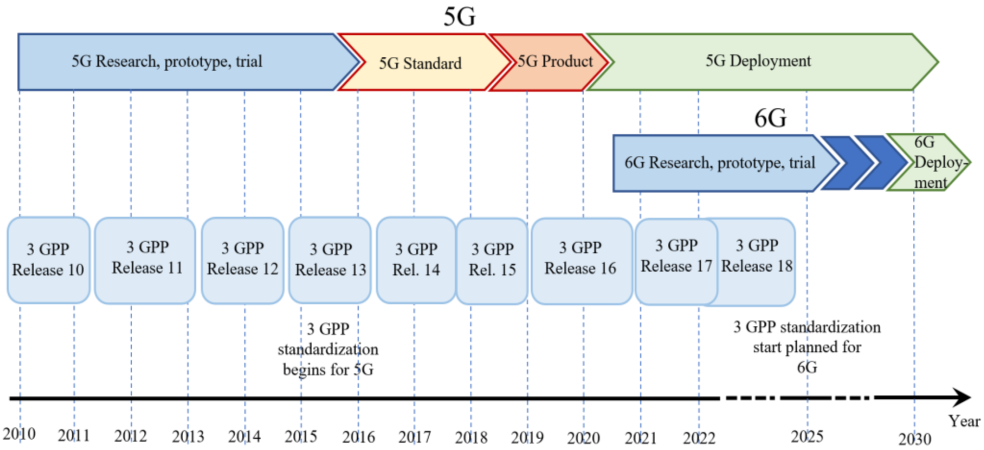


Fig. 2. 5G, 6G, and 3 GPP standard version roadmap [29], [37]

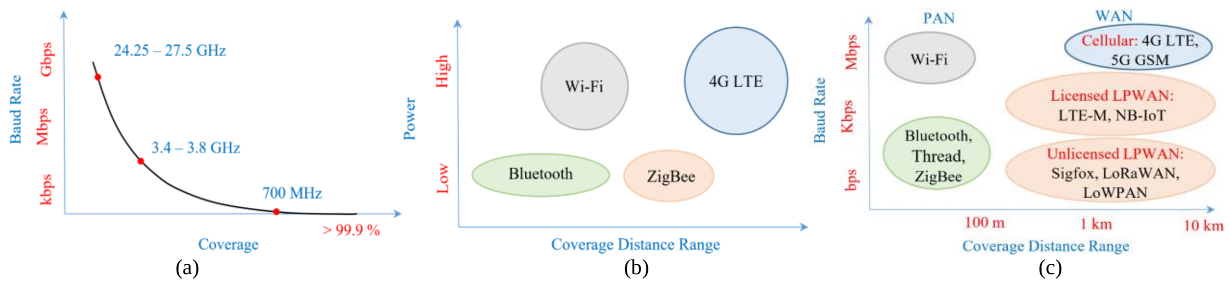


Fig. 3. (a) Data rate versus coverage distance range at different range of operating frequencies. (b) Energy consumption and coverage distance range are depended on the used wireless technologies. (c) Wireless technologies dependent baud rate and coverage distance range (WAN: Wide Area Networks, PAN: Personal Area Networks)

3. 5G and 6G IoT Application Categories

The International Telecommunication Union (ITU) has defined three main uses for fifth-generation (5G) wireless technology, namely Enhanced Mobile Broadband (eMBB), Ultra-reliable and Low-latency Communications (uRLLC), and Massive Machine Type Communications (mMTC), respectively. The eMBB aims to achieve the people's demand for an increasingly digital lifestyle, and focuses on services that have high requirements for bandwidth, such as high definition (HD) videos, virtual reality (VR), augmented reality (AR), and broadband IoT.

On the other hand, the uRLLC and mMTC are designed for critical IoT and massive IoT, respectively. The uRLLC refer to using the network that requires uninterrupted and robust data exchange, such as assisted and automated driving, as well as remote management. While, the mMTC is used to connect to a large number of low power, low-cost devices, which have high scalability and increased battery lifetime, in a wide area, such as smart city and smart agriculture as shown in Table 2 [46]. The applications of eMBB, uRLLC, and mMTC scenarios are shown in Figs. 4, 5, and 6, respectively. The available industrial IoT subcategories, applications, technologies, and used protocols are listed in Table 3 [45].

As mentioned earlier, the use of devices connected to the internet will increase and reach the state of 'Internet of Everything (IoE)' in the near future. Therefore, the three 5G scenarios require to be strengthened and separated into more sub-scenarios for more diversified applications, namely 6G application scenarios. Starting in 2019, several 6G application scenarios have been proposed [9], [11, 12]. For instance, Saad *et al*. (2019) [9] extended 6G applications to four scenarios, namely MBRLLC, muRLLC, HCS, and MPS. On the other hand, Zhang *et al*. (2019b) [11] proposed five 6G usage scenarios, such as FeMBB, eURLLC, LDHMC, umMTC, and ELPC. In addition, Zong *et al*. (2019) [12] enhanced the available three 5G usage scenarios suitable for 6G applications, re-named as uMUB, uHSLLC, and uHDD. While, Letaief *et al*. (2019) [8] named 6G usage scenarios as CAeC, EDuRLLC, and COC, as listed in Table 4. Besides, the comparison of 5G and 6G requirements of specifications, performances, and applications is tabulated in Table 5.

4. 5G and 6G IoT Access Networks

Although 5G communication can provide a peak data rate, *C* of 20 Gbps, however, when the capacity needs to be shared with multiple users and the large number of IoT devices, the performance of data rate will be significantly reduced (may be decreased by 80% above) (typical 0.1 Gbps of experienced data rate). Therefore, the higher target peak data rate, *C* that exceeds the expected value of 20 Gbps needs to be considered and the data rate limit needs to be increased based on the continuous increase in the number of connected IoT devices.

Based on the Shannon capacity theorem, the peak data rate, *C* is affected by channel bandwidth, *B* and the received signal-to-noise ratio, SNR as:

$$C = (n \times BW)\log_2\left(1 + \frac{S}{N}\right) \quad (1)$$

where *n* and *BW* are the number of channels and the channel bandwidth (in Hertz), respectively. On the other hand, *S* and *N* are the transmit power and noise on the channel (in Watts), respectively. Clearly, to increase the data rate, *C*, the channel bandwidth, *BW*, number of channels, *n*, and power transmission, *S* needs to be increased, while noise, *N* on the channel needs to be reduced. To obtain bandwidth, *BW* of more than 800 MHz, the high operating frequency up to mmWave range (> 24 GHz) need to be utilized [40]. As the frequency increases, a given percentage of bandwidth provides a greater share of the spectrum.

Table 1. Coverage distance range and its protocol and network type [33], [36], [40]-[45]

Coverage distance	Protocol	Frequency (MHz)	Max. Distance (km)	Band-width (MHz)	Data Rate (Mbps)	Downlink (s)	Link Budget (dB)	Num. Device	Network Type
Short range (≤ 200 m)	Near-Field Communication (NFC) (use for QR codes, bar codes, and RFID tags)	13.56	~0.0001	1	0.106, 0.212, 0.424, 0.848	–	–	2	Wireless Personal Area Network (WPAN) - Wearable and mobile
	IEEE 802.15.4: 1. Zonal Intercommunication Global-standard (Zigbee)	2400	~0.1	0.6, 1.2, 2, 5	0.02 – 0.25	10 m	–	65000	
	2. International Society of Automation (ISA100.11a)	2400	~0.2	5	0.25	~100 m	–	Unlimit-ed	
	3. Wireless Highway Addressable Remote Transducer Protocol (WirelessHART)	2400	~0.2	3	0.25	10 – 50 m	–	30,000	
	4. Microchip Wireless (MiWi)	2400	0.2 – 0.5	–	0.25	–	–	–	
	5. IPv6 over Low-Power Wireless Personal Area Networks (6LoWPAN)	2400	0.01 – 0.1	0.0078 – 0.5	0.02, 0.04, 0.06	–	–	65000	
	6. Thread	2400	~0.03	–	0.04 – 0.25	–	–	–	
	7. Subnetwork Access Protocol (SNAP)	–	–	–	–	–	–	–	
	8. Z-Wave	868.42 (Eur) 908.42 (US)	~0.03	0.2	0.0096, 0.04, & 0.1	–	–	232	
	IEEE 802.11ad: 9. Wireless Gigabit Alliance (Wi-Gig or 60 GHz Wi-Fi)	60000, 57000–66000	~0.01	2160	6760	–	–	–	
	Low-power Bluetooth 5	2400	~0.01	~2	1 – 3	< 3m	–	32,767	

Medium range (≤ 1 km)	IEEE 802.11ah: Wi-Fi HaLo	Regional	–	1, 2, 4, 8, & 16	0.1– 40	–	–	–	Wireless Local Area Network (WLAN) - Indoor
	IEEE 802.11p: Wireless Fidelity (Wi-Fi) generations	2400, 3600 4900, 5000 5900	< 1	1 – 16, ~ 22	0.150 – 78	1 – 3 m	–	–	
Long range (>1 km)	Long-Range Wide-Area Network (LoRa/LoRaWAN)	169, 470 868 (Eur) 915 (US) 433 (Asia)	5 – 32	–	0.0003 – 0.05	–	~150 – 157	50,000	Wireless Wide Area Network (WWAN) - Outdoor
	SigFox	868 902	> 50	0.0001 – 0.0006	0.1 – 0.6	–	~146 – 162	100	
	Wireless Smart Utility Network (Wi-SUN)	2400	~1	0.2 – 1.2	0.05 – 1	–	–	–	
	Ingenu	2400	~4	1	0.02	–	–	–	
	DASH-7	433, 868, 915	~2	0.5– 1.75	0.167	–	~140	–	
	Long-range cellular: 1. 2G-Global System for Mobile Communications (2G-GSM)	900, 1800	–	~25	0.64	–	–	–	
	2. General Packet Radio Service (GPRS)	800, 900, 1800, & 1900	–	–	0.014 – 0.171	–	–	–	
	3. Code Division Multiple Access (CDMA)	1600 – 2000	–	100	0.144 – 2	–	–	–	
	4. Universal Mobile Telecommunications System (UMTS)	1885 – 2025, 2110 – 2200	–	~5	0.38 – 2.05	–	–	–	
	5. Long Term Evolution (LTE)	2000 – 8000	–	100	100 – 1000	–	–	–	
	6. Narrowband-IoT (NB-IoT)	LTE Cellular bands	1 – 10	0.18	0.159	1.6 – 10	~ 164	100,000	
	7. Long Term Evolution-Machines (LTE-M)	Cellular bands	>11	5	4 (D. Link) 7 (Up Link)	10 – 15 m	–	>100,000	
	8. Citizens Broadband Radio Service (CBRS)	3550 – 3700	–	150	–	–	–	–	
	9. Multi-Fire	–	–	–	–	–	–	–	
	10. 5G New Radio (5G NR)	FR 1 (Low) 410 – 2690	–	> 20	30 – 250	–	–	–	
		FR 1 (Med.) 3300 – 7125	–	> 100	100 – 900	–	–	–	
		FR 2 (High) 24250 – 52600	–	> 800	> 1000	–	–	–	

Terminology: **QR codes** — Quick Response codes, **IPv6** — Internet Protocol version 6, **RFID** — Radio Frequency Identification, **IEEE** — Institute of Electrical and Electronics Engineers, **5G NR FR 1** — 5G New Radio Frequency Range 1 (410 MHz to 7.125 GHz), **5G NR FR 2** — 5G New Radio Frequency Range 2 (24.25 GHz to 52.6 GHz).

