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State-of-the-Art Strategies and Research Challenges In Wireless Communication for Building Smart Systems

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Abstract. The upcoming 6G communication network will revolutionize the scenario of customer services and related applications by building smart, autonomous systems. We first discuss here about 6G enabled smart applications like healthcare, smart city building, industrial IoTs, etc. We next provide a brief survey of the enabling technologies for achieving the required goals of 6G, such as terahertz communication, cell-free communication, holographic communication using beamforming, wireless power transfer, ultra-low latency communication, etc., with a view to tackle very large amounts of data traffic from several billions of smart interconnected devices while supporting ultra-low end-to-end communication latency. Finally, we present various research challenges involved in 6G communication towards building such smart systems.

Keywords: Smart Systems · Low-latency Communication · 6G Networks

1 Introduction

Compared to its earlier generations, 5G will provide an environment with significant improvements in communication services with regard to the volume of data traffic, communication latency, ubiquitous connectivity, user mobility, data rates and network security. Of particular focus in 5G is implementing the concept of the Internet of Things (IoT) with millions of smart devices being connected to the Internet. Due to its enormous potential in enhancing the quality of service (QoS) in various real-life applications, IoT has become an important component of the Internet [1]. IoT promises to provide significant benefits to society through completely automated smart management of heterogeneous devices without human interferences. 5G provides strong support for IoT-based environments with integrated low latency, high bandwidth and energy efficient features like communication with extremely high reliability and very low end-to-end latency, massive machine-to-machine communication, and enhanced mobile broadband (eMBB) connectivity [2], [3].

However, with the projected huge expansion of IoT networks and its ever-increasing demand, 5G will not be capable of providing the needed scalability in services in the coming years. Due to various upcoming novel IoT applications and services, further enhancements to the 5G technology are essential [4]. This trend of having an ever-growing demand for higher traffic volume at increased data rates with ultra-low end-to-end communication latency for various applications has already spawned the development of the next evolution in wireless communication technology, termed as *Beyond 5G* (B5G) and 6G. The sixth generation (6G) communication standards to be supported by the emerging technologies in the domain of wireless communication, are aimed at outperforming 5G and B5G in terms of overall throughput to meet the requirements of various sophisticated computation-intensive applications and services.

Of late, research on 6G wireless communication [7] and its related technologies has got huge attention from both academia and industry in order to provide high user experience and quality-of-service (QoS) with its exciting features like extremely high date rate, ultra-low latency, massive and autonomous networks, satellite based customer services [8]-[10]. QoS will be enhanced using advanced caching schemes, smart resource sharing, and increased use of artificial intelligence and deep learning techniques [19]. 6G will provide robot-to-server and robot-to-robot direct communication, complete automation such as automated devices, automated control process and complete automated system. In 6G, unmanned-aerial-vehicles (UAVs) can be used as access points or base stations, instead of conventional base stations for getting higher data rate and ubiquitous connectivity coverage [20]. 6G will provide high-end healthcare facilities using artificial intelligence, robotics, automation and extended reality [23] by leveraging its high data rate, ultra-low latency, high throughput and secure communication solutions. In addition, 6G will also support the hitherto unexplored technology for terahertz communication that would enable the use of novel nano-scale smart devices to operate with human body [24] - [27] for various healthcare-related services.

In this communication, we first present the vision of 6G with a comparison of different performance parameters between 5G and 6G networks. Then we discuss about various smart services and applications that may be supported by 6G. We next discuss about some emerging technologies for enabling 6G communication, such as terahertz communication, cell-free wireless communication, artificial intelligence (AI) based latency sensitive applications [5], [6], holographic communication using beamforming, wireless power transfer along with various possible approaches for achieving ultra-low latency communications in 6G. Finally we mention some future research challenges in the areas of device capabilities, terahertz communication, network security, design of transceivers and antennas, followed by conclusion.

2 Preliminaries on 6G Networks

The intelligent information society of the coming decade aims at a global, data-driven, intelligent, fully connected, highly digitized society [7]. 6G is purported to be an umbrella technology that will connect almost anything, anytime and anywhere with integration of functions for computing, control, positioning, communication, sensing, imaging, navigation, etc. 6G will be a fully automated, intelligent, self-contained, integrated system which will have various ways to interact and communicate with smart systems even through neuro-signals like brain-wave, iris signal, audio and touch signals, etc.

