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CAPACITY ON WIRELESS QUANTUM CELLULAR COMMUNICATION SYSTEM

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Abstract

The demand for wireless connectivity has grown exponentially over the last few decades. Fifth-generation (5G) communications, with far more features than fourth-generation communications, will soon be deployed worldwide. A new paradigm of wireless communication, the sixth-generation (6G) system, with the full support of artificial intelligence, is expected to be implemented between 2027 and 2030. Beyond 5G, some fundamental issues that need to be addressed are higher system capacity, higher data rate, lower latency, higher security, and improved quality of service (QoS) compared to the 5G system. This paper presents the vision of future 6G wireless communication and its network architecture. This article describes emerging technologies such as artificial intelligence, terahertz communications, wireless optical technology, free-space optical network, blockchain, three-dimensional networking, quantum communications, unmanned aerial vehicles, cellfree communications, integration of wireless information and energy transfer, integrated sensing and communication, integrated accessbackhaul networks, dynamic network slicing, holographic beamforming, backscatter communication, intelligent reflecting surface, proactive caching, and big data analytics that can assist the 6G architecture development in guaranteeing the QoS. Besides, expected applications with 6G communication requirements and possible technologies are presented. We also describe potential challenges and research directions for achieving this goal.

Keywords: *Capacity, Wireless, Cellular, Communication*

Introduction

WOC communication is considered as the next frontier for high-speed broadband connection due to its unique features: extremely high bandwidth, ease of deployment, tariff-free bandwidth allocation, low power 1/2 of radio-frequency (RF) systems), less mass 1/2 of RF systems), small size 1/10 the diameter of RF antenna), and improved channel security. It has emerged a good commercial alternative to existing radio-frequency communication as it supports larger data rates and provides high gain due to its narrow beam divergence. It is capable of transmitting data up to 10 Gbps and voice and video communication through the atmosphere/free space. WOC have two broad categories, namely, indoor and outdoor wireless optical communications. Indoor WOC is classified into four generic system configurations, i.e., directed line-of-sight (LOS), non-directed LOS, diffused, and quasi diffused. Outdoor wireless optical communication is also termed as free-space optical (FSO) communication. The FSO communication systems are also classified into terrestrial and space systems. Figure 1.1 shows the classification of WOC systems. Over the last few years, massive expansion in WOC technology has been observed due to huge advances in optoelectronic components and tremendous growth in the market offering wireless optical devices. It seems to be one of the promising technologies for addressing the problem of huge bandwidth requirements and “last mile bottleneck.” There are many commercial applications of WOC technology which includes ground-to-LEO, LEO-to-GEO/LEO-to-ground, GEOto-ground, LEO/GEO-to-aircraft, deep space probes, ground stations, unmanned aerial vehicles (UAVs), high-altitude platforms (HAPs), etc. [1–4]. It also finds applications in the area of remote sensing, radio astronomy, space radio communication, military, etc. When WOC technology is used over very short distances, it is termed as FSO interconnects (FSOI), and it finds applications in chip-tochip or board-to-board interconnections. FSOI has gained popularity these days

