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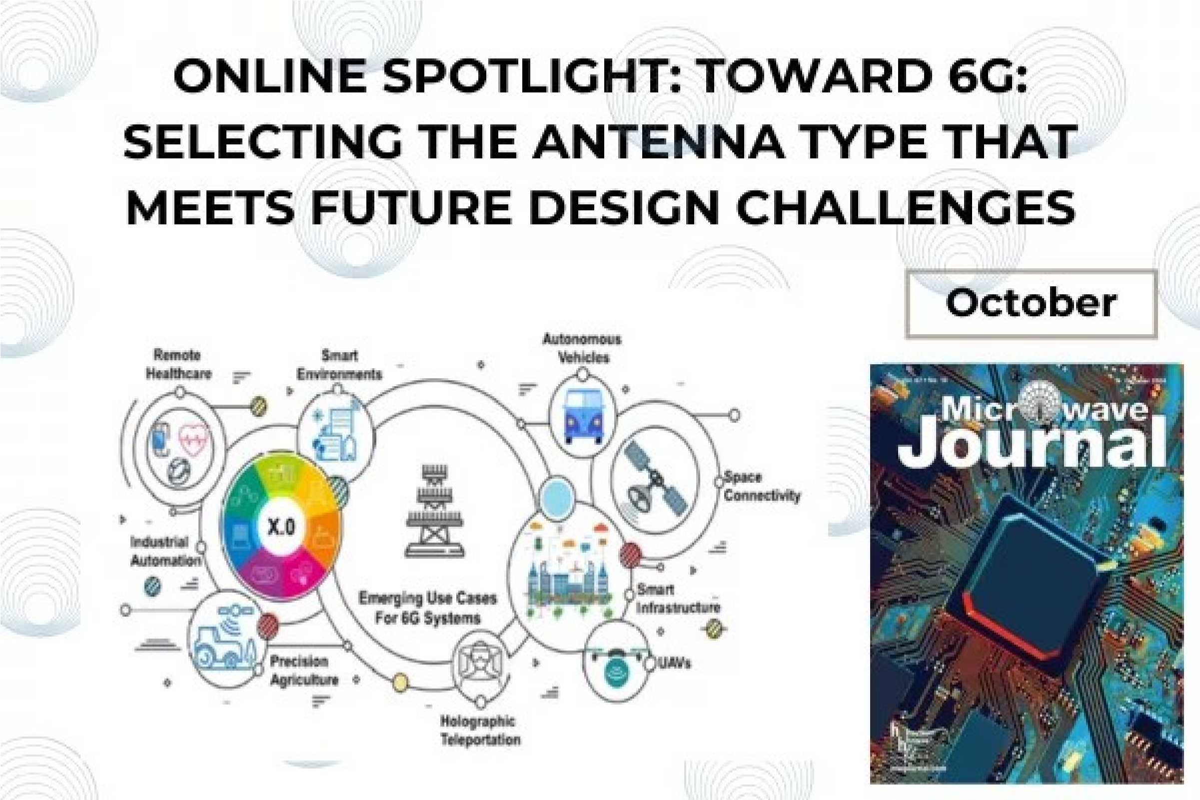


Online Spotlight: Toward 6G: Selecting the Antenna Type that Meets Future Design Challenges

Sunday Achimugu, Abraham Usman Usman, Suleiman Zubairu, Federal University of Technology, Minna Minna, Nigeria and David Michael, Abdulkadir Olayinka Abudlbaki, Federal University of Technology, Minna Minna, Nigeria
October 16, 2024

The antenna is a pivotal component in the design of any wireless system, playing a crucial role in facilitating wireless communication. The antennas for sixth generation (6G) and future communication systems are expected to be highly directional, have ultra-wide bandwidth and be efficiently reconfigurable. To meet these evolving requirements, diverse antenna designs have been conceptualized and proposed. The sub-THz (100 to 300 GHz) and THz (0.1 to 10 THz) spectra have been identified for 6G and future communication systems. Such high frequencies are characterized by high path loss and high atmospheric absorption. This article *delineates the prerequisites of antennas for beyond 5G applications, addresses associated design challenges, surveys various antenna types suitable for 6G and future communication systems and provides a comprehensive guide for selecting antennas tailored to specific use cases such as ubiquitous Mobile Broadband (uMBB) and ultra-Reliable and Low-Latency Communications uRLLC, spectra (including mmWave and Terahertz) and enabling technologies. Three prominent types of antennas receive particular attention: patch antennas, extremely massive Multiple-Input-Multiple-Output (emMIMO) antennas and reconfigurable metamaterial antennas.*

By 2030, the wireless connectivity landscape will comprise over 90 billion interconnected devices.[1] This surge in connectivity is driven by emerging use cases, such as holographic presence, tactile internet and the demand for ubiquitous connectivity, including extremely high-definition video applications. These transformative paradigms necessitate unprecedented attributes such as vast bandwidth, elevated data traffic handling capabilities, remarkably low latency and heightened reliability.[2, 3]

At the core of these connected devices lies the antenna, which plays a fundamental role in wireless communication. All electronic communication systems and wireless networking equipment have antennas or elements that serve as antennas for the transmission and reception of electromagnetic signals.[4] The antenna that will meet 6G and future communication system requirements is expected to be highly directional, intelligently reconfigurable, have ultra-wide bandwidth and be highly efficient.

This article provides a comprehensive exploration of 6G, delineates the key antenna performance requirements for 6G and future communication scenarios, reviews various antenna types suitable for these contexts and outlines prospective directions in the ongoing design and development of antennas for future communication systems.

THE ROAD TO 6G

To enable voice services, the first generation of mobile communication, 1G, was introduced in the 1980s, offering a data rate of 2.4 kbps. However, owing to its analog transmission nature, 1G suffered from limitations such as poor capacity, inconsistent delivery and inadequate security. Addressing these issues, second-generation (2G) networks emerged in the 1990s, leveraging digital modulation technology. With a data rate of 64 kbps on the Global System for Mobile Communications (GSM), 2G not only facilitated traditional voice communication but also introduced encrypted data services like Short Message Services (SMS). Both 1G and 2G systems were rooted in the public switched telephone network (PSTN).[5]