In addition, the available bandwidth, *BW* spectrum without interference in the low frequencies and sub-6GHz band is limited due to many applications and wireless protocols falls in that frequency range, such as Wi-Fi, Bluetooth, and Industrial, Scientific, & Medical (ISM) applications. For instance, recently, several suppliers are provided 2.5 Gbps transceivers in a single box using frequency band above sub-6 GHz (6 GHz to 42 GHz) for radio access network [47]. In order to improve the received signal-to-noise ratio, *S/N*, a high transmit power, *S* needs to be generated. Therefore, the usual high data rate wireless protocol is high energy consumption, as shown in the Fig. 3 (b). Besides, high-quality, high-sensitivity, and low-noise receivers also contribute greatly to data rate performance. Hence, in recent years, the evolution of 5G wireless networks has gradually unfolded to solve and optimize quality of service (QoS), such as the mentioned data rates, bandwidth, and power consumption issues.

Table 2. 5G usage categories and specifications

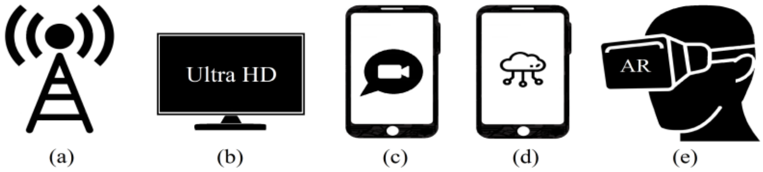
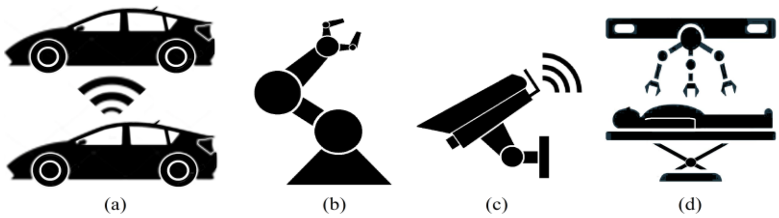
5G Services	**Target:**
Enhanced Mobile Broadband **(eMBB)**	High data rate, large data applications, massive devices, user capacity. **Features:** 1. Transfer all data all the time. 2. Cover 2 billion people on social media. 3. Support 500 km/h mobility. 4. Peak data rate: 20 Gbps for downlink & 10 Gbps for uplink. **Main Applications:**  Fig. 4. (a) Fixed wireless, (b) Ultra high definition (UHD) video, (c) Video call, (d) Mobile cloud computing, and (e) Virtual reality (VR) /Augmented reality (AR)
Ultra-Reliable, Low Latency Communications **(uRLLC)**	**Target:** Fast and highly reliable, perfect coverage and uptime, strong security. **Features:** 1. Ultra-high reliability (99.9999 % reliability). 2. Ultra-responsive. 3. Data rate from 50 kbps to 10 Mbps. 4. Less than 1 ms air interface latency and 5 ms end-to-end latency. **Main Applications:**  Fig. 5. (a) Vehicle-to-vehicle, (b) Industrial automation, (c) Public safety, and (d) Remote surgery
Massive Machine Type Communications **(mMTC)**	**Target:** Massive connection density, energy efficiency, reduced cost per device **Features:** 1. Cover 30 billion 'things' connected. 2. Low cost and low energy consumption. 3. Connectivity density of 10^5 to 10^6 devices/km^2 4. 1 to 100 kbps/device. 5. 10 year battery life. **Main Applications:**  Fig. 6. (a) Wearables, (b) Health care monitoring, (c) Smart home/city, and (d) Smart sensors

Table 3. Internet of Things (IoT) categories and applications

IoT categories	Applications	Sensory devices	Protocols
Process Monitoring/ Predictive Maintenance 1. Smart Energy 2. Industry Automation 3. Smart Agriculture	Machine health monitoring (precision CNC, conveyor belt) Asset monitoring (Hydraulic hose, pipeline, wellhead, steam trap, corrosion/structural integrity, seismic monitoring, tank level) Remote visualization (Force sensors, laser measurement devices, cameras)	Temperature sensor Camera Humidity sensor Pressure sensor Level sensor Gas sensor Proximity sensor Acoustic sensor Chemical sensor Accelerometer	LPWAN WirelessHART ISA100.11a Cellular Zigbee
Facility Management 1. Smart City 2. Smart Healthcare 3. Smart Agriculture	Health and safety monitoring (Emissions/Toxin) Environmental monitoring/control (Lighting, HVAC, smart metering) Perimeter security	Gas sensor Chemical sensor Light sensor Infrared sensor Camera Radar sensor	Wi-Fi Cellular Bluetooth ISA100.11a WirelessHART LPWAN
Inventory Management 1. Smart Wearables 2. Smart Homes 3. Industry Automation	Asset Tracking (RTLS)	Bluetooth beacons RFID & QR code Camera Infrared sensor	Bluetooth Wi-Fi UWB
Fleet Management 1. Smart Vehicles	Delivery truck tracking, passenger car tracking, route development	GPS module GLONASS module BeiDou module	Cellular LPWAN NB-IoT LTE-M1

Terminology: **RFID** — Radio Frequency Identification, **LPWAN** — Low-Power Wide-Area Network, **GPS** — Global Positioning System, **CNC** — Computer Numerical Control, **HVAC** — Heating, Ventilation, and Air Conditioning, **RTLS** —Real Time Location Systems, **UWB** — Ultra-wideband

4.1. Terrestrial Radio Access Networks (TRAN)

The evolution of 5G wireless access network is transferred from the macrocell environment to the small cell coverage area as shown in Fig. 7. In fact, the small cell is a miniature version of the traditional macrocell, which has all the same characteristics and features as the traditional macrocell [48]. However, the small cell feature is suitable for 5G deployments that promise ultra-high data rates, a million devices per square mile, and millisecond latency. The small cell hardware units are designed to reduce complexity, hence the hardware implementation is faster, easier, and low-power consumption (extends battery life).

For indoor cases, the performance of the wireless access signal will degrade interior of the building, especially in large buildings having multiple rooms, due to high loss building materials, such as low emissivity glass, metal, and concrete can degrade the wireless signals. Therefore, the distributed antenna system (DAS) is proposed to solve the indoor signals degradation issues by distributing the available external cell signals over the system of small antennas installed around the building in order to disperse and amplify the cell signal throughout the building to achieve perfect coverage. In addition, the small cells and distributed antenna system (DAS) solutions can support multiple standards, such as the 3G/4G cellular and implement carrier aggregation with the LTE Advanced (LTE-A) systems [48]. There are three types of small cells, namely femtocells, picocells, and microcells as listed in Table 6.

The efficiency of the 5G access network has been further improved, and it has begun to focus on the antenna design that will be installed on the base station, so-called multi-user MIMO (MU-MIMO) systems or large-scale antenna systems (LSAS). The general MU-MIMO is the base station (BS) with multiple antennas simultaneously serves a set of single-antenna users and the multiplexing gain can be shared by all users over the same frequency band. The base station uses antenna array (N > 100 antenna elements) as a beamforming antenna to simultaneously implement oriented signal transmission and reception (full-duplex). In order to change the direction of the array, the beamformer adjusts the phase shifts, β and amplitudes, a of the signal at each antenna element. The change of phase shifts, β alone would be sufficient to achieve beam steering in different directions. In addition, the ability to change the amplitude, a enables optimization of the side lobe suppression. For instance, the beamforming direction of the 2D antenna array can be modelled using antenna factor, AF as (see Fig. 7):

$$\mathrm{AF} = \mathrm{AF}_z \times \mathrm{AF}_y \tag{2}$$

where AF_z and AF_y are the array factor for K isotropic elements along z-axis and V isotropic elements along y-axis, respectively.

$$\mathrm{AF}_z = \sum_{\kappa=1}^{K} a_\kappa \exp\left\{ j\left(\kappa-1\right)\left(kd_z \cos\theta + \beta_z\right)\right\} \tag{3a}$$

$$\mathrm{AF}_y = \sum_{v=1}^{V} a_v \exp\left\{ j\left(v-1\right)\left(kd_y \sin\theta \sin\phi + \beta_y\right)\right\} \tag{3b}$$

The total number of antenna elements, $N = V \times K$. The β_z and β_y are the adjustable phase shifts for antenna elements along z-axis and y-axis, respectively. On the other hand, the a_κ and a_v are the adjustable amplitudes of each antenna element along z-axis and y-axis, respectively. Symbols d_z and d_y are the separation distance between the antenna elements. The k, θ, and ϕ are the propagation constant of free-space, space elevation, and azimuth angles, respectively.

Therefore, the beamforming of each antenna can increase the received power level of the user's device, mitigates interference to other users, and improve overall system efficiency. Recently, the problem of bandwidth and energy consumption is partly solved by massive MIMO (a large number of antenna elements, N). For instance, the 256 elements transmit antenna array normally having the gain of 28 dB. If 6.2 mW of transmit power is supplied for each antenna element, thus the total transmitted power can be achieved by 32 dBm [$10\log_{10}(256\times6.2$ mW/1mW)]. Finally, the combination of 32 dBm of transmitted power and 28 dB of antenna gain meets the 60 dBm of effective isotropic radiated power (EIRP) target [49].