Current 5G communication suffers from some critical constraints with respect to device density, network latency, capability of mobile traffic. In contrast, 6G will bring some exciting network capabilities with the following features:

1. Providing extremely low values (10-100 μ sec) of end-to-end network latency for its effective use in haptic applications such as autonomous driving and e-healthcare.
2. Providing a very high density of device connectivity with about 107 devices/km^2 to support ultra-dense deployment of IoT network.
3. Achieving an extremely high value of data rate (1 Tbps) to enable the coexistence of mobile traffic, available spectrum, unlimited mobility for a massive-scale IoT connectivity,
4. Enhancing mobile traffic capability to meet IoT device density and high throughput.

The next avatar of IoT - the Internet of Everything (IoE) and mobile Internet will play the role of two key drivers of 6G standards. For example, the IoE is expected to utilize holographic communications for various haptic and tactile applications [20] in order to provide a complete sensory experience. This in turn would require a support from the underlying communication technologies for extremely high data-throughput, and ultra-low end-to-end latencies. Other examples of 6G enabled application scenarios include:

- Industrial IoT or IIoT with extremely low-latency communication. [20].
- Internet of Bodies supported by implantable nano-sensors and nano-devices with ultra-low energy consumption.
- Extreme high-definition (EHD) and super-high-definition (SHD) videos, which will need extremely high throughput.
- Emerging scenarios such as super high-speed-rail (HSR).
- Future communication scenarios like the Internet-in-the-sky for space, and underwater communications for application scenarios such as deep-sea exploration and tourism.
- Improved 5G vertical applications, like the fully autonomous vehicles and Massive Internet of Things (IoT) [36].

For a comparison between 5G and 6G networks, various performance parameters of the two networks are shown in Table 1.

Table 1: Feature-wise Performances of 5G and 6G Networks

Characteristics features	**5G**	**6G**
Communication band	3-300GHz	upto 1THz
Data rate (Uplink)	10Gbps	1 Tbps
Data rate (Downlink)	20Gbps	1Tbps
Maximum mobility	500Km/hr	1000Km/hr
Latency (U-plane)	0.5msec	0.1msec
Latency (C-plane)	10msec	1msec
Processing Time	100 ns	10 ns
Capacity of data traffic	10Mbps/m^2	1-10Gbps/m^2
AI integration	Partly	Completely
XR integration	Partly	Completely
Haptic communication integration	Partly	Completely
Automation integration	Partly	Completely
Satellite integration	No	Completely

2.1 Concept of Separate User-plane (U-plane) and Control-plane (C-plane)

3GPP (3rd Generation Partnership Project) 5G core infrastructure system architecture describes the User Plane Function (UPF) that involves the data plane evolution of a Control and User Plane Separation (CUPS) method for improving network traffic processing in 5G and future cellular networks. The existing Evolved Packet Cores (EPCs) by the 3GPP in their Release 14 specifications initially introduced CUPS as an extension. CUPS allows traffic aggregation and packet processing to be done in close proximity with the network edge, reducing network latencies and enhancing bandwidth efficiencies, by decoupling Packet Gateway (PGW) user and control plane functions.

Authors in [48] introduced a new strategy for handling the connections between small cell nodes and mobile terminals by splitting the Control and User (C/U) planes of the radio link which finally led to enhancement of the capacity of LTE cellular networks.

The C-plane controls a number of U-planes with the latency in the C-plane higher than that in a U-plane. The User-Plane-Function (UPF) is allowed to be located along with the edge server (in an edge computing environment) and is placed closer to the user side. Services are offloaded by the UPFs to the local server of edge computing for reducing latency by minimizing the redundant data transmission paths when it finds a local destination address of a service flow [41].

3 Potential Smart Services Enabled by 6G

The performance features of 6G, as mentioned in the previous section, will enable the creation of a number of new futuristic services. A few of those are summarized below.

