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Beyond 5G: Reinventing Network Architecture With 6G

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***Abstract*— The roll-out of 5G has begun in many parts of the world and ought to get completed by the end of 2021. However, given the ever-increasing bandwidth demand and need for automation, the existing capacity of even the most technologically advanced network architecture is expected to run out by 2030. The aim of this paper is to have a peep into the future of wireless communication and its associated technologies. With a higher transmittal rate, improved spectrum efficiency, greater connection proportions, a greater spectrum coherence, and much shorter latency, 6G is expected to revolutionize the digital world. This paper presents the findings of a detailed study regarding the construction of 6G. The main focus of this detailed survey is on the 6G along the lines of mobile communication and the key technologies likely to be fielded on 6G enable networks. Towards the end, this paper also presents ongoing research initiatives being carried out by various research organizations.**

***Index terms*— 6G, terahertz communication, 5G new radio, metamaterial, radio stripes, cell-free massive MIMO**

I. INTRODUCTION

The 6G era will be an integration of satellite and ground communication networks. The 6G band is an expansion from 5G milimetre wave to the terahertz frequency band. Wireless communication systems are the Eureka coequals of our time, courtesy of the rapid technological advancements in the last few decades.. In addition, today's exponential growth of advanced technologies, such as artificial intelligence (AI), robotics, virtual reality (VR), three-dimensional (3D) media, and the internet of everything (IoE) may change the future of wireless communication but this growth has also resulted in a significant increase in the volume of traffic. [1]. A survey carried out in 2010 showed that the global mobile traffic volume was 7.462 EB/month, and it is predicted to be 5016 EB/month in 2030 [2]. As part of the development of current wireless-based technologies, new infrastructure components such as long-term evolution (LTE) and high-speed packet access (HSPA) have been launched. Ranging from automation, security to IoT, the prototypes and models of these new technology components may provide means of accessing greater spectrum and substantially higher frequency ranges [3]. Just like the case with any other technology, the plenteous advancements of mobile communication networks, in terms of its potentiality, have led to the growth of various applications and these applications will eventually be incorporated for better mobile connectivity and to tackle the resultant exponential growth in network traffic. 6G would provide the canvas over which the complex processes and interfaces would seamlessly operate with minimum human interaction. Our future will be powered by innovations that arise as cutting-edge technologies such as, HSPA, 3rd Generation Partnership Project (3GPP) LTE technology, and Wi-Fi converge in multiple domains [4].

The rest of the paper goes as follows: In Section II, a brief history of wireless communication is presented. In Section III, the trends that 6G network will envisage are discussed. In Section IV, the proposed 6G cellular network architecture, as well as its requirements, from architectural to trustworthiness is explained. Section V presents the key technologies associated with 6G network. The paper concludes in Section VII, after the inclusion of a brief timeline and progress made on 6G around the globe in Section VI.

II. EVOLUTION OF WIRELESS COMMUNICATION

Since the development on the idea of networks started, the cellular architecture has come a long way. With the launch of first-generation mobile network in 1980s, networking has gone through many advancements with the launch of 2G (cellular calling), 3G (video calling, mobile TV),4G ,5G (self-driving cars, controlled apps on one device, and now 6G. In 1985, Marconi, an Italian inventor, paved the way for modern wireless communications by transmitting a three dot Morse code wirelessly over a range of 3.2 Km [4]. This was a significant step in the technological advancements in networking as it was the first wireless transmission. Later, an American engineer, Martin Cooper, who worked at Motorola, invented the first-generation mobile phone way back in 1970s. Fig. 1 illustrates the evolving generations of wireless technologies in terms of data rate, mobility, coverage, and spectral efficiency. The figure also explains

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switching used in first generation and second-generation technologies. 2.5 G and 3G use packet and circuit switching both. The remaining technologies after that 3.5 G to 5G started using packet switching. It also distinguishes between licensed and unlicensed spectrum based on these factors [5].