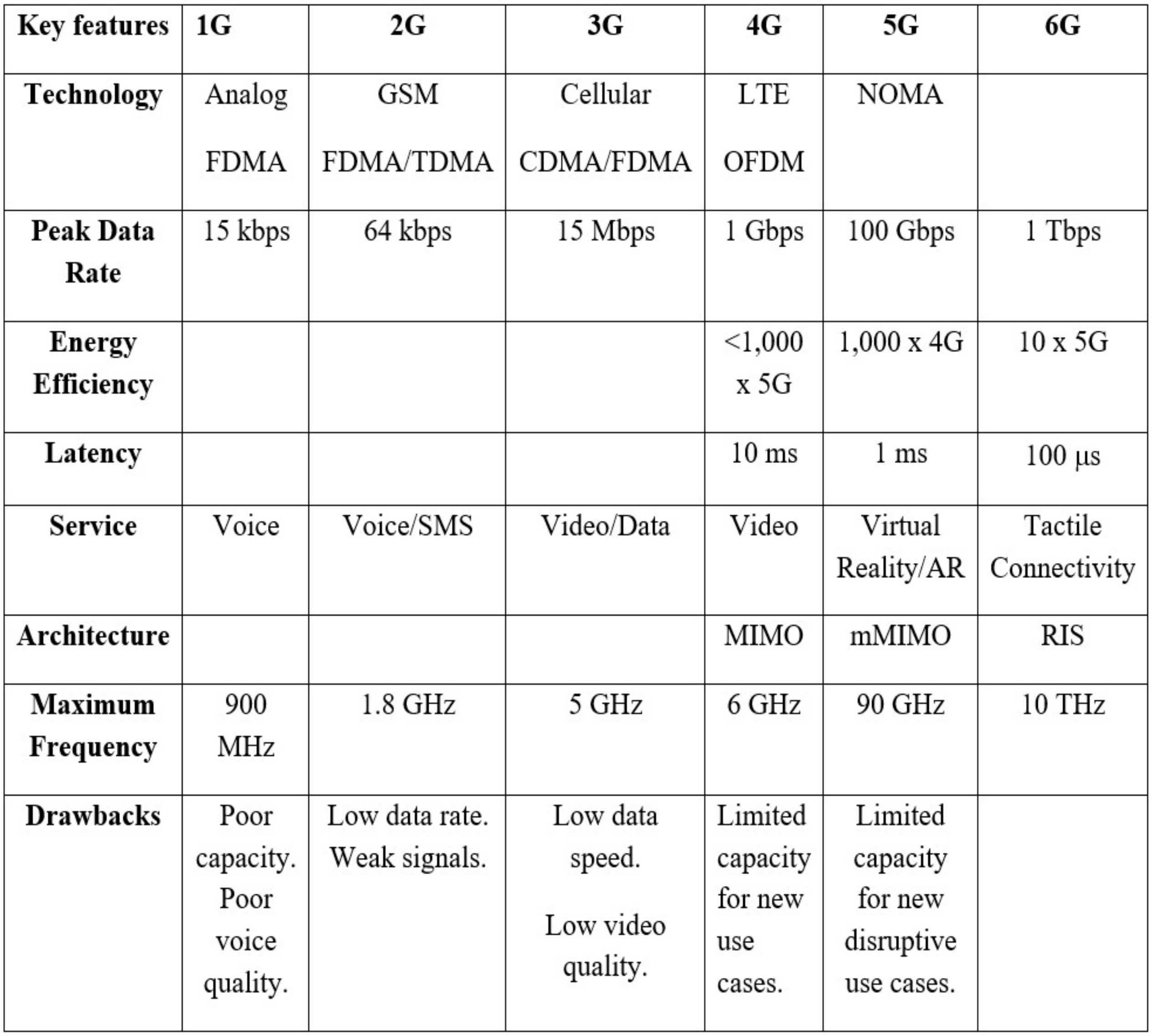
The third generation (3G) of mobile communications networks was developed around 2000 in response to the growing demand for various multi-data services, including internet browsing and video conversations. Code Division Multiple Access (CDMA) and Frequency-Division Multiple Access (FDMA) were exploited to create worldwide interoperability for microwave access (WiMAX), wide-CDMA, CDMA-2000 and synchronous CDMA with time division (TD-SCDMA) to meet the growing demand.[6] 3G networks provide a data rate of up to 14 Mbps.[7]

The fourth generation (4G) mobile communication standard was introduced in 2009. Known as Long-Term Evolution (LTE), it used both Frequency-Division Duplex (FDD) and Time-Division Duplex (TDD) modes. Orthogonal Frequency-Division Multiplexing (OFDM) technology in 4G enhanced data rates and spatial efficiency compared to earlier technologies. As data rates continued to rise, Multiple-Input-Multiple-Output (MIMO) and Coordinated Multiple Transmission/Reception (CoMP) technologies were introduced to support higher data rates, larger MBB connections and increased transmission bandwidth. The LTE mobile communication standard was upgraded to LTE-Advanced in 2011, allowing the use of unlicensed spectrum.[7, 8]

Current fifth-generation (5G) technology, employing non-orthogonal multiple access (NOMA), achieves nearly 100 Gbps data rates. However, future 6G networks are envisioned to use AI-driven MIMO-OFDM transceivers, potentially delivering up to 1 Tbps data rates. 5G networks deploy massive MIMO (mMIMO) and Beam Division Multiple Access (BDMA) to enhance system capacity, with BDMA enabling the allocation of orthogonal beams to users based on their locations.[9]

Recognizing the limitations of existing wireless communication technologies in handling the surge in data traffic and new applications, 6G networks are now emerging as the next frontier. These networks aim to meet evolving use cases and scenarios, promising ultra-high reliable data speeds with extremely low latency, high efficiency and ubiquitous connectivity.[3, 6, 10] **Table I** provides a summary of the key features of mobile communication from 1 to 6G.

TABLE I - KEY FEATURES OF 1 THROUGH 6G COMMUNICATION TECHNOLOGY



Key features	1G	2G	3G	4G	5G	6G
Technology	Analog FDMA	GSM FDMA/TDMA	Cellular CDMA/FDMA	LTE OFDM	NOMA	
Peak Data Rate	15 kbps	64 kbps	15 Mbps	1 Gbps	100 Gbps	1 Tbps
Energy Efficiency				<1,000 x 5G	1,000 x 4G	10 x 5G
Latency				10 ms	1 ms	100 μs
Service	Voice	Voice/SMS	Video/Data	Video	Virtual Reality/AR	Tactile Connectivity
Architecture				MIMO	mMIMO	RIS
Maximum Frequency	900 MHz	1.8 GHz	5 GHz	6 GHz	90 GHz	10 THz
Drawbacks	Poor capacity. Poor voice quality.	Low data rate. Weak signals.	Low data speed. Low video quality.	Limited capacity for new use cases.	Limited capacity for new disruptive use cases.	

6G KPIs

6G networks aim to provide ubiquitous connectivity, ultra-high data rates (1 Tbps), ultra-low latency (<1 ms), ultra-high reliability, ultra-high bandwidth, enhanced security and intelligent communication (see **Figure 1**). The values of these key performance indicators (KPIs) can be obtained from Alqahtani.[11]