- **Extreme high-definition (EHD) video**: With the exceptional increase in demand for video content processing in the Internet, 16K and 32K format of extremely-high-definition videos are going to be realistic due to the lower latency and higher bandwidth technologies of wireless communication networks [63].
- **Tactile Internet**: With highly reliable, secure and low-latency communication , the real-time service interaction in various sectors such as industry, education, medical, entertainment etc., are going to be supported [55].
- **Holographic tele-presence applications**: With 1Tbps bandwidth, immersive live models or real personal communication along with multiple digital formats from various locations will become realistic [55].
- **Haptics**: Haptic communications will be based on sensory signals which are critical for providing Virtual and Augmented Reality (VAR). It will be useful in various industries including healthcare, education, gaming, manufacturing, smart services and others. All these applications would require massive real-time data transfers with ultra-low latency [55].
- **Manufacturing and automation**: With precise indoor positioning and low-latency network connectivity, potential applications like massive integration of robots and automation, extended reality, warehouse transportation, and others will be feasible for implementation [62].
- **Smart healthcare**: For doing remote disease diagnosis and ubiquitous health monitoring, we need a very secure, all-time available, dependable high-definition video conferencing, thus establishing a smart healthcare system.
- **The Internet of Nano-Things and Bodies**: This technology can be used in many application scenarios such as smart city, health care, military, etc. which will be using implantable sensors, smart wearable devices and low-power devices [56], [57].
- **Massive IoT integrated smart cities**: Realization of futuristic smart cities will heavily depend on the development of a highly secure and reliable system capable of handling massive data in various sectors such as transportation, healthcare, parking, utilities, etc. [58], [59].
- **Fully autonomous vehicles**: With high reliability, high bandwidth, low latencies, a new generation vehicle-to-everything (V2X) communication can be realized through 6G for fully autonomous vehicles, which would lead to revolutionary changes in the transportation and automotive industry [60].
- **Extended reality**: 6G will be supporting another advanced technology known as Extended Reality which can be viewed as a suitable combination of Virtual

Reality, Augmented Reality and Mixed Reality. Virtual Reality is a simulation-based reality experience where an imaginary scenario is created using images and sounds generated by a headset. In Augmented Reality, the real-world is augmented with a particular device like mobile phone where an interactive environment can be designed with some data from Global Positioning System, video, audio, etc. Mixed Reality generates a complex environment by combining the virtual world with the real world. The background features of Extended Reality such as high resolution and data rate, strong connectivity and low latency will require the support of the 6G technology [18].
- **Edge computing**: The multi-access edge computing reduces the latency by avoiding the redundant transmission paths for services. In this concept, the UPF, being along side the edge computing server, is to be located closer to the application side. Thus it can transfer services to the local edge computing server when it finds a local destination address of a service flow [52].
- **Space and underwater communications**: The next-generation wireless communication technologies are expected to cross all boundaries to provide unlimited coverage even in outer space and deep sea [61].

4 Emerging Technologies and Requirements for Smart Communications and Networking

To be usable and acceptable over an extended period of time, new applications and features should preferably be allowed to be incorporated into every communication system. Introduction of automation and artificial intelligence based features was first done in 5G network but with partial integration. However, essential and high-end features like ultra reliability, higher security, lower latency, higher data transmission rates are needed to be introduced in 6G. We briefly elaborate on some of the technologies that will help achieving these features of 6G networks.

4.1 TeraHertz Wireless Communication

In wireless communication technology, since the radio frequency band is almost exhausted and unable to adapt to the increasing demand of ultra-high data transmission rates, higher bandwidth and security, etc., concept of terahertz communication is recommended for 6G with frequency band from 0.1THz to 10THz. This terahertz communication leads to extremely fast and secure communication within a coverage area corresponding to a distance upto ten meters [11] from the transmitter. This would support formation of small cells, such as nano, pico and femto cells, and would also facilitate the Internet of Nano-things [12], [13]. With this terahertz communication, 6G will be able to meet the goal of providing Tbps links, since this cannot be implemented with frequency bands lower than 0.1 terahertz.