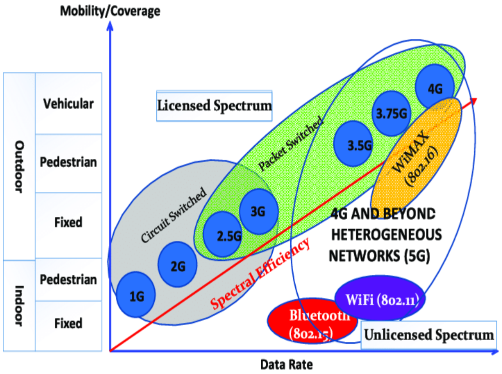

Fig. 1. Evolution of wireless communication.

The first-ever mobile phones were actually 0G and even calling them mobile is a bit of a stretch. 1G was the first time that the general public could make phone calls. From this point onwards, every ten years, wireless communication saw one generational leap after another. 2G took the 2.4 kbps speed of 1G and made it 40kbps (15 times faster), which made phones not just capable of calling, but also sending texts and even picture messages. 3G was 50 times faster than 2G, which made it powerful enough to support internet-based applications. And when 4G came out, it was not surprising that it was between 50-5000 times faster than that. That brings us to today to the age of 5G. 4G will now be easily replaced with 5G that works on technologies like, Beam Division Multiple Access (BDMA) and Non- and quasi-orthogonal or Filter Bank multi-carrier (FBMC) multiple access [6].

III. GLOBULAR TRENDS TOWARDS 6G

Wireless communications are being used for more than just connecting people; they're also being used to link different objects. Nearly every human being on the planet is connected given the fact that everyone has a means to access the Internet[9]. As a result of these conditions, four big megatrends are moving toward 6G: wired computers, AI for wireless networking, mobile communications transparency, and enhanced commitment to social objectives.

A. Connected Machines

In the future, machines will increasingly need to be linked through wireless communications. Examples of connected machines include vehicles, robots, drones, home appliances, screens, smart sensors mounted in various infrastructures, construction machinery, and factory equipment. It is worth highlighting that by 2030 the number of all connected devices on earth will cross a staggering count of 500 billion [7]. In Table I, perception proficiency of human and machine is compared. This comparison goes to show as to what performance targets are needed to truly realize the vision of connected machines.

TABLE I
COMPARISON OF THE PERCEPTION COMPETENCE OF HUMANS AND MACHINES

	Human	Machine
Maximum Resolution	1/150° (Smartphone display 290 ppi at 30 cm)	
Latency Perception	‹100 ms	
Audible Frequency	250-20,000 Hz	Exceeds Human Limitations!
Visible Wavelength	280-780 nm	
Viewing Angle	Azimuth 200°, Zenith 130°	

B. AI & ML – New Implementations for Wireless Communications

The potential benefits of artificial intelligence (AI) applied to wireless communications are promising. The use of AI in wireless communications can boost efficiency while lowering capital expenditure (CAPEX) and operating costs (OPEX). But there is a limit to what is currently possible, as AI implementation in communication networks was not considered when existing communication systems such as 5G were created. Considering AI from the beginning of the process of developing 6G concepts and technologies would provide us with more opportunities to use AI to enhance overall network capacity, cost, and ability to provide various services.

Machine Learning will always be there for non-communication functions. Be it autonomous vehicles, drones, or any sort of applications that will use ML for issues that are not related to communication and as such 6G must at least be able to support those. One could condense the role of ML in 6G to three categories:

- Data analytics for proactiveness,
- AI based optimization and control, and
- Edge learning and small distributed data.

C. Social Goals and Mobile Communications

5G is expected to play a critical role in addressing a variety of social problems, including climate change, poverty, and educational inequality, as mobile communications become a more important aspect of social infrastructure [8]. For example, it is worth noting that by 2030, the mix of innovations, such as 5G and global digitization, is. The United Nations introduced the Sustainable Development Goals (SDGs) in the Agenda 2030 to address fundamental social issues [23]. By the time, 6G is deployed widely, nonconformity in economic, regional, and social infrastructure opportunities will be significantly reduced.