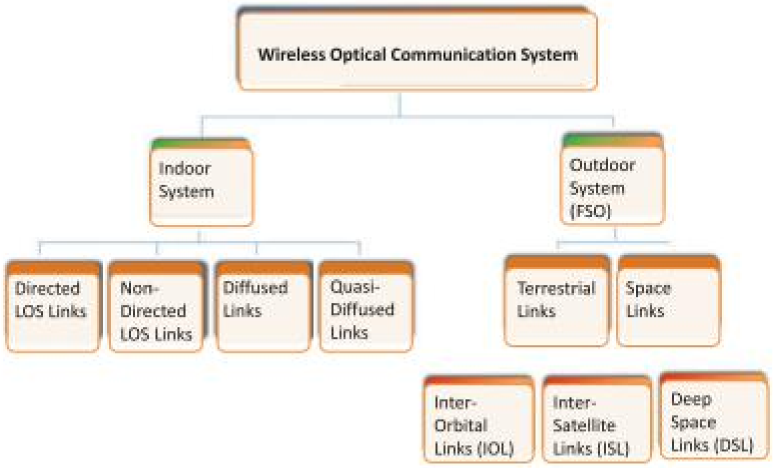

Fig. 1. Classification of wireless optical communication systems

TRENDS IN MOBILE COMMUNICATIONS

Since the beginning of the first analog communication system in the 1980s, a new generation of communication systems has been introduced almost every ten years. The transfer from one generation to another improves the QoS metrics, includes new services, and provides new features. The goal of B5G and 6G is to increase in the respective capability by a factor of 10–100 compared to the previous mobile generation upgrades. During the last ten years, mobile data traffic has grown tremendously because of the introduction of smart devices and machine-to-machine (M2M) mobile connectivity. It is expected that the global mobile traffic volume will increase 670 times in 2030 compared to mobile traffic in 2010 [2]. By the end of 2030, the International Telecommunication Union (ITU) predicts overall mobile data traffic will exceed 5 ZB per month. The number of mobile subscriptions will reach 17.1 billion as compared with 5.32 billion in 2010.

Moreover, the use of M2M connectivity will also increase exponentially. The traffic volume for each of the mobile devices will also increase. The traffic volume of a mobile device in 2010 was 5.3 GB per month. However, this volume will grow 50 times in 2030. The number of M2M subscriptions will increase 33 times in 2020 and 455 times in 2030, as compared with 2010. Table 2 presents a few comparisons of the use of mobile connectivity in 2010, 2020, and 2030.

Recently, research interests have shifted to data-driven adaptive and intelligent methods. The 5G wireless networks will build a foundation of intelligent networks that provide AI operations [3]. It is estimated that by 2030, the capacity of 5G will reach its limit [14]. Then, fully intelligent network adaptation and management for providing advanced services will only be realized using 6G networks. Hence, 6G wireless communications is the result of the user needs growing beyond what the 5G network can offer. Researchers worldwide are already studying what 6G communications would be like in 2030; they are also looking at the possible drivers for successful 6G wireless communications. A few of the critical motivating trends behind the evolution of 6G communication systems are as follows: high bit rate, high reliability, low latency, high energy efficiency, high spectral efficiency, new spectra, green communication, intelligent networks, network availability, communications convergence, localization, computing, control, and sensing. Therefore, 6G will be a world of fully digital connectivity.

SPECIFICATIONS AND REQUIREMENTS

5G technologies are associated with trade-offs of several issues, such as throughput, delay, energy efficiency, deployment costs, reliability, and hardware complexity. Likely, 5G will not be able to meet the market demands after 2030. Then, 6G will fill the gap between 5G and market demand. Based on the previous trends and predictions of future needs, the main objectives for the 6G systems are (i) extremely high data rates per device, (ii) a very large number of connected devices, (iii) global connectivity, (iv) very low latency, (v) lowering the energy consumption with battery- free Internet of Things (IoT) devices, (vi) ultra-high reliable connectivity, and (vii) connected intelligence with machine learning capability. Table 3 shows a comparison of 6G with the 4G and 5G communication systems. It is anticipated that 6G will require a new key performance indicator (KPI) drivers besides the KPIs of 5G communication systems. Many KPIs of the 5G system will be also valid for 6G. However, the 5G KPIs must be reviewed and new KPIs must be considered for 6G. There are several KPI classes that are currently difficult to define for 6G and expected to be finalized by future investigations. 5GB communication systems target in most of the technology domains once again to increase in the respective capability by a factor of 10–100 compared to the previous generation of communication systems. Some researchers from academia and industry target the KPIs for 6G communication as follows: peak data rate of 1 Tbps, radio latency of 0.1 ms, the battery lifetime of 20 years, device connectivity of $100/m^3$, traffic increase of 10,00 times, the energy efficiency of 10 times, maximum outage of 1 out of 1 million, and 10 cm indoor and 1 m outdoor precision in positioning [15]. The initial 6G KPIs can be broadly classified into two categories [15] namely, (i) technology and productivity-driven KPIs and (ii) sustainability and societal driven KPIs. The first category includes KPIs for several parameters such as jitter, link budget, extended range/coverage, 3D-mapping, mobile broadband, positioning accuracy, cost, and energy-saving. The second category includes KPIs for several facts such as standardization, privacy/security/trust, open-source everything, ethics, intelligence, and global use case. The KPIs related to capacity, spectrum efficiency, energy efficiency, data rate, latency, and connectivity are the basic requirements of all the traditional communication systems. However, the KPIs regarding security and intelligence are newly designed for 6G. All the potential KPIs toward 6G systems will be achieved along with the evolution of 5G systems.