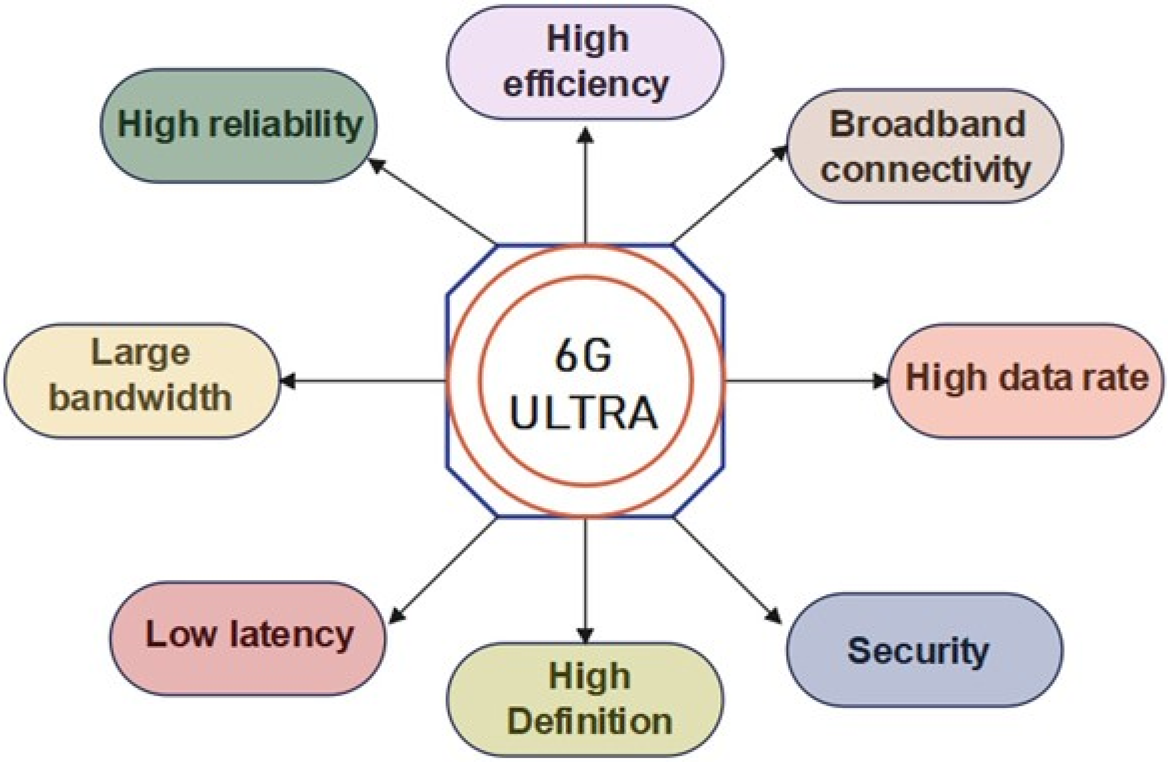


Figure 1 6G KPIs.

New disruptive use cases for 6G (see **Figure 2**) will lead to enormous bandwidth and hence, more energy consumption.[2] To reduce energy consumption and increase cloud radio access, efficient network planning and allocation schemes have been proposed. 6G is expected to provide ubiquitous connectivity. This will be achieved by combining terrestrial and satellite communication, uncrewed aerial vehicles (UAVs), high-altitude platforms (HAPs), and heterogeneous networks. 6G communications systems will provide ultra-reliable and highly secured data transmission. To achieve this, it will use AI, blockchain technology and quantum communication to provide ultra-secure and reliable connections.

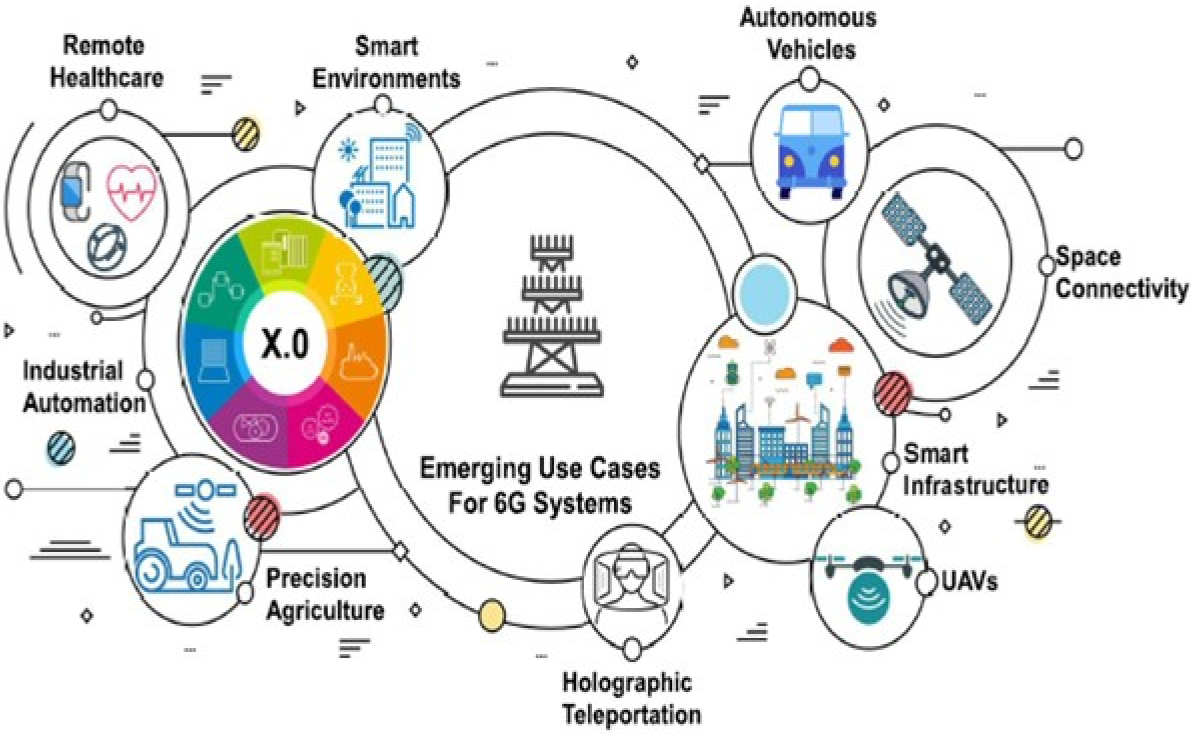


Figure 2 6G. disruptive use cases.[3]

There are three major drivers of 6G development: the explosive increase in mobile traffic, novel use scenarios and disruptive use cases (see **Figure 3**). It is expected that the number of machine-to-machine (M2M) connections will be over 90 billion by 2030.[1, 12] There is now high demand for extremely high-definition video applications, enhanced screen resolution, M2M communications, vehicle-to-vehicle (V2V) communication and mobile-cloud services. 5G will not be able to effectively serve these needs. The features of 6G will enable its use in these applications and others such as holographic type communication (HTC), extended reality, global ubiquitous connectivity, intelligent transport, telemedicine and tactile internet.[13, 14]

5G was initially developed to meet three service scenarios: massive machine-type communications (mMTC), uRLLC and enhanced MBB (eMBB). The technical needs of future communication use cases (see Figure 2) cannot be satisfied by these 5G service scenarios. New use cases for 6G include uMBB (the availability of mobile communication all over the earth's surface), and massive URLLC (mURLLC).[15]