IV. REQUIREMENTS

After 2030, 5G is unlikely to be able to satisfy consumer demands. Following that, 6G is projected to bridge the gap between 5G and consumer demand. As the wireless communication systems advance and by the time 6G becomes widely used, it is inevitable that services that run on such technologies will demand very low latency, non-existent data processing time, and extremely fast data rates.

TABLE II
6G VERSUS 5G

Major factors	6G	5G
Peak data rate	> 100Gb/s	10[20] Gb/s
User experience data rate	> 10Gb/s	1Gb/s
Traffic density	> 100Tb/s/km^2	10Tb/s/km^2
Connection density	> 10million/km^2	1million/km^2
Delay	< 1ms	ms level
Mobility	> 1000km/h	350km/h
Spectrum efficiency	> 3x relative to 5G	3~5x relative to 4G
Energy efficiency	> 10x relative to 5G	1000x relative to 4G
Coverage percent	> 99%	About 70%
Reliability	> 99.999%	About 99.9%
Positioning precision	Centimeter level	Meter level
Receiver sensitivity	< −130dBm	About −120dBm

Table II [10] presents a side-by-side comparison of the proposed 6G architecture with the 5G communication systems. To realize the new 6G services, it might not be sufficient to rely solely on the improvement of the communication connection efficiency. This is because, as shown in Figure 2 [11], it is evident the rate of inclination in mobile computing capacity struggles to match up with the rate of growth in power requirements as far as computation is concerned.

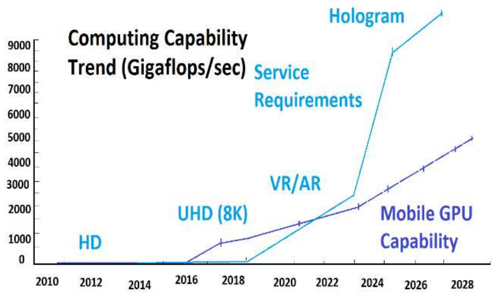

Fig. 2. Computing power: requirement against capability.

A. Architectural Requirements

Although no formal 6G architecture has been created, the communication network should be designed in such a way that it can address the issues that emerge from mobile devices' limited computing capabilities. When we eventually hit that upper limit, the communication network should be well built holistically to make the most of the computing capacity that can be made accessible by different network entities. For 4G communications, computation processes for IT services were done in the cloud [11]. In the present architecture, the signals are administered by a Base Station (BS) in the vertical direction. The base station contains three directive antennas with high directivity. To reach every user on planet, multiple base stations are set up so as to create a network with "cells". Still, this does not guarantee ultimate coverage and the cost of construction is fairly high. So, to overcome this drawback, massive multiple-input, multiple-output (MIMO) technology was developed for a better experience in 5G. In massive MIMO, the antenna is split up into multiple antennas of same size and oriented horizontally. This gives narrower beams, horizontally and vertically, than the 120 degrees that the classical antenna is supposed to cover. But this technology does not solve all problems. 6G should be designed to achieve true integration of communications and computing, allowing end users' different devices to easily access the network's computing resources. Furthermore, AI would play a crucial role and need to be integrated with all system elements in 6G network, on top of networking and computing convergence. This design methodology is called "native AI" [11].

B. Performance Requirements

6G would need to have a much higher data rate than 5G to realize innovative interactive services like fully immersive XR, mobile hologram, and digital replica. Moreover, 6G aims for tremendous amounts of real-time data processing, extremely fast data transfer, and very low latency. To meet these advanced services, 6G should have a user-experienced data rate of 1 Gbps and a peak data rate of 1,000 Gbps. Latency-related performance must dramatically improve. Air latency of fewer than 100 seconds, end-to-end (E2E) latency of less than 1 ms and exceptionally low delay fidgeting in the microsecond range are all performance objectives [12]. Network coverage has always been crucial in previous generations and will continue to be critical in 6G. It will go beyond 5G in terms of coverage.