A. *Service Requirements*

The 6G communication systems are expected to be featured by the following types of KPI associated services [16]:

- Ubiquitous mobile ultra-broadband (uMUB)
- Ultra-high-speed with low-latency communications (uHSLLC)

- Massive machine-type communication (mMTC)
- Ultra-high data density (uHDD)

TABLE 1: Comparison of 6G with 4G and 5G communication systems

Issue	4G	5G	6G
Per device peak data rate	1 Gbps	10 Gbps	1 Tbps
End-to-end (E2E) latency	100 ms	10 ms	1 ms
Maximum spectral efficiency	15 bps/Hz	30 bps/Hz	100 bps/Hz
Mobility support	Up to 350 km/hr	Up to 500 km/hr	Up to 1000 km/hr
Satellite integration	No	No	Fully
AI	No	Partial	Fully
Autonomous vehicle	No	Partial	Fully
XR	No	Partial	Fully
Haptic Communication	No	Partial	Fully
THz communication	No	Very limited	Widely
Service level	Video	VR, AR	Tactile
Architecture	MIMO	Massive MIMO	Intelligent surface
Maximum frequency	6 GHz	90 GHz	10 THz

The following key factors will characterize the 6Gcommunication system:

- AI integrated communication
- Tactile internet
- High energy efficiency
- Low backhaul and access network congestion
- Enhanced data security

It is estimated that the 6G system will have 1000 times higher simultaneous wireless connectivity than the 5G system. Compared to the enhanced mobile broadband (eMBB) in 5G, it is expected that 6G will include ubiquitous services, i.e., uMUB. Ultra-reliable low-latency communications, which is a key 5G feature, will be an essential driver again in 6G communication providing uHSLLC by adding features such as E2E delay of less than 1 ms more than 99.99999% reliability and 1 Tbps peak data rate. Massively connected devices (up to 10 million/km^2) will be provided in the 6G communication system It is expected that 6G aims to provide Gbps coverage everywhere with the coverage of new environments such as sky (10,000 km) and sea (20 nautical miles) Volume spectral efficiency, as opposed to the often-used area spectral efficiency, will be much better in 6G [14]. The 6G system will provide ultra-long battery life and advanced battery technology for energy harvesting. In 6G systems, mobile devices will not need to be separately charged.

B. New Network Characteristics

Satellite integrated network: Satellite communication is a must to provide ubiquitous connectivity. It is almost unconstrained geographical circumstances. It can support a seamless global coverage of various geographic locations such as land, sea, air, and sky to serve the user's ubiquitous connectivity. Hence, to provide always-on broadband global mobile collectivity, it is expected to integrate terrestrial and satellite systems to achieve the goal of 6G. Integrating terrestrial, satellite, and airborne networks into a single wireless system will be crucial for 6G. Only this integration can achieve the demand of uMUB services.

Connected intelligence: In contrast to the earlier generation of wireless communication systems, 6G will be transformative, and will update the wireless advancement from "connected things" to "connected intelligence" AI will be introduced in each step of the communication process as well as radio resource management. The pervasive introduction of AI will produce a new paradigm of communication systems. Compared to 5G, a complete AI system must be needed for ultra-dense complex network scenarios of 6G, allowing intelligent communication devices to acquire and perform the resource allocation process.

Seamless integration of wireless information and energy transfer: The 6G wireless networks will also transfer power to charge battery devices, such as smart phones and sensors. Hence, wireless information and energy transfer (WIET) will be integrated.

Ubiquitous super 3D connectivity: Accessing the network and core network functionalities on drones and very low earth orbit satellites will make the super-3D connectivity in 6Guniversal.

C. Few General Requirements in Network Characteristics Small cell networks: The small cell networks idea has been introduced to improve the received signal quality as a consequence of throughput, energy efficiency, and spectral efficiency enhancement in cellular systems As a result; small cell networks are an essential characteristic for the 5G and beyond (5GB) communication systems. Therefore,6G communication systems also adopt this network characteristic.

Ultra-dense heterogeneous networks: Ultra-dense heterogeneous networks will be another critical characteristic of 6G communication systems. Multi-tier networks consisting of heterogeneous networks will improve the overall QoS and reduce the cost.

High-capacity backhaul: The backhaul connectivity mustbe characterized by high-capacity backhaul networks to support a considerable volume of 6G data traffic. High-speed optical fiber and free-space optical (FSO) systems are possiblesolutions for this problem.

Radar technology integrated with mobile technologies: High-accuracy localization with communication is also one of the features of the 6G wireless communication system. Hence, radar systems will be integrated with 6G networks.