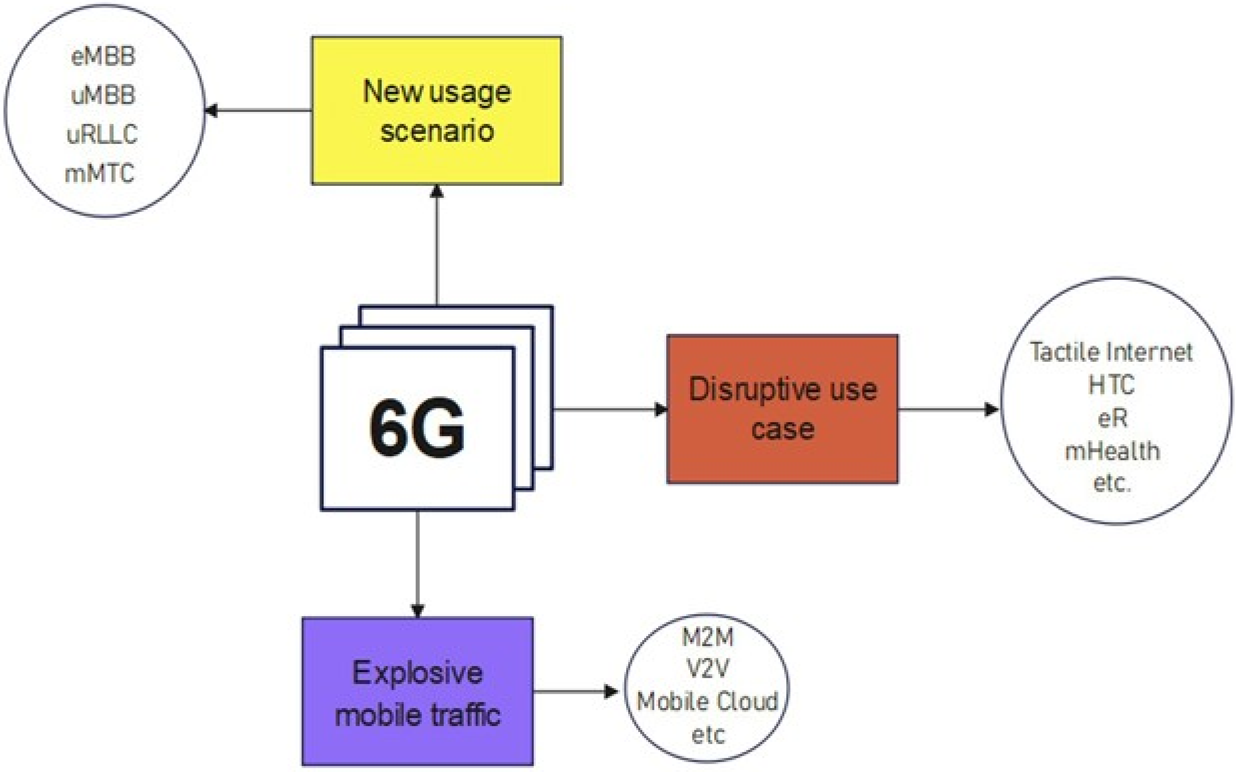


Figure 3 6G technology drivers.

6G ENABLERS

6G enablers and new technologies are shown in **Figure 4** and listed in **Table II**. Emerging wireless technologies will rely on new air interfaces, new spectrum, a new paradigm, new networking and a new architecture to deliver ultra-reliable data transfer.

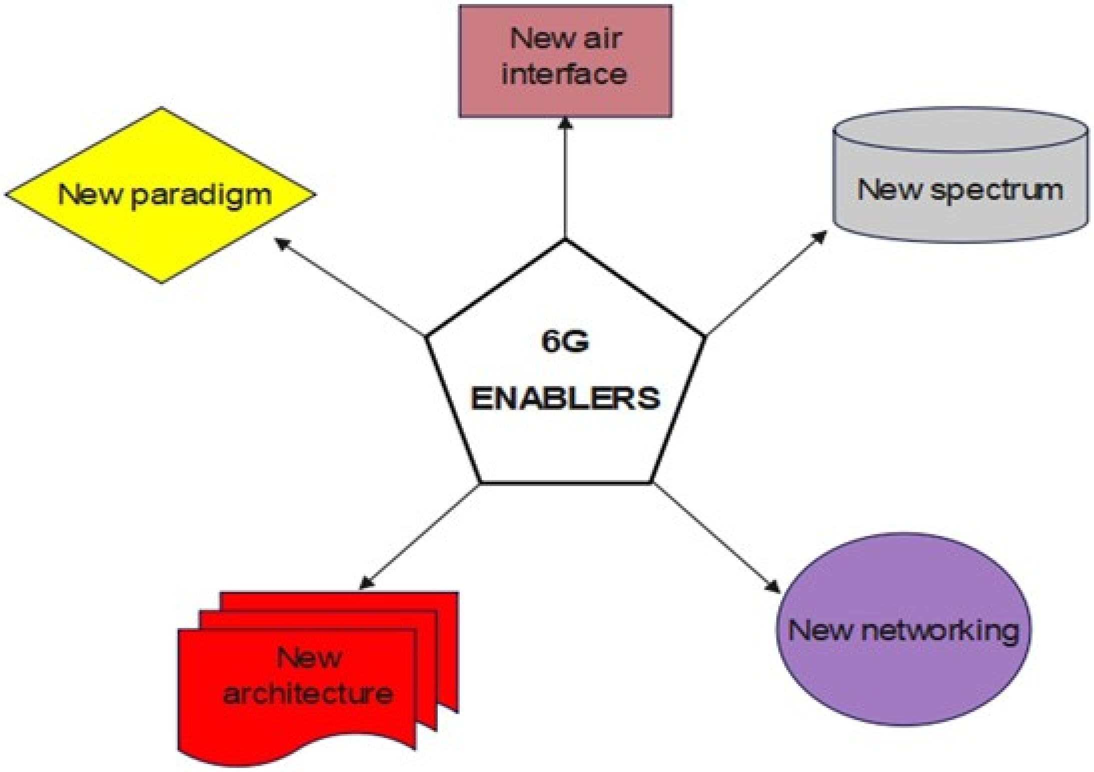


Figure 4 6G enablers.

New Air Interface

Active MIMO antenna arrays have been widely deployed in 4 and 5G. However, fast fading, high propagation loss, low diffraction and low non-line of sight path diversity[16] are challenges that are faced as we move toward extremely high frequencies. 6G and future communication will go from small MIMO and active antennas to mMIMO and reconfigurable intelligent surfaces.[17] These new air interfaces are expected to enhance system capacity, spectral/spatial efficiency and multiplexing gain while allowing incoming electromagnetic waves to be reflected in the desired direction.

New Spectrum

With an increasing number of connected devices, the widely used mmWave spectrum will be insufficient to accommodate new usage scenarios. Future communication technologies are expected to address wide bandwidth and high data rate needs through the use of the THz spectrum (0.1 to 10 THz),[18] visible light communication (VLC) (400 to 800 THz) and optical wireless communication (OWC).[19] Much work is ongoing in defining the use parameters, challenges and deployment scenarios associated with the new spectra.