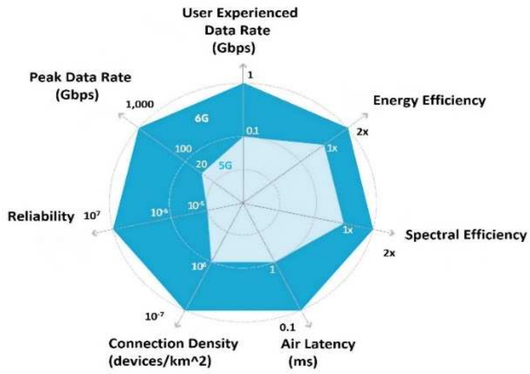

Fig. 3. Comparison of various performance requirements between 5G and 6G.

Depending on the evolution of transportation networks, it will need to change even further in 6G. Because of the rapid increase in the number of connected computers, 6G would be expected to support approximately 107 devices per square kilometer. This is ten times more than what 5G needs in terms of link density. Figure 3 depicts the transition from 5G to 6G in terms of main specifications.

While this might look quite impressive on the face of it, on a closer look one realizes it is not a linear scale. Meaning that while it looks like the peak data rate will triple or even quadruple, on this scale it is 50 times faster than the fastest 5G connection, offering $1/10th$ of the latency[25].

C. Fiducial Requirements

The extensive use of personal user details and open-source software would make communication networks more open, increasing the attack surface. This may well make the entire ecosystem more prone to security and privacy risks. The more advanced the network architecture, the more complicated is the modulation system. Thus, a lot of the measurements are made over-the-air. There are measurements on how well packets are received and packet-flow from one place to the other. Thus, the 6G threat surface issues could be much broader than 5G.

The key is to add an additional level of security of physical layer for 6G networks. It could help in facing threats in heterogeneous networks with different levels of node complexity. This would also assist in maintaining the confidentiality and integrity of the system without sabotaging the rich user-experience. For instance, open-source software codes cannot be properly validated against potential security threats. Second, the user data is fairly easily accessible to the respective service providers.

V. Candidate Technologies

The 6G framework will be powered by a variety of technologies. Technologies that could be the main enablers for achieving 6G have been implemented in this section. Although these innovations are exciting and important, additional technologies will be considered in the future. The core 6G services identified/expected for improved performance combined with 5G will include:

A. Terahertz Technologies

Electromagnetic waves already have many popular uses courtesy to the ability of being able to produce and control them, but while our current technology can create optical waves or radio waves easily, we lack the means to produce a very useful type of electromagnetic waves located right between the radio and optical regimes. These are called terahertz (THz) waves. In an important project funded by the European Research Council, at the laboratory for Nanoscale Electro-Optics, experts in the interaction between light and nanomaterials have successfully engineered a family of sophisticated nano-structured meta materials.

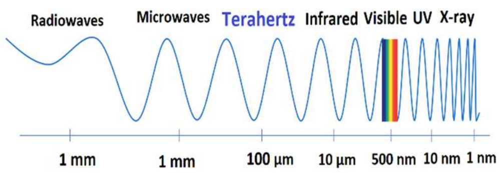

Fig. 4. Terahertz waves on EM spectrum.

These waves provide interesting opportunities as their unique interaction with matter is not found in other regions of the EM spectrum and so to open up a host of new applications of industrial, societal and academic benefit [13].

A large number of materials exhibit characteristic absorption signatures at THz frequencies allowing terahertz radiation to examine and identify these materials. These radiations can also probe the motion between molecules in crystal, making terahertz spectroscopy sensitive to crystalline structure. Thus, it is quite likely that mobile communications will implement THz bands (0.1-10 THz [24]) in future wireless network. Additionally, ability of THz waves to penetrate through many non-metallic materials can be used to reach as many users as possible while not compromising the low latency and delay rate of 6G. Furthermore, implementation of operating 5G new radio (NR) systems operating in bands above 52.6 GHz have started [15]. Given the advancement of related technologies, it is safe to assume that 6G will have to be developed to use up to no less than 3,000 GHz.