Softwarization and virtualization: Softwarization and virtualization are two critical features that are the basis of the design process in 5GB networks to ensure flexibility, reconfigurability, and programmability. In addition, they will allow billions of devices to be shared on a shared physical infrastructure.

PROSPECTS AND APPLICATIONS

Fully-AI will be integrated into the 6G communication systems. All the network instrumentation, management, physical-layer signal processing, resource management, service-based communications, and so on will be incorporatedby using AI It will foster the Industry 4.0 revolution, which is the digital transformation of industrial manufacturing Fig. 2 shows the communication architecture scenario toward envisioning the 6G communication systems. The 6G applications can be characterized under uMUB, uHLSLLC, mMTC, and uHDD services. Some key prospects andapplications of 6G wireless communication are briefly described below.

Super-smart society: The superior features of 6G will accelerate the building of smart societies leading to life quality improvements, environmental monitoring, and automation using AI-based M2M communication and energy harvesting This application can be characterized under all uMUB, uHLSLLC, mMTC, and uHDD services. The 6G wireless connectivity will make our society super-smart through the use of smart mobile devices, autonomous vehicles,and so on. Besides, many cities in the world will deploy flying taxis based on 6G wireless technology. Smart homes become a reality because any device in a remote location can be controlled by using a command given from a smart device.

Extended reality: Extended reality (hereinafter referred to as XR) services, including augmented reality (AR), mixed reality (MR), and VR are essential features of 6G communication systems. All these features use 3D objects and AI as their critical driving elements. Besides providing perceptual requirements of computing, cognition, storage, human senses, and physiology, 6G will provide a truly immersive AR/MR/VR experience by joint design integration and high-quality 6G wireless connectivity Advanced features of wearable devices such as XR devices, high- definition images and holograms, and the five senses of communications accelerate the opportunity for performing the human-to-human and things communications. Innovative entertainment and enterprise services such as gaming, watching, and sports are provided without time and place restrictions.

VR is a computer-simulated 3D experience in which computer technologies use reality headsets to generate realistic sensations and replicate a real environment or create an imaginary world. An actual VR environment engages all five senses. AR is a live view of a real physical world whose elements are augmented by various computer-generated sensor inputs, such as audio, video, visuals, and global positioning system (GPS) data. It uses the existing reality and adds to it by using a device of some sort. MR merges the real and the virtual worlds to create new atmospheres and visualizations to interact in real-time. It is also sometimes named as hybrid reality. One critical characteristic of MR is that artificial and real-world content can respond to one another in real-time. XR refers to all combined real and virtual environments and human- machine interactions generated by computer technology and wearables. It includes all its descriptive forms, such as AR, VR, and MR. It brings together AR, VR, and MR less than one term.