New Paradigm

One of the most important 6G enablers will be AI.[20] It is foreseen that 6G will shift from current conventional computing to a massive computer that integrates processing, storage, sensing, distributed communication and resource control to provide pervasive computing services.[21, 22] AI, edge computing, blockchain and digital twins will enable intelligent reconfiguration of the network architecture, providing a secure end-to-end transfer of data and the efficient use of network resources.[23]

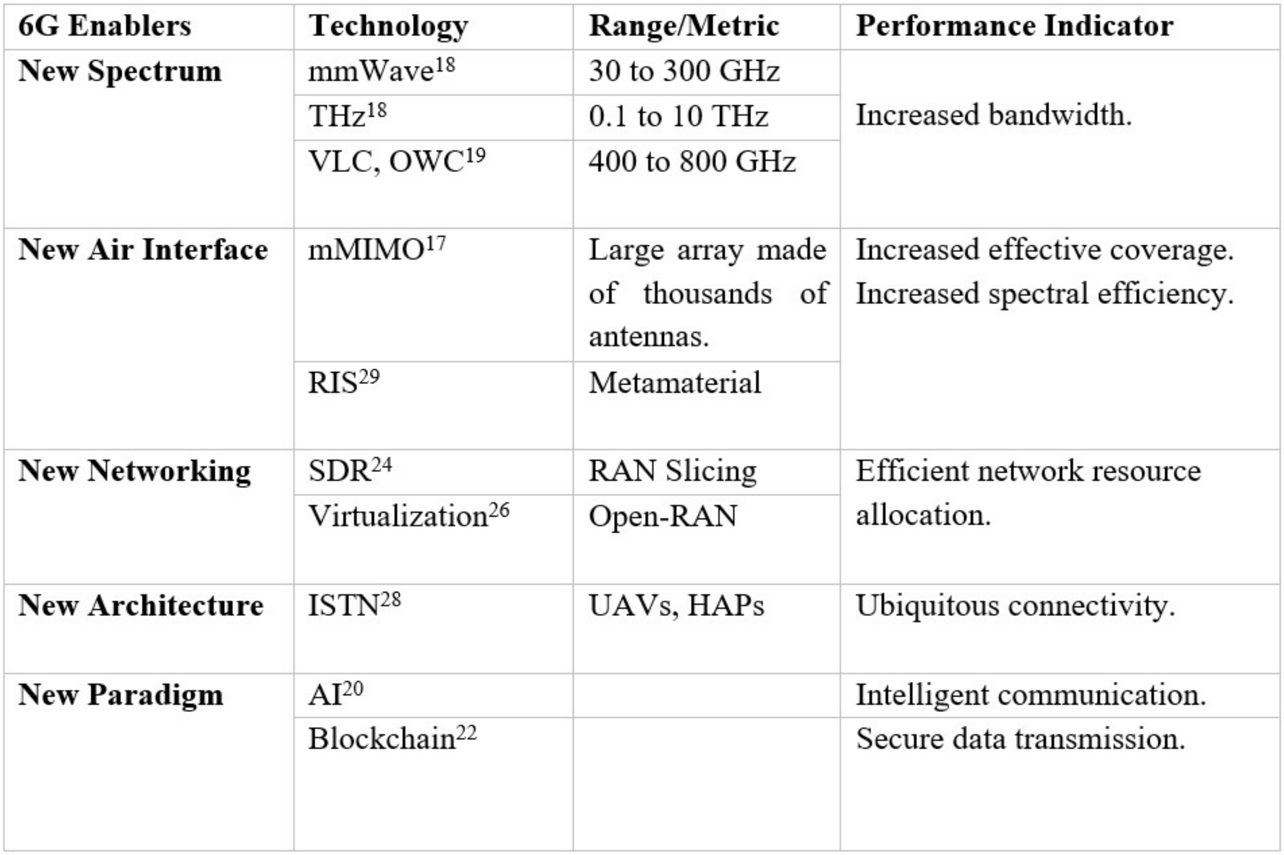
New Networking

The 5G core network currently deployed will not meet the internet work demand of future communication systems. Software-defined radio (SDR) and network function virtualization (NFV)[24] have been identified to improve the radio access network (RAN) of 6G and beyond, while RAN slicing[25] and open-RAN26 using software-defined networking (SDN) and network function virtualization (NFV) are potential ways of providing centralized and efficient network resource allocation. However, the increased number of virtual networks, placement of SDR controllers and traffic management are concerns.[27]

New Architecture

The network technologies of the past and those in use today were created to enable two-dimensional (2D) connections between network access points and user devices located on the ground. However, in 6G and future communication systems, an integrated space and terrestrial network (ISTN) is envisioned. An ISTN consists of three layers: the airborne layer (powered by UAVs and HAPs), the spaceborne layer (implemented by satellites) and the ground-based layer (terrestrial base stations).[28] These layers will work collaboratively to realize the ubiquitous connectivity promise of 6G and future communication systems.

TABLE II - FUTURE COMMUNICATION-ENABLING TECHNOLOGIES



6G Enablers	Technology	Range/Metric	Performance Indicator
New Spectrum	mmWave[18]	30 to 300 GHz	Increased bandwidth.
	THz[18]	0.1 to 10 THz	
	VLC, OWC[19]	400 to 800 GHz	
New Air Interface	mMIMO[17]	Large array made of thousands of antennas.	Increased effective coverage. Increased spectral efficiency.
	RIS[29]	Metamaterial	
New Networking	SDR[24]	RAN Slicing	Efficient network resource allocation.
	Virtualization[26]	Open-RAN	
New Architecture	ISTN[28]	UAVs, HAPs	Ubiquitous connectivity.
New Paradigm	AI[20]		Intelligent communication.
	Blockchain[22]		Secure data transmission.

ANTENNAS FOR 6G AND FUTURE COMMUNICATION SYSTEMS

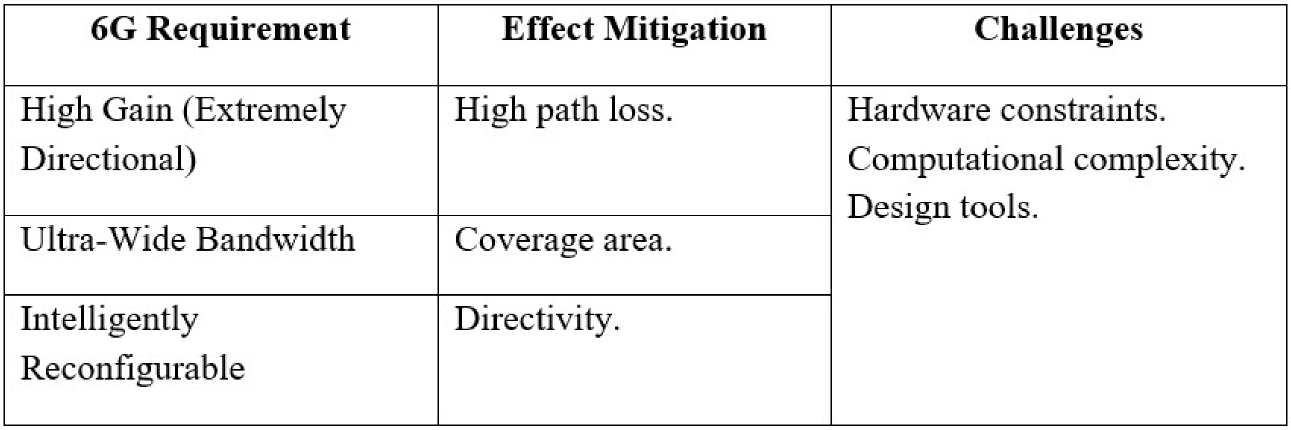
Driven by the data-centric and large bandwidth requirement of 6G, the mmWave frequency range from 30 to 300 GHz and the THz frequency range from 0.1 to 10 THz) will be used for 6G and beyond.[30] Antennas to meet 6G and future communication system requirements are discussed in this section.