For 3GPP, the 5G NR standard distinguishes between two ranges for carrier frequencies, namely Frequency Range 1 (Low frequencies and sub-6 GHz) and Frequency Range 2 (mmWave band from 24.25 GHz to 52.6 GHz). It should be noted that the sub-6 GHz band is extended operating frequencies under 5.925 GHz to 7.125 GHz. Although the coverage of sub-6 GHz is larger than the mmWave frequency band, operating frequencies below 6 GHz require a larger antenna aperture size, which leads to antenna weight, surface roughness, and antenna manufacturing costs. Hence, nowadays, hybrid beamforming (analog + digital) is most commonly used in mmWave bands to increase bandwidth usage (> 800 MHz), high data rates (20 Gbps download rates), and wireless network capacity (10^6 devices/km^2). For instance, China is planning and preparing 5G mmWave deployment for the 2022 Winter Olympics [50].

As the connectivity of IoT devices increases and the IoT devices are required to operate for increasingly complex tasks, such as artificial intelligence (AI) and machine learning (ML), thus the higher bandwidth (more than 5 GHz) and sub-millimeter wave operating frequencies (up to 100 GHz) had to be used. For example, most functions of smart cars (driverless cars) are still in the research stage, such as the radar resolution of identifying the number of cars gathered at a long distance up to 120 m from the observation car requires a bandwidth of at least 5 GHz using operating frequencies from 76 GHz to 81 GHz [51]. However, the maximum bandwidth that recent 5G can achieve is only 2 GHz. Furthermore, the possible geo-location update data rate requirement in the future maybe 0.1 Tbps (100 Gbps) and near 100% geographical coverage (land, sea, and sky), as well as sub-centimeter geo-location accuracy [31]. Hence, for fully automated driverless vehicle, operating frequency up to sub-millimeter wave is essential to be adopted, in which enter the era of sixth-generation (6G) wireless technology. By 2030, terahertz frequency radio access networks from 90 GHz to 3 THz will be expected to be used for 6G IoT applications to meet the growing needs of users (IoT devices more than 80 billion), such as data rates of 0.1–1 Tbps and spectrum efficiency of 3–60 bps/Hz, 100 GHz channel bandwidth, and 1000 km/h mobility.

For the current 5G frequency spectrum (700 MHz to 95 GHz), the terrestrial radio access networks (TRAN) are still suitable for use as a wireless station for the IoT, since the propagation signal attenuation in the sea level atmospheric environment (barometric pressure, P = 101.325 kPa, air temperature, T = 20 $^{\circ}$C, and water vapor density, ρ = 7.5 gm^{-3}) only causes the loss of 0.385 dB/km at 50 GHz and ~0.5 dB/km in the range of 70 GHz to 100 GHz. However, TRAN experience higher transmitted signal loss issues when operating at high frequencies from 100 GHz to

1 THz, such as path losses due to oxygen/water vapor as shown in Fig. 8 (the data is calculated using MATLAB function 'gaspl'). The atmospheric absorption loss, γ_A is approximately 5 dB/km at 275 GHz and increases dramatically to 700 dB/km at 1 THz. In addition, Fig. 8 shows the peak loss at a certain frequency (from 1 GHz to 1 THz) due to the resonant absorption of oxygen/vapor that occurs at that frequency. Hence, the outdoor long-distance terrestrial radio access networks are not suitable for implementation at terahertz frequencies. As mentioned, the large antenna arrays with many elements and more precisely directed beams are needed to overcome higher path loss and make sub-terahertz frequencies usable.

Table 4. A comparative analysis of 5G and 6G usage scenarios [8, 9], [11, 12], [25]

Services / Usage Scenarios				
Recent 5G	**Future 6G**			
	[9], [25]	**[11]**	**[12]**	**[8]**
Enhanced Mobile Broadband (eMBB)	**Mobile Broadband Reliable Low Latency Communication** (**MBRLLC = eMBB + uRLLC**) i) XR/AR/VR ii) Autonomous vehicular systems iii) Autonomous drones iv) Legacy eMBB & uRLLC	**Further-Enhanced Mobile Broadband** (**FeMBB**) i) Holographic verticals & Society ii) Full-sensory digital sensing & reality iii) Tactile/ Haptic internet iv) UHD/SHD/EHD videos	**Ubiquitous Mobile Ultra-Broadband** (**uMUB**)	**Contextually Agile eMBB Communications** (**CAeC**)
Ultra-Reliable, Low Latency Communications (uRLLC)	**Massive Ultra-Reliable, Low Latency Communication** (**muRLLC = uRLLC + mMTC**) i) Classical IoT ii) User tracking iii) Blockchain & DLT iv) Massive sensing v) Autonomous robotics	**Extremely Ultra-Reliable, Low Latency Communications** (**eURLLC**) i) Fully automated driving ii) Industrial internet **Long-Distance and High-Mobility Communications** (**LDHMC**) i) Deep-sea sightseeing ii) Hyper-HSR iii) Space travel	**Ultra-High Speed with Low Latency Communications** (**uHSLLC**)	**Event Defined uRLLC** (**EDuRLLC**)
Massive Machine Type Communications (mMTC)	**Human-Centric Services** (**HCS**) i) BCI ii) Haptics iii) Empathic communication iv) Affective communication **Multi-Purpose 3CLS and Energy Services** (**MPS**) i) CRAS ii) Telemedicine iii) Environmental mapping & imaging iv) Some special cases of XR services	**Ultra-Massive Machine Type Communications** (**umMTC**) i) Internet of Everything (IoE) **Extremely Low-Power Communications** (**ELPC**) i) Internet of Bio-Nano-Things	**Ultra-High Data Density** (**uHDD**)	**Computation Oriented Communications** (**COC**)

Terminology: **UHD/SHD/EHD** — Ultra-High-Definition/ Super-High-Definition / Extreme-High-Definition, **Hyper-HSR** — Hyper-High-Availability Seamless Redundancy, **DLT** — Distributed Ledger Technology, **3CLS** — Control, Localization, and Sensing, **CRAS** — Connected Robotic and Autonomous System, **XR/AR/VR** — Extended Reality/Augmented Reality/Virtual Reality, **BCI** — Brain-Computer Interface

Table 5. Comparison specifications, performances, and applications between current 5G and future 6G [9], [11], [15], [20], [23], [25]

	Specifications, Performance & Applications	5G	6G
1	Operating frequency	700 MHz to 95 GHz	700 MHz to 95 GHz 95 GHz to 3 THz (or above 10 THz)
2	Max. Bandwidth	1 GHz	100 GHz
3	Peak data rate	10 to 20 Gbps	1 Tbps
4	Experienced data rate	0.1 to 0.5 Gbps	10 Gbps
5	Latency	1 ms	0.1 ms
6	Reliability	99.999 % ($1–10^{-5}$)	99.9999999 % ($1–10^{-9}$)
7	Spectrum efficiency	30 bps/Hz	60 bps/Hz
8	Traffic density	10 Tbps/km^2	100 Tbps/km^2
9	Connectivity density	10^6 devices/km^2	10^7 devices/km^2
10	Mobility support	500 km/h	1000 km/h
11	Positioning precision	Meter level	Centimeter level
12	Receiver sensitivity	-120 dBm	< - 130 dBm
13	Energy efficiency	-	1 Tb/Joule (100 $\times$ over 5G)
14	Delay jitter	-	1 μs
15	Coverage	~ 70 %	> 99 %
16	Time buffer	Not real time	Real time
17	Autonomous vehicle	Partial	Fully
18	Haptic communication	Partial	Fully
19	Satellite integration	No	Fully
20	Extended reality (XR)	Partial	Fully
21	Artificial intelligence	Partial	Fully
22	Usage scenario/Services	eMBB, URLLC, mMTC	FeMBB, ERLLC, mURLLC, umMTC, LDHMC, ELPC (or MBRLLC, muRLLC)
23	Communication Technologies	i) mmWave communications	i) Sub-mmWave communications
		ii) Massive MIMO	ii) Spatial modulation (SM) MIMO
		iii) LDPC and polar codes	iii) LIS and HBF
		iv) Flexible frame structure	iv) OAM multiplexing
		v) Ultradense networks	v) Laser and VLC
		vi) Non-Orthogonal Multiple Access (NOMA)	vi) Blockchain-based spectrum sharing
		vii) Cloud/Fog/Edge computing	vii) Quantum communications and computing
		viii) SDN/NFV/Network slicing	viii) AI/Machine learning
24	Applications	i) Virtual reality(VR) /Augmented reality (AR)/360^o videos	i) Holographic verticals and society ii) Tactile/Haptic internet
		ii) Ultra HD videos	iii) Full-sensory digital sensing/reality
		iii) Vehicle-to-everything (V2X)	iv) Fully automated driving
		iv) Smart city/factory/home	v) Industrial internet
		v) Telemedicine	vi) Space travel
		vi) Wearable devices	vii) Deep-sea sightseeing
		vii) Other Internet of Things (IoT)	viii) Internet of Bio-Nano-Things

Terminology: **eMBB** — Enhanced Mobile Broadband, **mMTC** — Massive Machine Type Communications, **URLLC** — Ultra-Reliable, Low Latency Communications, **mURLLC** — Massive URLLC, **FeMBB** — Further-Enhanced Mobile Broadband, **ERLLC** — Extremely Reliable, Low Latency Communications, **umMTC** — Ultra-Massive Machine Type Communications, **LDHMC** — Long-Distance and High-Mobility Communications, **ELPC** — Extremely Low-Power Communications, **MIMO** — Multiple Input, Multiple Output, **mmWave** — Millimeter Wave, **OAM Multiplexing** — Orbital Angular Momentum Multiplexing, **LIS** — Large Intelligent Surfaces, **HBF** — Holographic Beamforming, **LDPC** — Low-Density Parity-Check Codes, **VLC** — Visible Light Communication, **NFV** — Network Function Virtualization, **SDN** — Software Defined Networking.

Table 6. Macrocells and small cell types of the wireless network.