4.2 Cell-Free Wireless Communication

To maintain ubiquitous connectivity, an on-going call should always be transferred to the new cell wherever the user would move in. However, in certain scenarios, the user's call may be terminated during this movement with an adverse effect on the system's QoS. To avoid such disconnection due to user mobility, specifically in remote areas with no appropriate infrastructure, unmanned aerial vehicles (UAVs) have been proposed for providing the communication links. This technology allows cell-free communication which can be conveniently implemented in 6G. The user equipment (UE) will be connected to the whole network instead of a particular cell. The use of UAVs along with the related technologies will facilitate the user equipment to get complete coverage without any manual intervention [14].

4.3 AI-based Latency Sensitive Applications

Applications and features based on artificial intelligence (AI) and machine learning (ML) are of utmost importance in the automation of 6G [16] specifically in network selection, handover, resource allocation, etc. for enhanced performance. AI and ML based features are, however, partially used in 5G and B5G network with some interesting applications discussed in [15], [33] .

4.4 Holographic Communication Using Beamforming (HBF)

Beamforming involves employing directed beams using an array of antennas to get high transmission and receiving power in a narrow angular direction for increasing the throughput with improved SINR (Signal-to-Interference-and-Noise-Ratio) values and better coverage with less transmission power. An advanced concept such as Beamforming with Software-Defined-Antennas (SDAs) is termed as *holographic beamforming* that will use a hologram to steer the beam by the antenna, known as holographic beam steering. Radio frequency (RF) signals are fed to the antenna at its rear end and RF energy is radiated from the front end of the antenna, while small elements adjust the direction and shape of the beam. Software-Defined-Antennas [17] are lighter, smaller, less expensive and consume less power than the conventional phased arrays, facilitating efficient and flexible signal communication appropriate for 6G.

4.5 Wireless Power Transfer

Authors in [21] have identified that in 6G, wireless energy transfer may be utilized to provide battery power to sensors and smart-phones which have limited energy resources. An emerging technology termed as Wireless Information and Energy Transfer (WIET) might be used in 6G to increase the battery life of smart devices along with the evolution of wireless network charging and battery-less smart devices. In [40], authors discussed about the partial charging of sensor nodes and distributed control in large-scale Wireless Rechargeable Sensor Networks (WRSNs) along with a game theory-based distributed mobile charging protocol, taking idleness of mobile chargers and full heterogeneity of energy profiles of sensor nodes into account.

4.6 Ultra-low Latency Communication

To achieve a drastic reduction in end-to-end communication latency, several techniques have been described in the literature. We present a brief discussion on these techniques in the following section.

5 Enabling Technologies for Low-latency Communication

Achieving low latency was one of the major goals in 5G and earlier generations, while B5G and 6G wireless communication networks aim at further reduction in latency through significant improvements in the network architecture along with the related inherent technologies. Some of the notable strategies for reducing communication latency in 6G are presented below.

5.1 Grant-free configuration

A User Equipment (UE) is configured by a gNodeB to get pre-assigned periodic resources. The resources on the physical uplink shared channel (PUSCH) are requested by the UE, well in advance from the base station (BS) and the UE is further configured by the respective parameters. Whenever the UE finds any uplink resources, it directly transmits using these resources without further communicating to the BS for feedback. This would help achieving the low latency requirement of the overall communication [42].

5.2 5G integrated with time-sensitive networking (TSN)

For ensuring clock synchronization, time sensitive transmission can be implemented where either the physical broadcast channel (PBCH) or the radio-resource-control (RRC) layer can transmit the high-precision reference time to get accurate synchronization between the terminal clock and the master clock. Since time-sensitive-networking (TSN) is an IEEE 802.1 Ethernet-based technology, Ethernet frames need to be augmented by headers which can be compressed to get reduced latency and improved data transmission [43].

5.3 Multiplexing of eMBB and URLLC

Low latency application scenarios are characterized by strong data burst with low volume of data. So, a preemption based strategy is implemented by new radio (NR) where the physical resources of enhanced mobile broad band (eMBB) are allocated by the base transceiver station (BTS) to the services requiring ultra reliable communication with extremely low values of communication latency, and low latency service is informed by the BTS to the UE of eMBB [44].

5.4 Mini-slot with smaller scheduling period

Fourteen symbols are there in an LTE slot whereas in 5G NR two, four or seven symbols may be there as a mini-slot. Hence, with a smaller time-slot, feedback delay can be reduced and thus, latency can be lowered [45].