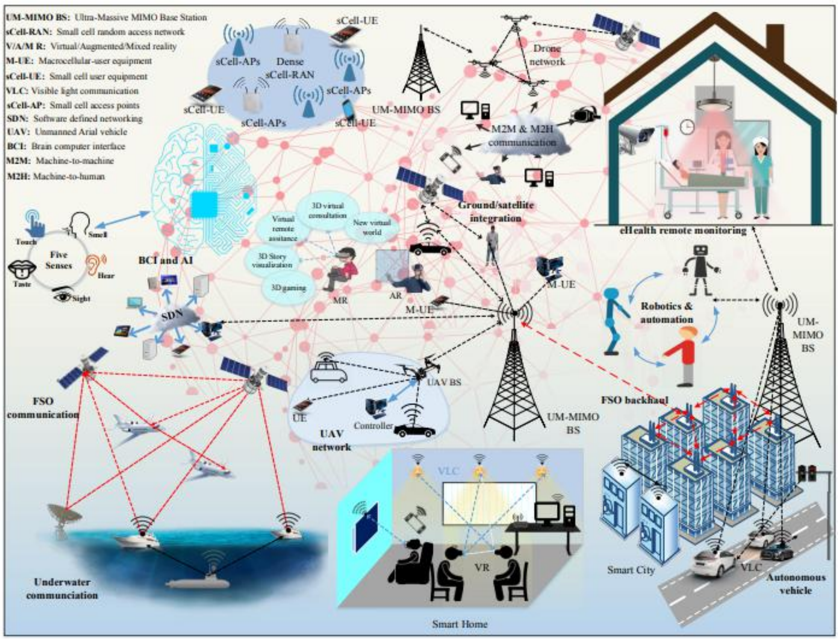

Fig. 2 Possible 6G communication architecture scenario

The high-data-rate, low latency, and highly reliable wireless connectivity provided in the 6G system are very important for a genuine XR (i.e., AR, VR, and MR) experience. The 6G service, uHLSLLC, will make it possible to deploy the XR applications in the future successfully. Connected robotics and autonomous systems: Currently, several automotive technology researchers are investigating automated and connected vehicles. The evolution of datacentric automation systems is currently surpassing the proficiencies of 5G. In some application domains, it is demanding even more than 10 Gbps transmission rates, such as XR devices. The 6G systems will help in the deployment of connected robots and autonomous systems. The dronedelivery UAV system is an example of such a system. The automated vehicle based on 6G wireless communication can dramatically change our daily lifestyles. The 6G system promotes the real deployment of self-driving cars (autonomous cars or driverless cars). A self-driving vehicle perceives its surroundings by combining a variety of sensors, such as light detection and ranging (LiDAR), radar, GPS, sonar, odometry, and inertial measurement units. The mMUB, and uHLSLLC services in the 6G system will confirm reliable vehicle-to-everything (V2X) and vehicle-to-server connectivity. A UAV is a type of unmanned aircraft. 6G networks will support the ground-based controller and the system communications between the UAV and the ground. UAVs help in many fields such as military, commerce, science, agriculture, recreation, law and order, product delivery, surveillance, aerial photography, disaster management, and drone racing. Moreover, the UAV will be used to support wireless broadcast and high rate transmissions when the cellular base station (BS) is absent or not working.

Wireless brain-computer interactions: The brain-computer interface (BCI) is an approach to control the appliances that are used daily in smart societies, especially home appliances and medical apparatus. It is a direct communication path between the brain and external devices. BCI acquires the brain signals that transmit to a digital device and analyzes and interprets the signals into further commands or actions. BCI services necessitate higher performance metrics compared to what 5G delivers Wireless BCI requires guaranteed high-data-rates, ultra-low-latency, and ultra-high-reliability. For example, both downlink (next-generation XR) and uplink (multi-brain-controlled cinema) brain-to-thing communication require very high throughput (>10 Gbps) and ultra-reliable connectivity. The features of uHLSLLC and uMTC in 6G wireless communication will support the actual implementation of BCI systems for a smart life. Haptic Communication: Haptic communication is a branch of nonverbal communication that uses the sense of touch. The proposed 6G wireless communication will support haptic communication; remote users will be able to enjoy haptic experiences through real-time interactive systems.

This type of communication is widely used in several fields such as AI and robotics sensors, physically challenged people to learn through touch, the medical haptic methods in surgery, and gaming. The implementation of haptic systems and applications can be facilitated by uHLSLLC, mMTC, and uHDD features of 6G communication networks. Smart healthcare and biomedical communication: Medical health systems will also be benefited by the 6G wireless networks because of innovations, such as AR/VR, holographic telepresence, mobile edge computing, and AI, will help to build smart healthcare systems. The 6G network will facilitate a reliable remote monitoring system for healthcare systems. Even remote surgery will be made possible by using 6G communication. High-data-rate, low latency, ultra-reliable (zero-error) 6G network will help transfer large volumes of medical data quickly and reliably, improving access to care, and the quality of care. On the other hand, THz, one of the critical driving technologies of 6G, has growing potential uses in healthcare services, such as terahertz pulse imaging in dermatology, oral healthcare, pharmaceutical industry, and medical imaging. Also, biomedical communication is an essential prospect of the 6G wireless communication system. The in-body sensors with the provisioning of battery-less communication technologies are predominantly desirable for reliable and long-term monitoring Body sensors can afford reliable and continuous monitoring of human physiological signals for applications in clinical diagnostics, athletics, and human-machine interfaces A near-field compatible battery-free body sensor interconnection system was introduced in R. Lin et al. with the ability to establish wireless power and data connections between may remote points around the body. The uMUB and uHLSLLC services of 6G can characterize these applications.

CONCLUSION

Each generation of communication system brings new and exciting features. The 5G communication system, which will be officially launched worldwide in 2020, has impressive features. However, 5G will not be able to support the growing demand for wireless communication in 2030 entirely. Therefore, 6G needs to be rolled out. Research on 6G is still in its infancy and the study phase. This paper envisions the prospects and ways to reach the goal of 6G communication. In this paper, we presented the possible applications and the technologies to be deployed for 6G communication. We also described the possible challenges and research directions to reach the goals for 6G. Besides clarifying the vision and goal of 6G communications, we have stated the various technologies that can be used for 6G communication.

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