Cell Type	Coverage Radius (m)	Indoor/Outdoor	Transmit Power (dBm)	Number of Users	Cost	Applications
Femtocells	10 to 50	Indoor	20	4 to 16	Low	Residential, home, and small offices.
Picocells	100 to 250	Indoor/Outdoor	24	32 to 64	Low	Offices, hospitals, shopping complexes, train stations, schools, universities, and in-aircraft.
Microcells	250 to 2500	Indoor/Outdoor	33 to 37	100 to 2000	Medium	Mall, hotels, stations, transportation hub, and urban.
Macrocells	5000	Outdoor	> 40	>2000	High	Suburban

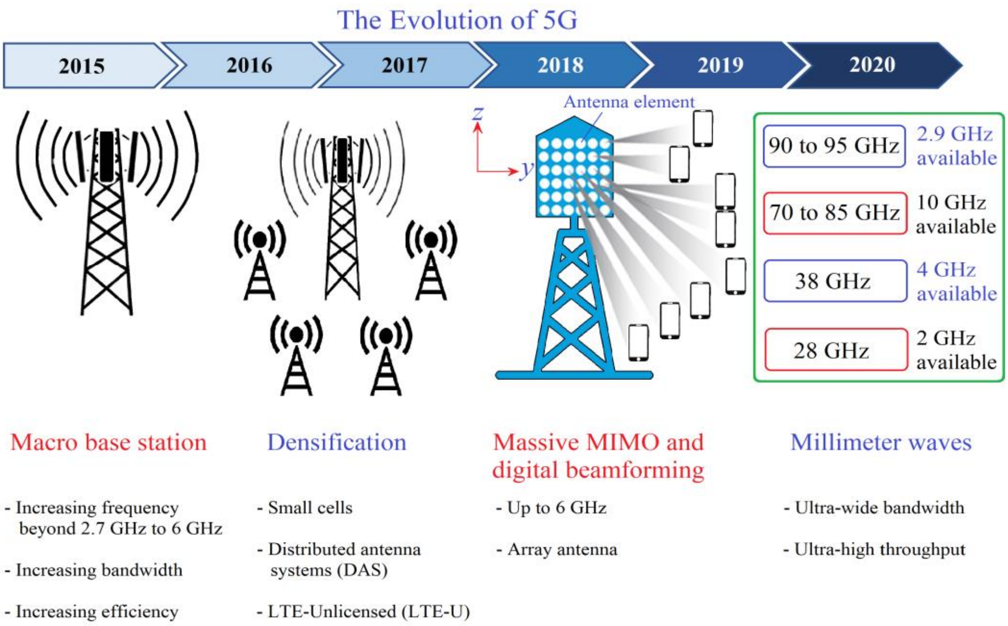


Fig. 7. The evolution of 5G wireless networks [2]

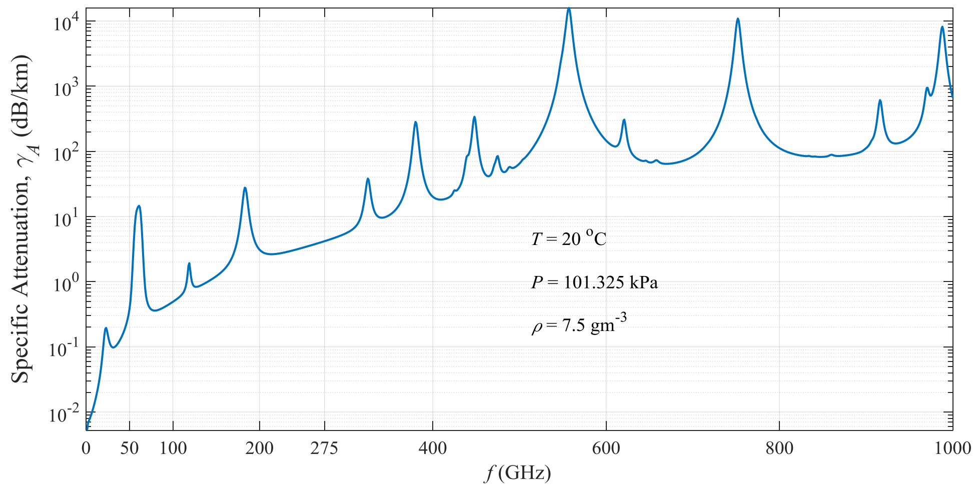
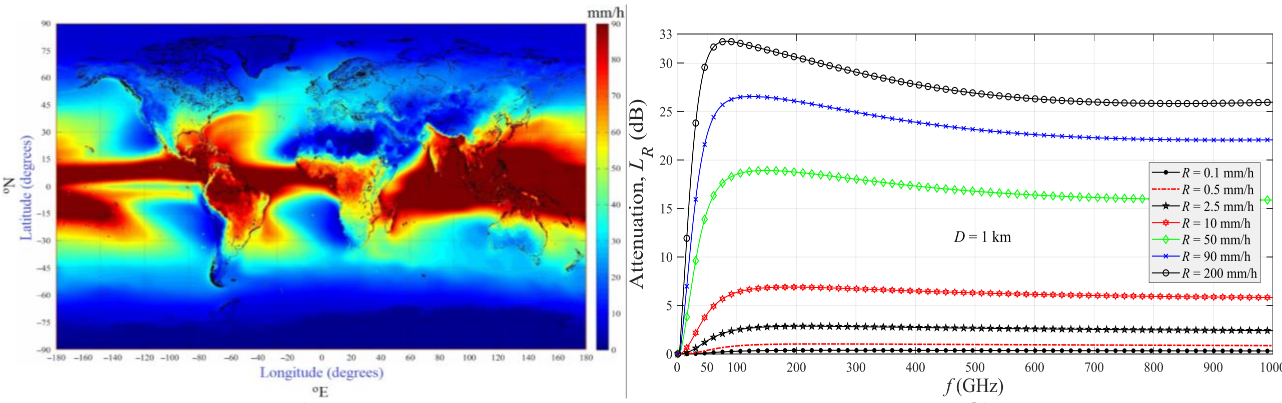


Fig. 8. Specific attenuation, γ_A in unit dB/km due to atmospheric oxygen and water vapor with sea level, h = 0 m, atmospheric pressure, P = 101.325 kPa, air temperature, T = 20 ^{o}C, and water vapor density, ρ = 7.5 gm^{-3}.

Besides, the tendency of water to absorb microwave energy can cause high path loss or wireless signal attenuation in rainy weather, especially at higher frequencies above 10 GHz. The rain rate, R value is dependent on the region, season, and weather. The global average annual rainfall, R distribution with a probability of 0.01% is illustrated in Fig. 9 (a) [52]. Obviously, the maximum R of 90 mm/h is distributed in the tropical regions ($0^o \leq {}^o$N $< 22^o$). The average value of R in middle latitudes regions ($22^o \leq {}^o$N $\leq 45^o$) is between 30 mm/h and 70 mm/h. Whereas, in polar latitudes (> 45 ^{o}N), the R value is less than 30 mm/h. Based on the rain rate, R value, the precipitation level can be divided into the categories listed in the Table 11. The calculated attenuation, L_R of different precipitation levels versus operating frequency, f at D = 1 km is plotted in Fig. 9 (b). The slight precipitation (R < 0.1 mm/h) only leads to the maximum attenuation, L_R of 0.37 dB at a signal propagation distance, D of 1 km. In heavy rain with R = 50 mm/h, the wireless signal may attenuate up to 19 dB. When rain rate, R reaches an extreme value of 200 mm/h, the maximum value of L_R is estimated to be 32.5 dB over 1 GHz to 1 THz.



(a) (b)

Fig. 9. (a) Rain rate, $R_{0.01}$ (mm/h) (p = 0.01 %) contour of the average year [52]. (b) Calculated attenuation, L_R of various rain rate, R levels at propagation distance of 1 km.

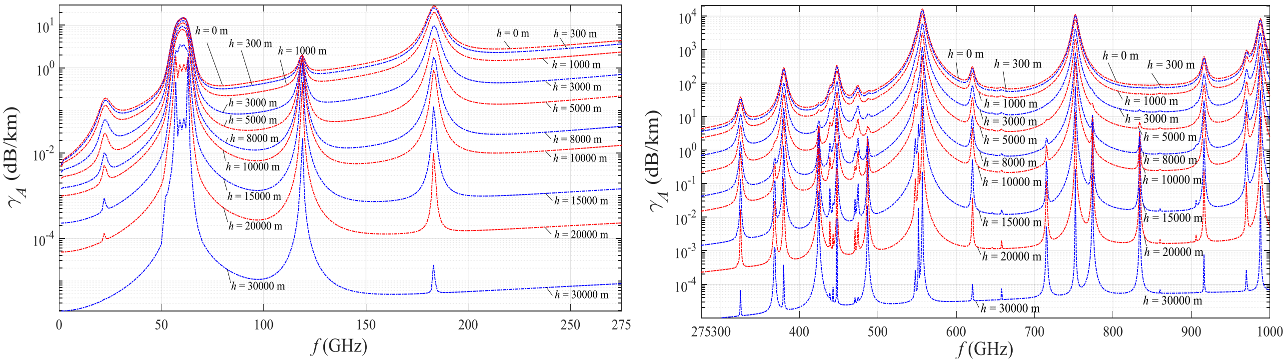
Table 7. Classification of daily rain rate and rainfall level

Precipitation grade	**Rain rate, *R* per hour (mm) [53]**	**Rain rate, *R* in a day (mm) [54]**
Light	< 0.1	<10
Moderate	0.1 – 0.5	10 – 25
Heavy	0.5 – 2.5	25 – 50
Very Heavy	2.5 – 10	50 – 100
Storm	10 – 50	100 – 250
Extreme storm	≥ 50	≥ 250

4.2. Aerial Radio Access Networks (ARAN)

Recently, non-terrestrial networks, such as unmanned aerial vehicle (UAV) access networks, are becoming an alternative method to solve the high loss due to atmospheric oxygen and water vapor for the transmitted signal of IoT devices up to THz, since the signal attenuation decreases with the height, h of the sea level as shown in Fig. 10. The attenuation, γ_A values are obtained by line-by-line model, which is expressed as a function of ambient temperature, T, pressure, P, water vapor density, ρ, and operating frequency, f from 1 GHz to 1 THz [55, 56]. The relationship between the sea level height, h and the variables (T, P, and ρ) in line-by-line model are tabulated in Table 8. The values of T, P, and ρ are calculated using equations proposed by ITU (2017) [57]. Finally, entering the calculated values of T, P, and ρ that are equivalent to the certain sea level, h in the line-by-line model in order to predict the attenuation, γ_A at the sea level. It can be seen from Fig. 10 that as the height above sea level, h increases, the attenuation γ_A is expected to decrease due to the oxygen content and water vapor density, ρ will decrease as the h increases. It should be noted that only the typical atmospheric temperature, T in middle-latitude ($22^o \leq {}^o$N $\leq 45^o$) is considered in the attenuation, γ_A calculation in Fig. 10.