5.5 Frame structure with flexibility

Latency can be lowered with wider subcarrier spacing. Subcarrier spacing of 30kHz, 60kHz, 120kHz and 240kHz are supported by 5G NR where adjustments of frame is supported. In comparison to LTE, 5G NR supports 1, 2, or 4 slots in a subframe. Hence, downlink-uplink ratio configurations will be made flexible which may lead to reduced latency [47].

5.6 Increased feedback in HARQ

A UE transmits hybrid-automatic-repeat-request (HARQ) acknowledgement using only one physical uplink control channel (PUCCH) in R15 (3GPP Release 15 the first full set of 5G standards), but repeat transmission in the same slot is not permissible. But in R16, for transmission of HARQ-acknowledgement, multiple PUCCH in one slot is allowed, which needs at least two HARQ-ACK codebooks in a UE. Thus latency can be lowered [46].

5.7 Hybrid Optical-Wireless Architecture

Some significant research attempts have recently been made focusing on a hybrid optical-wireless network architecture to minimize the end-to-end communication latency. Such an approach given in [39] is based on a grid structured high speed optical backbone network with the provision of wireless connectivity to end-users or UEs through different junction points of the grid, forming a wide area network (WAN) with sub-millisecond average communication latency.

An overview of 6G enabling technologies and different smart services provided by 6G are shown in Figs. 1 and 2, respectively.

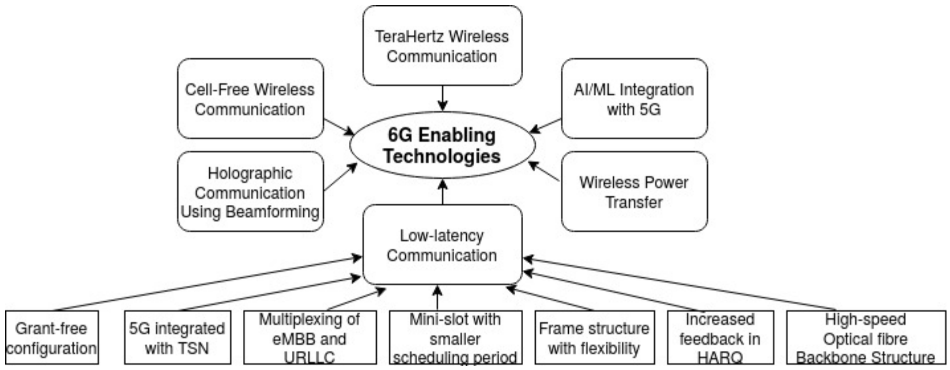

Fig. 1: 6G Enabling Technologies

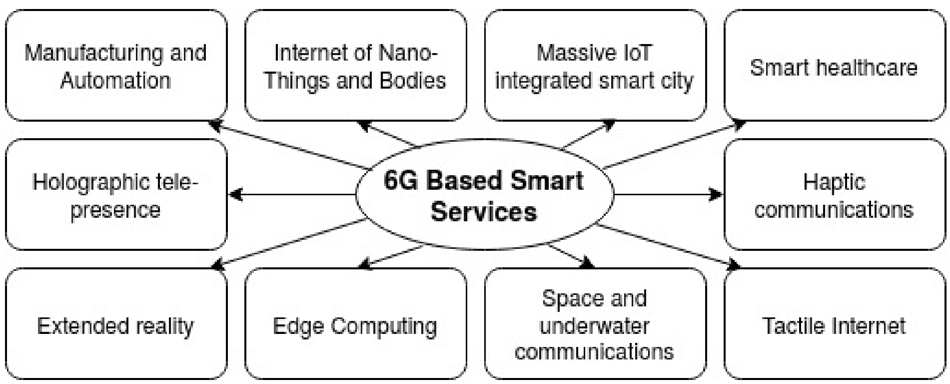

Fig. 2: 6G Based Smart Services

6 Research Challenges

The following is a survey of some of the challenging topics in B5G/6G wireless communication that may be addressed to cope up with the global communication need of the near future:

6.1 Device Capabilities

Smart devices which support 5G technology are still not fully operational due to the use of high-end features. Since 6G wireless communication will include all features of 5G with enhancements in terms of power, bandwidth, etc. and integration of technologies like extended reality, machine learning, artificial intelligence, teraherz communication, device-to-device communication [28], etc., it is really a challenge to come up with smart devices to support the 6G technology. Due to multiple high-end functionalities, smart devices need high energy and hence, frequent recharging. Thus, in 6G communication, there is an extreme need for efficient wireless energy transfer strategies [17] since a huge number of smart devices are to be connected to each other. But the actual challenge lies in the effective implementation of these expensive recharging methods.