6G Antenna Requirements

Antenna dimensions for future communication are expected to be tiny, from µm to mm.[31] This is attributed to the high operating frequencies (the higher the frequency, the smaller the wavelength). Thus, the first consideration is size. Fabricating and measuring a tiny antenna is a critical task that requires appropriate materials, technologies, facilities and equipment.

The next consideration is gain. 6G is expected to deliver extremely high spectral/spatial efficiency. To achieve this, a high gain and highly directional antenna is required. This mitigates high atmospheric absorption and high path loss.[32] The orientation and location of devices connected in 6G are not fixed; antennas are, therefore, expected to be intelligently reconfigurable to provide full antenna beam coverage, high directivity and stable radiation patterns. Requirements for an antenna to perform optimally beyond 5G are summarized in **Table III**.

TABLE III - ANTENNA REQUIREMENTS FOR 6G AND BEYOND



6G Requirement	Effect Mitigation	Challenges
High Gain (Extremely Directional)	High path loss.	Hardware constraints. Computational complexity. Design tools.
Ultra-Wide Bandwidth	Coverage area.	
Intelligently Reconfigurable	Directivity.	

Antenna Designs for 6G and Beyond

High path loss and atmospheric absorption are challenges identified for communication in the sub-THz and THz spectra.[12, 33] In this article, antennas for 6G and future communication are divided into three types: patch, large arrays (emMIMO) and metamaterial.

Patch Antennas

The patch antenna is the most widely used. In 6G, it is designed for use at frequencies in the sub-THz and lower part of the THz bands respectively and requires the integration of several elements to improve its performance. A tooth-shaped inset-fed patch antenna, for example, is shown in **Figure 5**. It is fabricated based on a Rodgers 5880 substrate and operates at the sub-THz band with a resonant frequency of 0.19 THz.32 It has a return loss of 47.71 dB and a gain of 9.58 dB.

Another example is an ultra-wideband (UWB) coplanar waveguide-fed microstrip patch antenna, also fabricated on a Rodgers 5880 substrate and designed using ANSYS HFSS, which operates from 23 to 150 GHz (see **Figure 6**).[34] Its gain increases gradually with frequency, peaking at 14.8 dB at 150 GHz with maximum efficiency at 90 GHz.

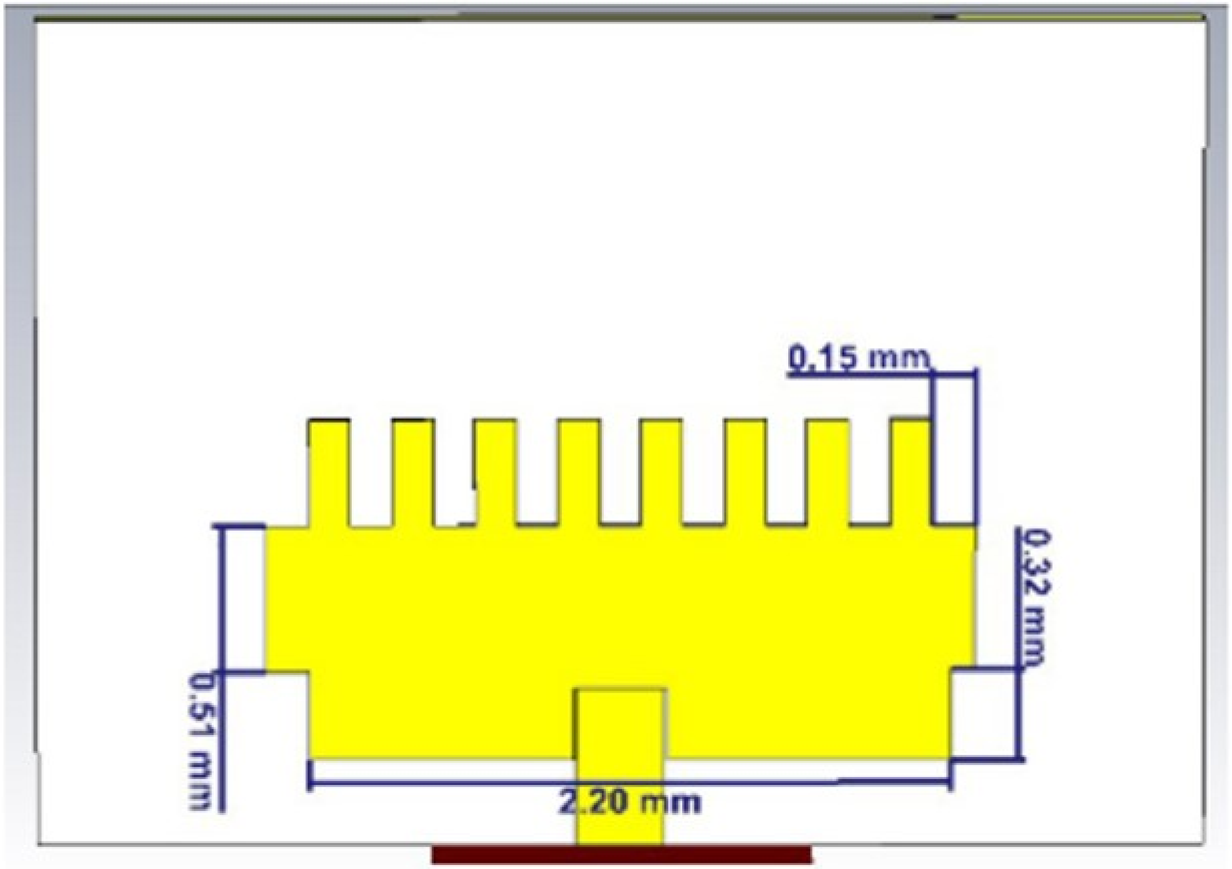


Figure 5 Tooth-shaped inset-fed patch antenna.[32]

Figure 6 CPW-fed UWB microstrip patch antenna.[34]

The bandwidth of patch antennas is comparatively small.[35, 36] However, Hedayatullah et al.[37] introduced a wideband aperture-coupled patch antenna for the 6G sub-THz band. A peak gain of 7.95 dBi and $|S_{11}| \leq -10$ dB was recorded across a wide frequency range of 90 to 128.5 GHz. Also, described in the work of Jeyakumar et al.,[38] a microstrip patch made of graphene, operating at 0.1 THz was designed and modeled using CST and ANSYS. A 27.7 dBi return loss, 98.30 percent radiation efficiency and 10.4 GHz bandwidth were achieved.