The infrastructures of non-terrestrial communication stations are normally handled by unmanned aerial vehicles, such as drones, vulture, and blimps. The aerial radio access networks can be divided into three types of platforms according to the height of the access network above sea level, h, namely low-altitude platforms (LAPs; h = 100 m to 10 km) and high-altitude platforms (HAPs; h = 10 km to 50 km), and spaceborne platforms [low earth orbits (LEO): h = 50 km to 1500 km, medium earth orbits (MEO): h = 7000 km to 25000 km, and geostationary earth orbits (GEO): h = 35786 km] for satellite networks [21], [58], respectively. The integration of terrestrial and aerial access networks infrastructure is shown in Fig. 11.



(a) (b)

Fig. 10. Specific attenuation, γ_A in unit dB/km due to atmospheric gases changes with height above sea level, *h* from (a) 1 GHz to 275 GHz and (b) 275 GHz to 1 THz in middle-latitude (22° ≤ °N ≤ 45°).

Table 8. Sea level-dependent atmospheric parameters [57].

Altitude above sea level, *h* (m)	Atmosphere temperature, *T* (°C)			Atmosphere pressure, *P* (Pa)	Water vapour density, *ρ* (gcm^{-3})	Effective oxygen (%)
	Tropical	Middle Latitude	Polar			
0	20.00	15.00	0.00	101325	7.50	20.9
300	18.33	13.12	-1.83	97773	6.46	20.1
500	17.22	11.86	-3.04	95461	5.84	19.6
1000	14.44	8.72	-6.09	89876	4.55	18.4
2000	8.89	2.44	-12.17	79501	2.76	16.3
3000	3.34	-3.84	-18.26	70121	1.67	14.4
4000	-2.22	-10.12	-24.34	61660	1.02	12.7
5000	-7.77	-16.40	-30.43	54048	0.62	11.2
8000	-24.43	-36.94	-48.68	35652	0.14	7.7
10000	-35.54	-49.90	-	26500	0.051	-
15000	-	-56.50	-	12112	4.2×10^{-3}	-
20000	-	-56.50	-	5529	3.4×10^{-4}	-
30000	-	-46.64	-	1197	2.3×10^{-6}	-
50000	-	-2.50	-	79.782	1.0×10^{-10}	-
80000	-	-74.51	-	1.0525	3.2×10^{-17}	-

Satellite networks connections complement terrestrial networks especially in remote areas for smart agricultural applications, asset tracking [such as Global Positioning System (GPS)], maritime and intermodal transportation, oil and gas industry exploration [2]. Therefore, the installed base of satellite IoT connections will increase exponentially to 15.7 million units by 2025 as shown in Fig. 12 [2]. On the LAPs, drones are mainly used to supplement terrestrial coverage by providing connections to hotspots and scenes with weak terrestrial signals. On the other hand, airplanes, balloons, and airships are the main infrastructure of HAPs. HAPs seem like an alternative to satellites because of its advantages such as rapid deployment, wide coverage, low upgrade costs, high flexibility, and low propagation delay. Recently, the use of high-altitude platform stations as International Mobile Telecommunications (IMT) base stations, so-called HIBS for mobile service below 2.7 GHz was proposed by IMT. The HIBS is particularly useful for providing low-latency mobile connectivity to unserved/underserved areas, such as rural and remote areas, and over large areas around 31,500 km^2 [59].

On the spaceborne platforms, LEO supports very low-latency 5G services, such as URLLC, while GEO implements extremely high data rates to promote eMBB services. Table 9 summarizes the comparative specifications between LEO, MEO and GEO satellite systems. The propagation channel model of the between unmanned aerial vehicles (UAV) and terrestrial base station (BS) is shown in Fig. 13 (a). The higher the UAV is off the terrestrial base station or ground, the greater the coverage area as shown in Fig. 13 (b). Therefore, HAPs networks have wider coverage and longer endurance compared to LAPs. The average free-space path loss, *PL* between unmanned aerial vehicles at HAPs level and terrestrial base station (UAV-BS) is given as [60, 61]:

$$PL = \left(p_{LoS} PL_{LoS}\right) + \left(p_{NLoS} PL_{NLoS}\right) \tag{4}$$

where PL_{LoS} and PL_{NLoS} are the path losses due to line-of-sight (LoS) and non-line-of-sight (NLoS) paths, respectively written (in unit dB) as:

$$PL_{LoS} = 20\log_{10} d + 20\log_{10} f - 147.558 + \eta_{LoS} \tag{5a}$$

$$PL_{NLoS} = 20\log_{10} d + 20\log_{10} f - 147.558 + \eta_{NLoS} \tag{5b}$$

where η_{LoS} and η_{NLoS} are the average additional loss of free-space propagation loss depending on the environment (rural, suburban, urban, dense urban, and high-rise urban). On the other hand, d (in unit meter) is the distance between the UAV-BS as:

$$d = \sqrt{h^2 + r^2} \tag{6}$$

Symbol f is the operating frequency. The p_{LoS} and p_{NLoS} in Eq. (4) are the propagation probabilities of LoS and NLoS propagation paths respectively, which strongly depend on the elevation angle, θ (in unit degree) [62]:

$$p_{LoS} = \left[a - \frac{a-b}{1+\left\{(\theta - c)/d\right\}^e} \right] \times 0.01 \tag{7}$$

where a, b, c, d, and e are empirical constant values which depend on the environment, namely rural, suburban, urban, dense urban, and high-rise urban. The values of a, b, c, d, and e for various kinds of environments are listed in Table 10 [62]. The p_{LoS} in Eq. (7) satisfies the condition $0 \le p_{LoS} \le 1$. For instance, the line-of-sight (LoS) and non-line-of-sight (NLoS) propagation paths in dense urban environment is shown in Fig. 13 (c). The p_{LoS} calculated using (7) varies with elevation angle, θ is plotted in Fig. 14 [62]. Obviously, the high-rise urban area has many high-rise buildings and social crowd activities, thus the value of p_{LoS} is the smallest and highly dependent on the elevation angle, θ compared to the suburban. This is because most transmitted wireless signals are NLos. After all, in such high-rise urban areas, signal attenuation is also noticeable as part of the transmitted signal is absorbed by people and building walls.

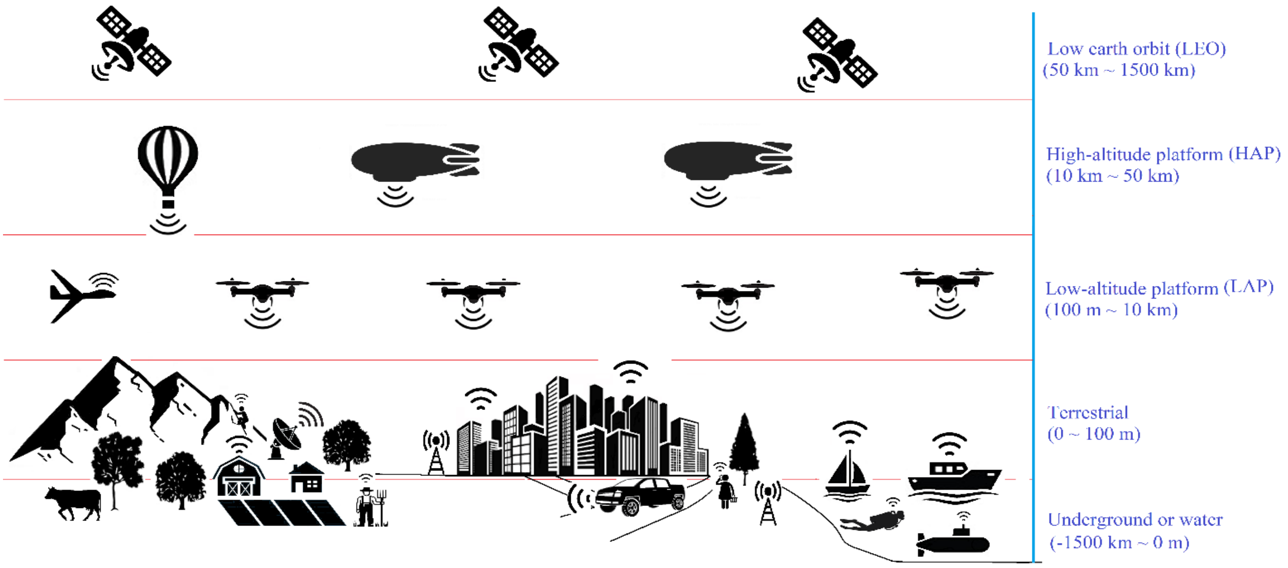


Fig. 11. 6G access networks infrastructure

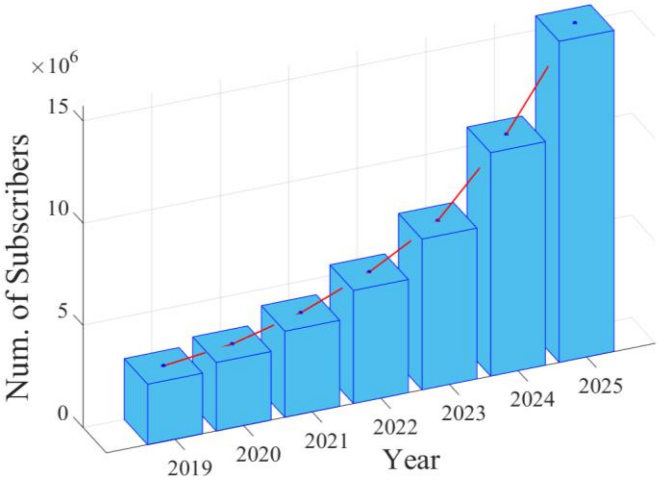


Fig. 12. Global satellite IoT subscribers [2]

Table 9. Comparison specifications between LEO, MEO, and GEO satellite systems [63]

Specification	LEO	MEO	GEO
Height, *h* from ground	700 to 1400 km	10000 to 15000 km	35786 km
Orbital period, *t*	10 to 40 minutes	2 to 8 hours	24 hours
Number of required satellites per operator	40+	10 to 15	3 to 4
Satellite life	3 to 7 years	10 to 15 years	10 to 15 years
Space segment cost	High	Low	Medium
Terrestrial gateway cost	High	Medium	Low
Propagation loss	Least	High	Highest
Coverage	Small	Medium	Large
Elevation angle, θ variation	Rapid	Slow	No variation
Main application	Weather forecasting	Communication & navigation	Telephony, data/TV distribution, mobile communication, broadcasting

The propagation probability, p_{LoS} of LoS path from LAPs level to terrestrial base station (BS) can be simplified as Sigmoid function [60, 61]:

$$p_{LoS} = \frac{1}{1+\alpha \exp\{-\beta(\theta-\alpha)\}} \tag{8a}$$

$$p_{NLoS} = 1 - p_{LoS} \tag{8b}$$

where α and β are the empirical constant values depending on the environment.