6.2 TeraHertz Band

As discussed in the earlier section, terahertz communication is one of the important challenges to be implemented in 6G wireless communication. Due to its high frequency band and data rate, it leads to high atmospheric absorption and loss in data propagation particularly for large distance communications. Hence, development of some novel multichannel technique is called for to tackle the issue of frequency dispersion caused by wide bandwidth [11]. The current coding and modulation strategies are not enough to deal with the terahertz band. Due to this, research needs to be carried out on designing new transceivers for functioning with large transmission power and sensitivity, low noise and ultra-high bandwidth. Also it has created a real research challenge to deal with the significant health hazards resulting from wireless communication at high frequency and high power.

6.3 Network Security

6G will require high-end security features due to the integration of advanced technologies like extended reality, artificial intelligence, machine learning, automation, etc., while connecting all sorts of smart devices. As the security features available in 5G are to be further enhanced for the use in 6G, emerging security strategies like integrated network security methods and physical layer security methods can be adapted for better security performance [29].

6.4 Design of Transceivers and Antennas

Every wireless communication technology specification is supported by some specific design of antenna and transceiver. Implementation of millimeter wave technology in 5G is a challenging task and will be even more difficult in 6G. Since 6G wireless communication will provide extremely high frequency band such as terahertz communication and supports resource and spectrum sharing, the designed antenna and transceiver need to support the system specifications for micrometer to nanometer components [30] - [33]. Transceivers based on meta-surface [34] might be able to provide better QoS and performance, but its use along with multiple-input-multiple-output orthogonal frequency-division multiplexing leads to a significant research challenge.

6.5 Other Open Research Issues

As can be anticipated, most of the advanced research issues in 6G revolve around the emerging technologies used in 5G and the related enhancements. We list below a few of those improvisations on some earlier works.

- Further Enhanced Mobile Broad Band (FeMBB): Further enhanced mobile broadband can be considered as successor of eMBB. It has higher requirements for huge data processing and transmission. It has some distinguishing features like (1) global compatible connections among various mobile service providers and (2) precise indoor positioning [49], [50].
- Extremely Reliable and Low-Latency Communications (ERLLC): It is an improvised version of ultra-reliable and low-latency communication (URLLC) with respect to latency and reliability. With ERLLC, military and industrial communications like high precision machine tools, robots, can be implemented along with autonomous vehicular communication [49], [50].
- Ultra-massive Machine-Type Communications (umMTC): It will be ten times higher version of massive machine-type-communication (mMTC) where huge connectivity density will give rise to new concepts known as the Internet of Bodies, the Internet of Nano-Things and also expanded version of e-health and smart city [49], [50], [51].
- Long-Distance Communications (LDC): With the objective of providing quality service to remote area subscribers in addition to the dense area subscribers, the network coverage may be enhanced using long-distance communication, particularly for futuristic application scenarios like free-space inter-satellite communication and hyper-high-speed railway [52], [53].
- Extremely Low-Power Communications (ELPC): Development of novel air-interfaces for ultra-low power communication with energy harvesting methods mayl allow new IoT use-cases like Internet of Bio-Nano-Things, nano robots, nano devices, nano sensors, etc. to work without batteries [54].

7 Conclusion

While 5G technology is expected to revolutionize wireless communication and applications based on it, yet it appears to be inadequate to satisfy the ever-increasing demands of the near future for various real-life smart application scenarios. This has triggered the conceptualization of 6G network standards. We have discussed about the potential features and technologies to be present in 6G wireless communication highlighting the strategies for realizing its desired performance goals for enabling truly smart systems and solutions. We have also identified some interesting research challenges and related issues in the implementation of 6G for designing tomorrow's hyper-connected, smart world.

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