In related work,[39] a reconfigurable circular patch antenna was developed for 6G cognitive radio applications (see **Figure 7**). With dimensions of 30 x 22 x 1.6 mm^3 and a simple design, it allows for easy reconfiguration to other required frequencies by changing its square ring diameters with PIN diodes. The antenna operates from 3 to 11 GHz with a peak gain of 4.8 dBi.

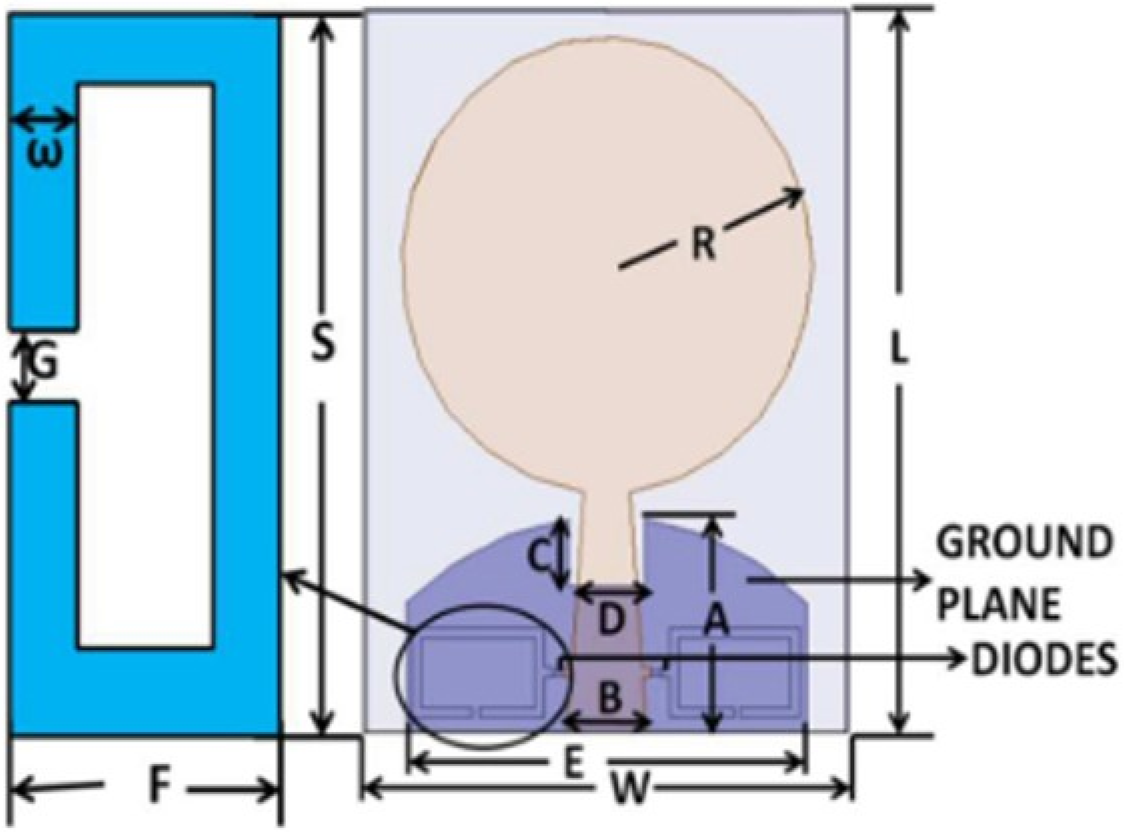


Figure 7 UWB frequency reconfigurable antenna.[39]

Large Arrays (emMIMO)

mMIMO is a cellular technology where the access points are equipped with a massive array of antennas[33] to improve beamforming and coverage area. mMIMO technology is currently used in 5G networks; however, hundreds or even thousands of array antennas are envisioned for 6G to achieve ultra-high spectral resolution, wide coverage and highly directional signals.[40, 41] This new technology is extremely massive MIMO (emMIMO). MIMO is a few hundred elements, mMIMO is several hundreds of elements, while emMIMO is a new term. It is expected that 6G emMIMO antennas will comprise several thousand array elements. This development is still in a preliminary stage.

The parameters used to determine the performance of emMIMO antennas include envelope correlation coefficient (ECC), which defines the correlation between adjacent antenna elements; diversity gain, which indicates the quality and reliability of the antenna; channel capacity loss (CCL), which defines the maximum limit of data that can be transmitted with almost zero loss in the communication channel and mean effective gain (MEG), which is the ratio of MIMO antenna power to isotropic received power of the antenna.[30]

The following are a few examples of research on the MIMO building blocks that may lead to effective mMIMO and emMIMO solutions:

Figure 8 is a tightly spaced 16-port 2 × 2 module array MIMO antenna on a 0.4 mm FR4 substrate.[42] The antenna operates from 7.025 to 8.4 GHz. To achieve a high spectral efficiency of 56 bps/Hz, the module array is a 16 × 8 MIMO system consisting of 16 receive antenna and eight spatial streams.

In the work of Khaleel et al.,[43] a double-port THz MIMO antenna made of graphene plasmonic on a 130 × 85 μm^2 Teflon substrate is described. It has a low CCL of 0.006, a consistent radiation pattern, a compact size, a low envelope ECC of 0.000168, a high gain of 7.23 dB, and a wide impedance bandwidth of 0.6 THz.