Table 10. Coefficient values of *a*, *b*, *c*, *d*, and *e* in (7) [62]

Area	*a*	*b*	*c*	*d*	*e*
Suburban	101.6	0	0	3.25	1.241
Urban	120.0	0	0	24.30	1.229
Dense urban	187.3	0	0	82.10	1.478
High-rise urban	352.0	-1.37	-53	173.80	4.670

Besides attenuation due to vegetation and building, the major attenuation of the wireless transmitted signal from the aerial radio access networks is due to clouds which are composed of small water droplets and air. This is caused by the polarization of water molecules contained in the clouds when exposed to microwaves (MW), millimetre wave (mmWave), and sub-millimeter wave (Sub-mmWave). Normally, the specific attenuation, γ_C (in unit dB/km) due to the cloud is assumed to be linearly proportional to liquid water content, *w* (in unit g/cm^3) in the cloud [64]. In fact, the liquid water content, *w* of the cloud is determined by the cloud's unevenness, type, and shape, as well as height, *h* above sea level as shown in Table 11. Cloud shapes can be categorized into ten types with different *w* value ranges. At height, *h* less than 2000 m, cumulonimbus-type clouds have maximum *w* values up to 3 g/cm^3. The higher the *h* (> 2000 m), the lower the *w* value of clouds, such as altocumulus, altostratus, and nimbus. The attenuation, γ_C due to the cloud versus operating frequency of different *w* values at 13.12 °C and -16.40 °C are respectively shown in the Fig. 15. From Table 8, the temperature of 13.12 °C and -16.40 °C correspond to heights above sea level, *h* of 300 m and 5000 m, respectively. The attenuation, γ_C at -16.4 °C is higher than the γ_C at 13 °C from 1 GHz to 100 GHz. When the operating frequency exceeds 100 GHz, the increase in γ_C at 13 °C has been exceeded for conditions at -16.4 °C. Overall, the γ_C increases with frequency from 1 GHz to 1 THz. In addition, the value of *w* also varies from region to region, and tropical regions have higher values of *w* as shown in Fig. 16.

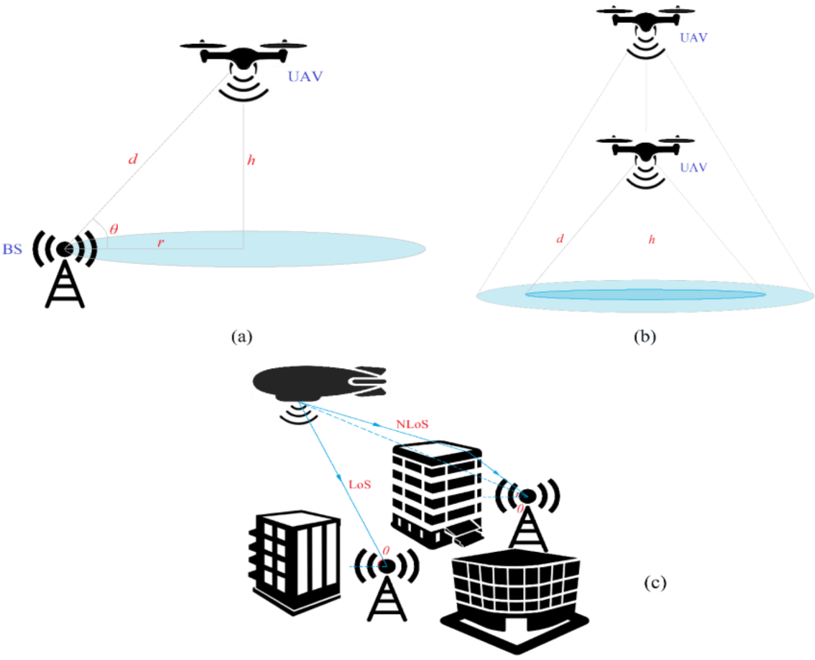


Fig. 13. (a) UAV-BS coverage model. (b) The coverage area depends on the altitude. (c) The line-of-sight (LoS) and non-line-of-sight (NLoS) propagation paths in dense urban.

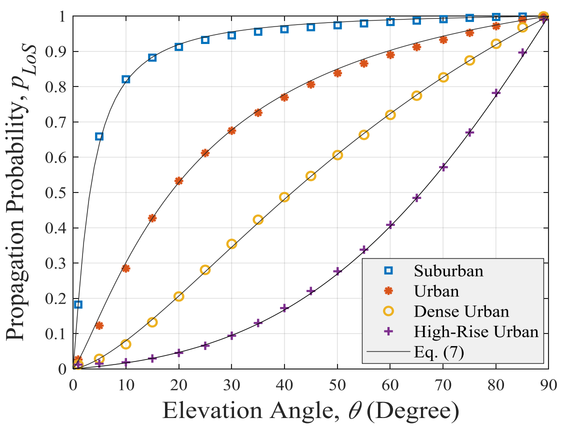


Fig. 14. Variation in propagation probability, p_{LoS} of LoS with elevation angle, θ at various kinds of environments [62].

Table 11. Cloud physical properties [53], [65]

Typ. Cloud base (km)	Cloud type	*w* (g/m^3)	Average composition
0.3 to 2 (Low clouds)	Stratocumulus	0.3 – 0.55	Water droplets (Ice crystals in winter)
	Stratus	0.29 – 0.42	
	Cumulus	0.2 – 1.0	
	Cumulonimbus	0.5 – 3	
2 to 6 (Middle clouds)	Altocumulus	0.2	Water droplets and/or Ice crystals
	Altostratus	0.41	
	Nimbostratus	0.27– 0.61	
6 to 12 (High clouds)	Cirrus	0.0003 – 0.06	Frozen water droplets or ice crystals
	Cirrocumulus	–	
	Cirrostratus	–	

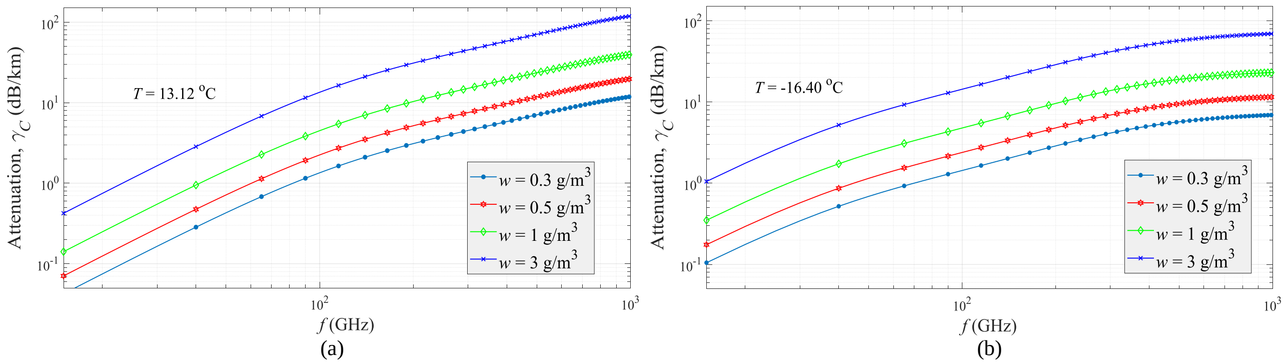


Fig. 15. Calculated attenuation, γ_C versus operating frequency, *f* of different liquid water content, *w* in clouds at (a) 13.12 °C and (b) -16.40 °C.

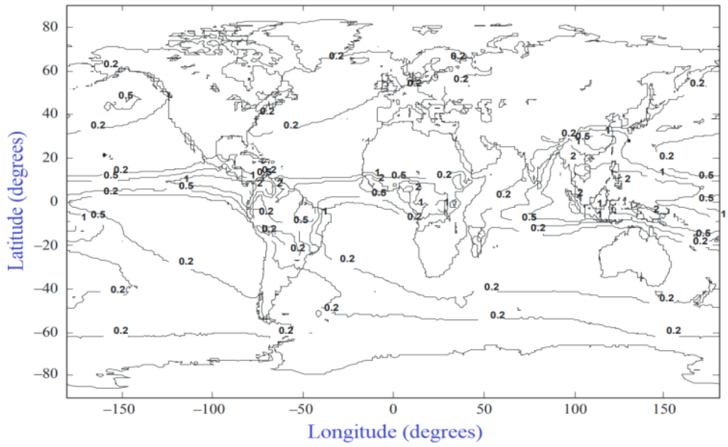


Fig. 16. The normalized total columnar content of cloud liquid water, $w \times D$ (kg/m^2) contour with a probability of exceeding 20% per year [64].

5. Conclusion

In fact, the number of available wireless protocols and standards are massive and overlap with each other, and even more new protocols will be proposed based on certain particular Internet of Things (IoT) applications in the future. Therefore, it is difficult to thoroughly and clearly discuss each protocol and standard in single manuscript. In addition, it is difficult to classify protocols and standards in in every detail because these policies are proposed by various telecommunications committees and international standardization organizations [such as US Federal Communications Commission (FCC), International Telecommunication Union (ITU), European Electronic Communications Committee (ECC), Institute of Electrical and Electronics Engineers (IEEE), 3rd Generation Partnership Project (3GPP)], and they have some things in common, but also differences. Despite that, this paper attempts to summarize a lot of facts and list them in the form of tables and charts so that readers can compare recent 5G and future 6G IoT, as well as understand their standard protocols, performance, specifications, and applications more easily and quickly. The usage scenario of 6G is expanded from the 5G and categorized it in more specify applications and indirectly illustrate the research direction, key performance indicators (KPIs), and potential for 6G in future [66].