B. Novel Antenna Technologies

The architecture of massive MIMO wireless infrastructure is based on base stations being mounted on tall structures, which means signals emitting from the antennas may not reach all users with equal strength, resulting in significant signal intensity variations. This centralized MIMO architecture can be oriented in such a way so as to spread out the antennas at different locations connected by wires and controlled by some sort of central processing unit. This is known as distributed MIMO or cell-free massive MIMO. This sort of technology can be implemented but not in an optimal manner.

This brings us to this segment where we briefly examine the potential alternatives.

1) Radio Stripes: The idea behind radio stripes µ is that if an antenna is to be put out to a particular location and draw a cable to that location, it would be much better, instead of having a passive cable going there, to put all of the antennas within the cable and turn that cable into the part of network architecture [14]. A radio stripes consists of a long stripe, containing a cable, antennas and each antenna. Illustrated in Fig. 5 is the 3.5 GHz band, which is a typical band for 5G. These antennas are connected to an antenna processing unit that contains all the hardware components needed in a typical antenna branch.

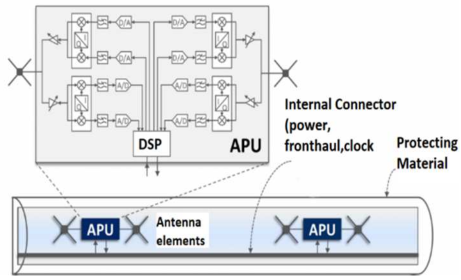

Fig. 5. A radio stripe where the antenna elements form the part of a cable

2) Metamaterial Based Antennas and RF Front-End: The simple execution of controlling light waves influencing material properties is the basic idea of metamaterials. Typically developed by arranging multiple tuneable elements in consecutive patterns, in sizes much more minute than wavelengths, metamaterial's physical properties of precise form, geometry, scale, orientation, and arrangement make it possible for smart properties capable of manipulating electromagnetic waves [16]. An important feature for metamaterials is the wavelength, which is the distance between one peak and the next peak. To begin designing metamaterials, wavelengths that are to be controlled are looked into and an array or grid is constructed. With metamaterials, we can put different material properties in each one the squares of the array, which enables us to create a flat lens where the wave travels slowly through the middle of the structure and more quickly through the edges. Metamaterials can be incorporated with network technology in three ways:

a) Metasurface enabled wide-angle Fourier lens: Fourier optics have been important to modern optics as the uses encompass holography, spatial filtering, and compressed sensing. As shown in Figure 6, Fourier metalenses or metasurface lenses in general change the direction of the beam on application of DC bias to its constituent components [17].

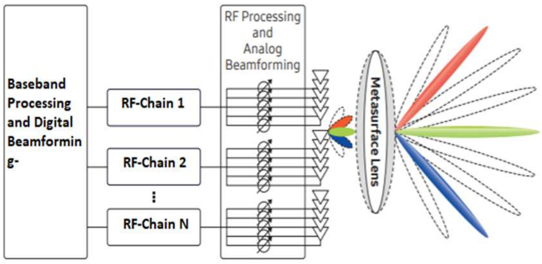

Fig. 6. Metasurface lens.

b) Metamaterial antenna: Integrating metamaterial technology with network antennas can reap fruitful benefits, like radiating directive beams as shown in Figure 7 [18]. Unlike the metasurface lens, there is no need for an individual antenna array.

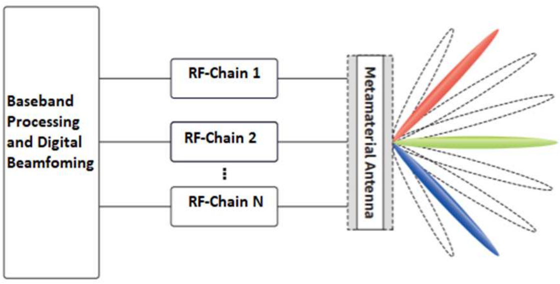

Fig. 7. Metasurface antenna.

c) Reconfigurable intelligent surface (RIS): RIS aided cellular communication is a promising technique for efficient implementation of 6G network. Given that these can be easily deployed and transfer waves wherever desired, these can be applied to provide a path of propagation where there is may not be any LoS link [19].