This paper focuses more on the discussion and analysis of 5G and 6G access networks, including 5G network evolution, terrestrial radio access networks (TRAN), and aerial radio access network (ARAN). The advantages and disadvantages between TRAN and ARAN have been analyzed in detail. Barrier factors and challenges to future ARAN have been discussed in terms of attenuation caused by atmospheric oxygen and water vapor, rainfall, and clouds or snow. In the future, the combination of TRAN and ARAN will be widely used to optimize coverage (>99%) and cover all the IoT access. This situation leads to more extensive research on wireless signal path loss condition for various environmental factors will conduct, such as signal path loss in the sky (loss due to weather effects), underwater (lossy liquid and density effects), dense cities (human and building effects), villages (life and vegetation effects), forests (vegetation effect), and indoor environmental (walls and furniture effects).

These emerging developments in the IoT will also indirectly affect the rapid progress of artificial intelligence (AI) and machine learning (ML), due to now is the era of the fourth industrial revolution (industry 4.0), most of the operating systems in the industry are based on fully automatic functional network [67]-[69]. In addition, huge IoT networks require large amounts of electricity to support, hence the fields of energy harvesting and energy sustainability have recently become important research topics. In addition, the development of 6G wireless technologies is highly dependent on the existing advanced monolithic microwave integrated circuits (MMICs), hence the field of semiconductors should also be a popular topic for researchers and the industrial sector in recent and future.

Appendix A

Table A. List of key acronyms

Acronyms	Definitions	Acronyms	Definitions	Acronyms	Definitions
2G-GSM	2G-Global System for Mobile Communications	HBF	Holographic Beamforming	NFV	Network Function Virtualization
3CLS	Control, Localization, and Sensing	HD	High Definition	NLoS	Non-Line-Of-Sight
3GPP	3rd Generation Partnership Project	HSR	High-Availability Seamless Redundancy	NOMA	Non-Orthogonal Multiple Access
5G	Fifth Generation Wireless Technology	HVAC	Heating, Ventilation, and Air Conditioning	NB-IoT	Narrowband-Internet of Things
5G NR	5G New Radio	IEEE	Institute of Electrical and Electronics Engineers	OAM	Orbital Angular Momentum
6G	Sixth Generation Wireless Technology	IIoT	Industrial Internet of Things	QoS	Quality of Service
6LoWPAN	IPv6 over Low-Power Wireless Personal Area Networks	IMT-2020	International Mobile Communications - 2020	QR	Quick Response
AI	Artificial Intelligence	IoE	Internet of Everything	RF	Radio Frequencies
AR	Augmented Reality	IoT	Internet of Things	RFID	Radio Frequency Identification
ARAN	Aerial Radio Access Networks	IPv6	Internet Protocol version 6	RTLS	Real Time Location Systems
BCI	Brain-Computer Interface	ISA100.11 a	International Society of Automation	SDN	Software Defined Networking
BW	Bandwidth	ISM	Industrial, Scientific, and Medical	SNAP	Subnetwork Access Protocol
BS	Base Station	ITU	International Telecommunication Union	SNR	Signal-to-Noise Ratio
CAeC	Contextually Agile eMBB Communications	LAPs	Low-Altitude Platforms	Sub-mmWave	Sub-Millimeter Wave
CBRS	Citizens Broadband Radio Service	LDHMC	Long-Distance and High-Mobility Communications	TDD	Time Division Duplex
CDMA	Code Division Multiple Access	LDPC	Low-Density Parity-Check Codes	THz	Terahertz
CNC	Computer Numerical Control	LEOs	Low Earth Orbits	TRAN	Terrestrial Radio Access Networks
COC	Computation Oriented Communications	LIS	Large Intelligent Surfaces	UAV	Unmanned Aerial Vehicle
CRAS	Connected Robotic and Autonomous System	LoRa/ LoRaWAN	Long-Range Wide-Area Network	uHDD	Ultra-High Data Density
D2D	Devices-To-Device	LoS	Line-Of-Sight	uHSLLC	Ultra-High Speed with Low Latency Communications
DAS	Distributed Antenna Systems	LPWAN	Low-Power Wide-Area Network	umMTC	Ultra-Massive Machine Type Communications
DLT	Distributed Ledger Technology	LSAS	Large-Scale Antenna Systems	UMTS	Universal Mobile Telecommunications System
ECC	European Electronic Communications Committee	LTE	Long Term Evolution	uMUB	Ubiquitous Mobile Ultra-Broadband
EDuRLLC	Event Defined uRLLC	LTE-A	Long Term Evolution-Advanced	uRLLC	Ultra-Reliable and Low-latency Communications
EIRP	Effective Isotropic Radiated Power	LTE-M	Long Term Evolution-Machines	UWB	Ultra-Wideband
ELPC	Extremely Low-Power Communications	LTE-U	Long Term Evolution-Unlicensed	V2X	Vehicle-to-Everything
eMBB	Enhanced Mobile Broadband	MBRLLC	Mobile Broadband Reliable Low Latency Communication	VLC	Visible Light Communication
eURLLC	Extremely Ultra-Reliable, Low Latency Communications	MIMO	Multiple Input, Multiple Output	VR	Virtual Reality
FCC	Federal Communications Commission	MiWi	Microchip Wireless	Wi-Fi	Wireless Fidelity
FDD	Frequency Division Duplex	ML	Machine Learning	Wi-Gig	Wireless Gigabit Alliance
FeMBB	Further-Enhanced Mobile Broadband	MMICs	Monolithic Microwave Integrated Circuits	Wi-Sun	Wireless Smart Utility Network
FR 1	Frequency Range 1	mMTC	Massive Machine Type Communications	WirelessHART	Wireless Highway Addressable Remote Transducer Protocol
FR 2	Frequency Range 2	mmWave	Millimeter Wave	WLAN	Wireless Local Area Network

GPRS	General Packet Radio Service	MPS	Multi-Purpose 3CLS and Energy Services	WPAN	Wireless Personal Area Network
GPS	Global Positioning System	MU-MIMO	Multi-User Multiple Input, Multiple Output	WWAN	Wireless Wide Area Network
HAPs	High-Altitude Platforms	muRLLC	Massive Ultra-Reliable, Low Latency Communication	XR	Extended Reality
HCS	Human-Centric Services	MW	Microwave	Zigbee	Zonal Intercommunication Global-Standard

References

[1] ITU, *Series Y: Global Information Infrastructure, Internet Protocol Aspects and Next-Generation Networks*. U.S.: Recommendation International Telecommunication Union ITU-T Y.2060, 2012.

[2] F. Johan, *The Satellite IoT Communications Market*. Sweden: Berg Insight, 2021.

[3] M. R. Palattella et al., “Internet of things in the 5G era: enablers, architecture, and business models,” *IEEE Journal on Selected Areas in Communications*, vol. 34, pp. 510–527, 2016.

[4] S. M. Riazul Islam, D. Kwak, Humaun, M. D. Kabir, M. Hossain, K. S. Kwak, “The Internet of Things for health care: A comprehensive survey,” *IEEE Access*, vol. 3, pp. 678–708, 2015.

[5] IoT For All, *What is the Internet of Things, or IoT? A Simple Explanation*. IoT For All, 2021. https://www.iotforall.com/what-is-internet-of-things

[6] Wikipedia, *Internet of Things*. Wikipedia, the free encyclopedia, 2021. https://en.wikipedia.org/wiki/Internet_of_things

[7] T. Y. Huang et al., “A survey on green 6G network: architecture and technologies,” *IEEE Access*, vol. 7, pp. 175758–175768, 2019.

[8] K. B. Letaief, W. Chen, Y. M. Shi, J. Zhang, and Y. J. Angela Zhang, “The roadmap to 6G: AI empowered wireless networks,” *IEEE Communication Magazine*, vol. 57, pp. 84–90, 2019.

[9] W. Saad, M. Bennis, and M. Z. Chen, “A vision of 6G wireless systems: applications, trends, technologies, and open research problems,” *IEEE Network*, vol. 34, pp. 134–142, 2019.

[10] L. Zhang, Y. C. Liang, and D. Niyato, “6G visions: mobile ultra-broadband, super internet-of-things, and artificial intelligence,” *China Communication*, vol. 16, pp. 1–14, 2019a.

[11] Z. Q. Zhang et al., “6G wireless networks vision, requirements, architecture, and key technologies,” *IEEE Vehicular Technology Magazine*, vol. 14, pp. 28–41, 2019b.

[12] B. Q. Zong et al., “6G technologies: key drivers, core requirements, system architectures, and enabling technologies,” *IEEE Vehicular Technology Magazine*, vol. 14, pp. 18–27, 2019.

[13] M. W. Akhtar, S. A. Hassan, R. Ghaffar, H. J. Jung, S. Garg, and M. S. Hossain, “The shift to 6G communications: vision and requirements,” *Human-centric Computing and Information Sciences*, vol. 10, pp. 1–27, 2020.

[14] M. H. Alsharif et al., “Sixth generation (6G) wireless networks: vision, research activities, challenges and potential solutions,” *Symmetry*, vol. 12, pp. 1–27, 2020.

[15] Ian F. Akyildiz, Ahan Kak, and Shuai Nie, “6G and beyond: the future of wireless communications systems,” *IEEE Access*, vol. 8, pp. 44983–44998, 2020.

[16] Y. L. Lee, D. H. Qin, L. C. Wang, and G. H. Sim, “6G massive radio access networks: key applications, requirements and challenges,” *IEEE Open Journal of Vehicular Technology*, vol. 2, pp. 54–66, 2020.

[17] E. T. Michailidis, S. M. Potirakis, and A. G. Kanatas, “AI-inspired non-terrestrial networks for IIoT: review on enabling technologies and applications,” *IoT*, vol. 1, pp. 21–48, 2020.

[18] R. Sekaran et al., “Survival study on blockchain based 6G-enabled mobile edge computation for IoT automation,” *IEEE Access*, vol. 8, pp. 143453–143463, 2020.

[19] B. Barakat et al., “6G opportunities arising from internet of things use cases: a review paper,” *Future Internet*, vol. 13, pp. 1–29, 2021.

[20] N. Chen and M. Okada, “Toward 6G internet of things and the convergence with RoF system,” *IEEE Internet of Things Journal*, vol. 8, pp. 8719–8733, 2021.

[21] N. N. Dao, Q. V. Pham, N. H. Tu, T. T. Thanh, V. N. Q. Bao, D. S. Lakew, and S. Cho, “Survey on aerial radio access networks: Toward a comprehensive 6G access infrastructure,” *IEEE Communications Surveys & Tutorials*, vol. 23, pp. 1193–1225, 2021.

[22] C. De Alwis et al., “Survey on 6G frontiers: trends, applications, requirements, technologies and future research,” *IEEE Open Journal of the Communications Society*, vol. 2, pp. 836–886, 2021.

[23] Dinh, C. Nguyen, Ming Ding, Pubudu, N. Pathirana, Aruna Seneviratne, Jun Li, Dusit Niyato, Octavia Dobre, and H. Vincent Poor, “6G internet of things: a comprehensive survey,” *IEEE Internet of Things Journal*, vol. 9, pp. 359-383, 2022.

[24] F. X. Guo, F. Richard Yu, H. L. Zhang, H. Ji, and C. M. Victor Leung, “Enabling massive IoT toward 6G: a comprehensive survey,” *IEEE Internet of Things Journal*, vol. 8, pp. 11891–11915, 2021.

[25] A. L. Imoize, O. Adedeji, N. Tandiya, and S. Shetty, “6G enabled smart infrastructure for sustainable society: opportunities, challenges, and research roadmap,” *Sensors*, vol. 21, pp. 1–58, 2021.

[26] B. F. Ji et al., “A survey of computational intelligence for 6G: key technologies, applications and trends,” *IEEE Transactions on Industrial Informatics*, vol. 17, pp. 7145–7154, 2021.

[27] W. Jiang, B. Han, M. A. Habibi, and H. D. Schotten, “The road towards 6G: a comprehensive survey,” *IEEE Open Journal of the Communications Society*, vol. 2, pp. 334–366, 2021.

[28] P. K. Padhi and F. Charrua-Santos, “6G enabled industrial internet of everything: towards a theoretical framework,” *Applied System Innovation*, vol. 4, pp. 1–28, 2021.

[29] C. Schroeder, “Early indications of 6G,” *Microwave Journal*, vol. 64, pp. 5–9, 2021.

[30] Y. Spyridis et al., "Towards 6G IoT: tracing mobile sensor nodes with deep learning clustering in UAV networks," *Sensors*, vol. 21, pp. 1–16, 2021.
[31] X. H. You et al., "Towards 6G wireless communication networks: vision, enabling technologies, and new paradigm shifts," *Science China Information Sciences*, vol. 64, pp. 110301:1–110301:74, 2021.
[32] M. Sheng, D. Zhou, W. G. Bai. J. Y. Liu, and J. D. Li, "6G Service coverage with mega satellite constellations," *China Communications*, vol 19, pp. 64–76, 2022.
[33] M. Gupta, R. K. Jha, and S. Jain, "Tactile based intelligence touch technology in IoT configured WCN in B5G/6G-A survey," *IEEE Access*, in press.
[34] P. H. Siegel, "Terahertz technology," *IEEE Transactions on Microwave Theory and Techniques*, vol. 50, pp. 910–928, 2002.
[35] H. Elayan, O. Amin, B. Shihada, R. M. Shubair, and M. Slim Alouini, "Terahertz band: the last piece of RF spectrum puzzle for communication systems," *IEEE Open Journal of the Communications Society*, vol. 1, pp. 1–32, 2020.
[36] Qorvo and RFMW, *Wi-Fi Convergence with IoT and 5G*. U.S.: Microwave Journal, 2020.
[37] International Telecommunication Union, *IoT Standards Part II: 3GPP Standards. Training on Planning Internet of Things (IoTs) Networks*. U.S.: ITU Report, 2018.
[38] A. Díaz Zayas, F. J. Rivas Tocado, and P. Rodríguez, "Evolution and testing of NB-IoT solutions," *Applied Sciences*, vol. 10, pp. 7903 (1–17), 2020.
[39] S. Henry, A. Alsohaily, and E. S. Sousa, "3GPP 5G new radio system with the ITU IMT-2020 requirements," *IEEE Access*, vol. 8, pp. 42828–42840, 2020.
[40] Huawei, *5G Spectrum Public Policy Position*. Shenzhen, China: Huawei Technologies Co., Ltd, 2017.
[41] W. Ayoub, A. Samhat, F. Nouvel, M. Mroue, and J-C. Prévotet, "Internet of mobile things: overview of LoRaWAN, DASH7, and NB-IoT in LPWANs standards and supported mobility," *IEEE Communications Surveys & Tutorials*, vol. 21, pp. 1561–1581, 2019.
[42] J. Huang, Y. Liu, C. X. Wang, J. Sun, and H. L. Xiao, "5G millimetre-wave channel sounders, measurements, and models: recent developments and future challenges," *IEEE Communications Magazine*, vol. 57, pp. 138–145, 2018.
[43] Keysight Technologies, *How to Ensure IoT Devices Work in Their Intended Environment (Locate and Identify Interference)*. U.S.: Keysight Technologies, 2019.
[44] F. Meneghello, M. Calore, D. Zucchetto, M. Polese, and A. Zanella, "IoT: Internet of threats? a survey of practical security vulnerabilities in real IoT devices," *IEEE Internet of Things Journal*, vol. 6, pp. 8182–8201, 2019.
[45] T. Oza, "Understanding the underlying sensor and wireless technologies in IIoT apps," *Microwaves & RF*, vol. 9, pp. 18–22, 2020.
[46] S. DeTomasi, "Navigating the 5G NR standards," in *Advanced 5G Over the Air Testing (OTA) Challenges and Solutions*, Pat Hindle, Ed. U.S.: Microwave Journal, 2019, pp. 10–13.
[47] T. Madarasz, *Microwave will drive the development of 5G*. In Pat Hindle (Ed), Design Ideas and Tradeoffs for 5G Infrastructure (pp. 10–13). U.S.: Microwave Journal, 2019.
[48] N. Y. Tuan, "Small cells help keep 5G connected," in *Focus on: 5G Technology and Challenges*, Bill Wong, Ed. U.S: Microwaves & RF, 2020, pp. 2–4.
[49] Admin, *Beamforming in 5G mmWave Radios*. 5G mmWave, 2020. https://www.5gmmwave.com/5g-mmwave/beamforming-in-5g-mmwave-radios/
[50] Admin, *Economics of 5G mmWave: Is It Cost Effective?*. 5G mmWave, 2021. https://www.5gmmwave.com/5g-mmwave/economics-of-5g-mmwave-is-it-cost-effective/
[51] A. Himmler and R. N. Alexander, *How 4D Imaging Radar Sensors Can Be Validated*. India: Autocar Professional, 2021. Available online: https://www.autocarpro.in/opinion-blogs/how-4d-imaging-radar-sensors-can-be-validated-79866 (accessed on 22 September 2021).
[52] ITU, *Reference Standard Atmospheres*. U.S.: International Telecommunication Union Radiocommunications Sector, ITU-R Report P. 835-6, 2017.
[53] G. A. Siles, J. M. Riera, and P. García-del-Pino, "Atmospheric attenuation in wireless communication systems at millimeter and THz frequencies," *IEEE Antennas and Propagation Magazine*, vol. 57, pp 48–61, 2015.
[54] Q. Li, Q. Zhu, J. S. Zheng, K. H. Liao, and G. S. Yang, Soil moisture response to rainfall in forestland and vegetable plot in Taihu Lake Basin, China. *Chinese Geographical Science*, vol. 25, pp. 1–12, 2014.
[55] H. J. Liebe, T. Manabe, and G. A. Hufford, Millimeter-wave attenuation and delay rates due to fog/cloud conditions. *IEEE Transactions on Antennas and Propagation*, vol. 37, pp. 1617–1623, 1989.
[56] ITU, *Attenuation by Atmospheric Gases and Related Effects*. U.S.: International Telecommunication Union Radiocommunications Sector, Recommendation ITU-R P. 676-12, 2019.
[57] ITU, *Reference Standard Atmospheres*. U.S.: International Telecommunication Union Radiocommunications Sector, ITU-R Report P. 835-6, 2017.
[58] F. Rinaldi et al., "Non-terrestrial networks in 5G & beyond: a survey," *IEEE Access*, vol. 8, pp. 165178–165200, 2020.
[59] A. Weissberger, *ITU-R Future Report: High Altitude Platform Stations as IMT Base Stations (HIBS)*. IEEE Communication Society Technology Blog, 2021. https://techblog.comsoc.org/2021/02/17/itu-r-future-report-high-altitude-platform-stations-as-imt-base-stations-hibs/
[60] A. Al-Hourani, S. Kandeepan, and S. Lardner, "Optimal LAP altitude for maximum coverage," *IEEE Wireless Communications Letters*, vol. 3, pp. 569–572, 2014.
[61] T. F. Zhao, H. Wang, and Q. W. Ma, "The coverage method of unmanned aerial vehicle mounted base station sensor network based on relative distance," *International Journal of Distributed Sensor Networks*, vol. 16, pp. 1–12, 2020.
[62] J. Holis and P. Pechac, "Elevation dependent shadowing model for mobile communications via high altitude platforms in built-up areas," *IEEE Transactions on Antennas and Propagation*, vol. 56, pp. 1078–1084, 2008.
[63] INFOLYSiS, A Comparative CAPEX Techno-Economic Analysis of NFV Applicability on the Ground Segment of GEO/MEO/LEO Satellite Systems. Athens, Greece: INFOLYSIS P.C, 2017.

[64] ITU, *Attenuation Due to Clouds and Fog*. U.S.: International Telecommunication Union Radiocommunications Sector, Recommendation ITU-R P. 840-8, 2019.
[65] L. D. Carey, J. G. Niu, P. Yang, J. A. Kankiewicz, V. E. Larson, and T. H. V. Haar, "The vertical profile of liquid and ice water content in midlatitude mixed-phase altocumulus clouds," *Journal of Applied Meteorology and Climatology*, vol. 47, pp. 2487–2495, 2008.
[66] J. B. Tan and L. L. Dai, "THz precoding for 6G: challenges, solutions, and opportunities," *IEEE Wireless Communications*, in press.
[67] S. K. Ali Shah and W. Mahmood, "Smart home automation using IoT and its low cost implementation," *International Journal of Engineering and Manufacturing*, vol. 5, pp. 28–36, 2020.
[68] K. A. Kumar and D. Aju, "An internet of thing based Agribot (IoT-Agribot) for precision agriculture and farm monitoring," *International Journal of Education and Management Engineering*, vol. 4, pp. 33–39, 2020.
[69] A. Urbonavicius and N. Saeed, "IoT leak detection system for buiding hydronic pipes," *International Journal of Engineering and Manufacturing*, vol. 5, pp. 1–21, 2019.

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