3) OAM Multiplexing Technology: It is comparatively easier to expand the bandwidth in the milimetre wave frequency range, as it is unexplored and not congested yet. It is also effective to increase the multiplexing order to increase the capacity proportionally. To achieve this orbit angular momentum (OAM) technology can be used. This technology enables spatial multiplexing by sing the orbital angular momentum of radio waves. By changing the degree of rotation, different radio waves can be generated. Even when transmitted simultaneously, these radio waves can be received successfully without interfering each other. In the case of electromagnetic waves, experiments have shown that the production of different OAM modes is possible with the help of simultaneous manipulation of a transmit antenna array [20].

With the increased wireless communication capacity, the technology can be used for temporary network connection at places where it is difficult to install fibre optic cables and the mobile fronthaul and the mobile backhaul of future radio communication networks [21]. Terabit-class wireless transmission can be achieved by increasing the multiplexing order by 10 times and the bandwidth by 10 times.

4) Comprehensive AI: As a method to address previously considered unwieldy issues because of its immense complexity or lack of the appropriate models and algorithms, AI receives much attention. We address a detailed AI system for optimizing system efficiency and network activity in this section. Overall, four levels of organizations are composed: UE, BS, basis network, application server, and network architecture. The unity of AI can be divided into three stages: 1) local AI, 2) joint AI, and 3) E2E AI [11].

VI. 6G TIMELINE

Geopolitical rifts have seen some countries strip Chinese-made equipment from their 5G networks and the concerned organization and interested parties have already begun to fight for the 6G supremacy. South Korea, the USA, Japan, and the EU are some of the nations that have started making progress in the field.

The very first 6G chips have already been built with a speed of 11 Gb/s. Although it is not as fast as the actual 6G is going to be, it has already passed the theoretical limits of 5G. One example of this is the research at the Nanyang Technological University of Singapore and Osaka University of Japan where scientists announced they have created such a chip. In October 2020, the Alliance for Telecommunications Industry Solutions (ATIS) launched a "Next G Alliance", with the motives of pushing limits of current network architecture. China successfully launched the first 6G test satellite into orbit, on November 6, 2020, which is a technical demonstration of terahertz communications scenarios in space. The satellite is expected to offer communication speeds 100 times faster than 5G.

Figure 8 [11] shows that the time taken to define the vision and establish technical standards has decreased for 3G from 15 years to 8 years for 5G. This trend continues for each successive generation. This can be due in recent decades to the rapid development in mobile communications technology and consumer requirements.

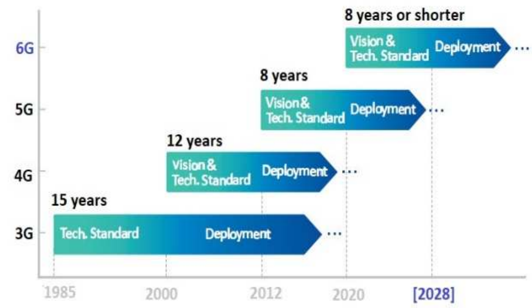

Fig. 8. Timeline of different network architectures.

VII. CONCLUSION

While it is still very relevant to work for the commercial success of 5G in the next few years, now is the time to start preparations for 6G, as it is bound to take many years. 5G has laid the groundwork and 6G has to carry it over the line and be good enough to carry humanity from 2030 to 2040. It is the technology that is made to serve the needs of the future generation, not the society of today. So, to facilitate the next generation of tech, the next generation of the network is required. Thus, in this spirit, this paper presents the initial view of various aspects of 6G from development to standardization and commercialization.

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