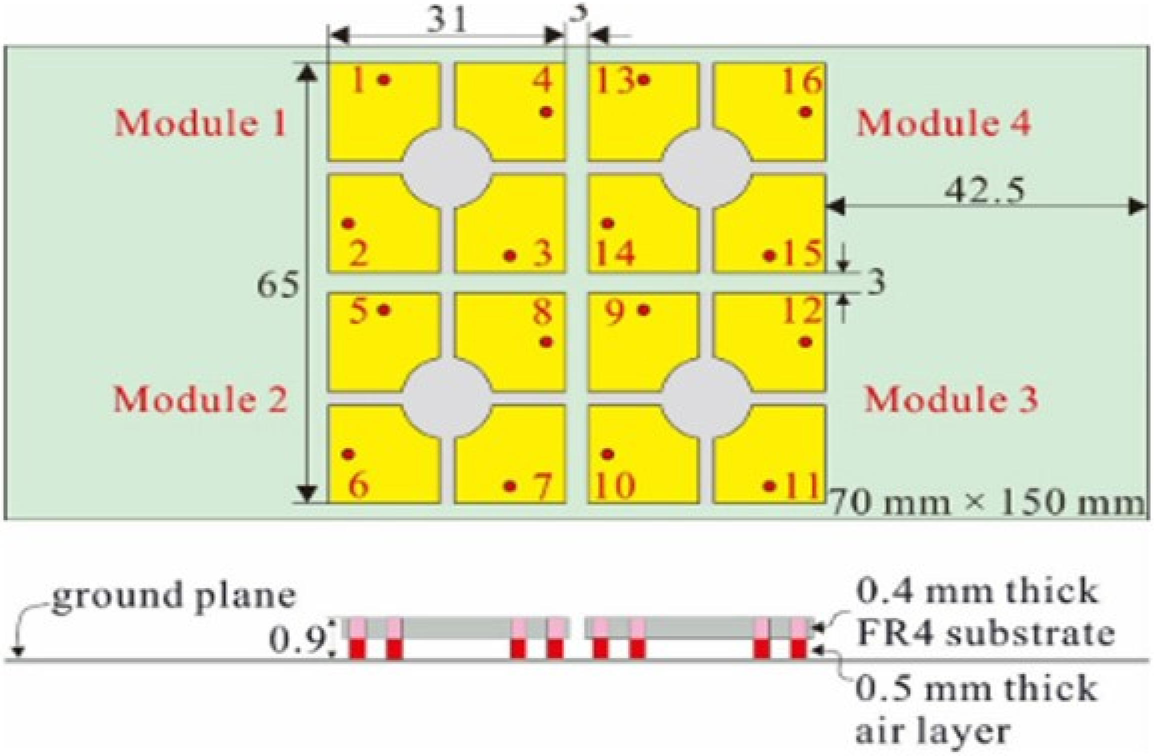


Figure 8 16-port 2 × 2 module array antenna.[42]

Wu and Zhang[44] designed a 7.1 to 13 THz graphene-based antenna (see **Figure 9**) on a 10 μm thick SiO2 substrate measuring 100 by 100 μm^2. A high gain of 8.3 dB was realized at 11 THz with a return loss of 30 dB. With an ECC of less than 0.005 dB and a diversity gain of 9.97 dB, the antenna is capable of functioning in mMIMO applications for THz point-to-point wireless communication.

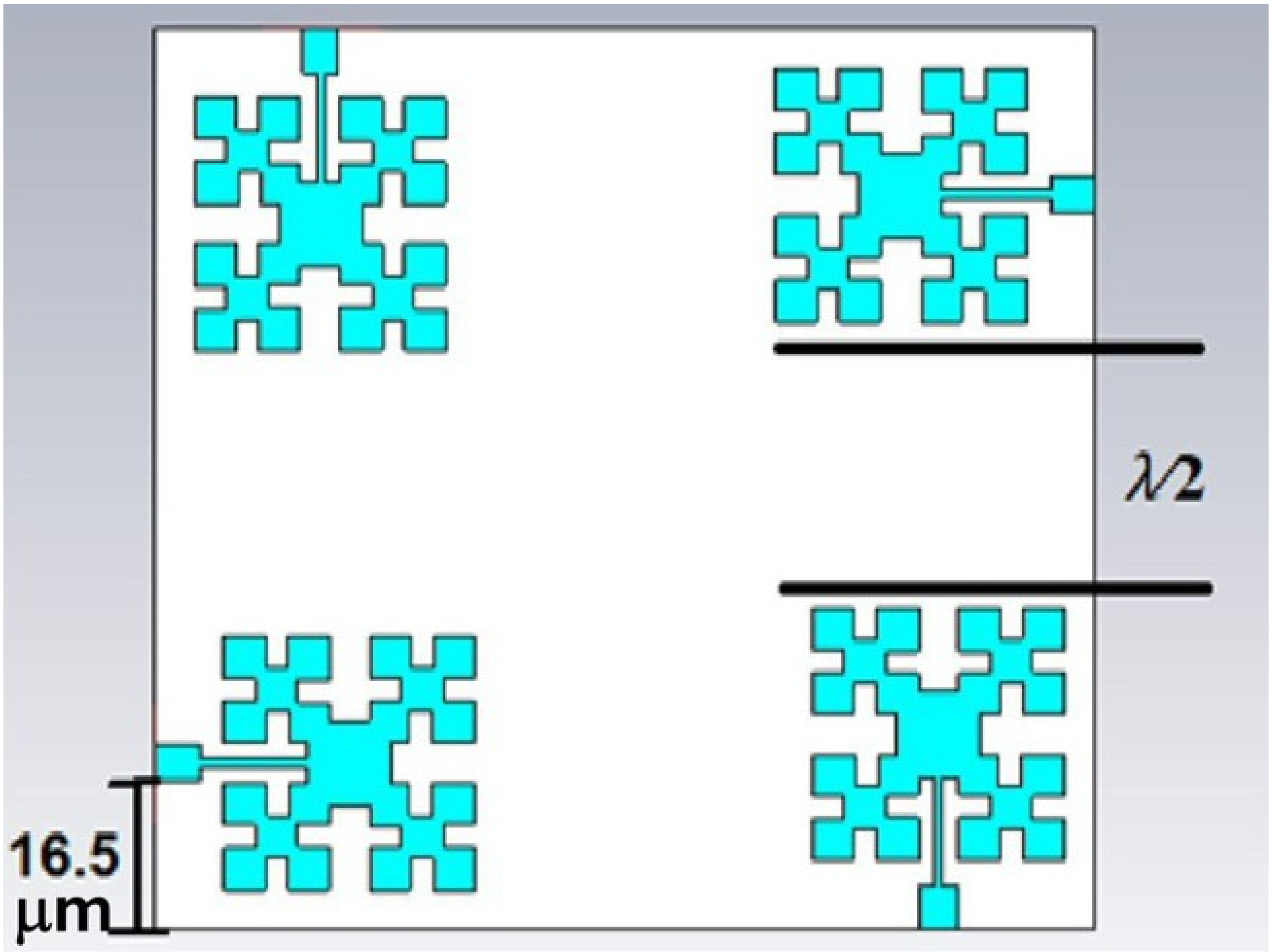


Figure 9 Graphene-based THz MIMO antenna.[44]

Metamaterial (MM) Antennas and Reconfigurable Intelligent Surfaces (RIS)

MMs are materials that have characteristics different from those found in nature and whose electromagnetic properties are described by their electric permittivities (ε) and magnetic permeabilities (μ).[45, 46] MMs are capable of absorbing unwanted radiation and only permitting the desired radiation, improving antenna gain, controlling scattering, improving bandwidth and intelligently directing a signal to the desired user.[47-49]

Muqdad et al.[50] described a novel metasurface reconfigurable antenna for 6G. Fabricated on an FR4 epoxy substrate, the metasurface concentrates the antenna's main beam to enhance directivity. The antenna resonates at 1.35 GHz and does not require any mechanical movement; hence, it is intelligent.

Xie et al.[51] proposed an ultra-wideband achromatic metalens antenna for operation between 50 and 102 GHz. The antenna consists of a convex-like metalens and a concave-like metalens integrated as a metalens group. A gain of 23.27 dBi and a return loss greater than 15 dB at 68 GHz were realized.

It was suggested by Muqdat et al.[50] to use PIN photodiodes to create a metasurface antenna whose radiation properties could be optically controlled for 6G mobile communication applications (see **Figure 10**). The antenna operates from 0.978 to 1.73 GHz with a return loss greater than 10 dB, realizing a peak gain of 9 dBi at 1.35 GHz. The antenna is a rectangular patch incorporating a 3-order H-tree fractal slot. The radiator is positioned above a metasurface layer that has a small air gap between it and the radiator. The metasurface layer is a lattice structure formed from unit cells that are joined to each other by PIN photodiodes that enable antenna reconfiguration.

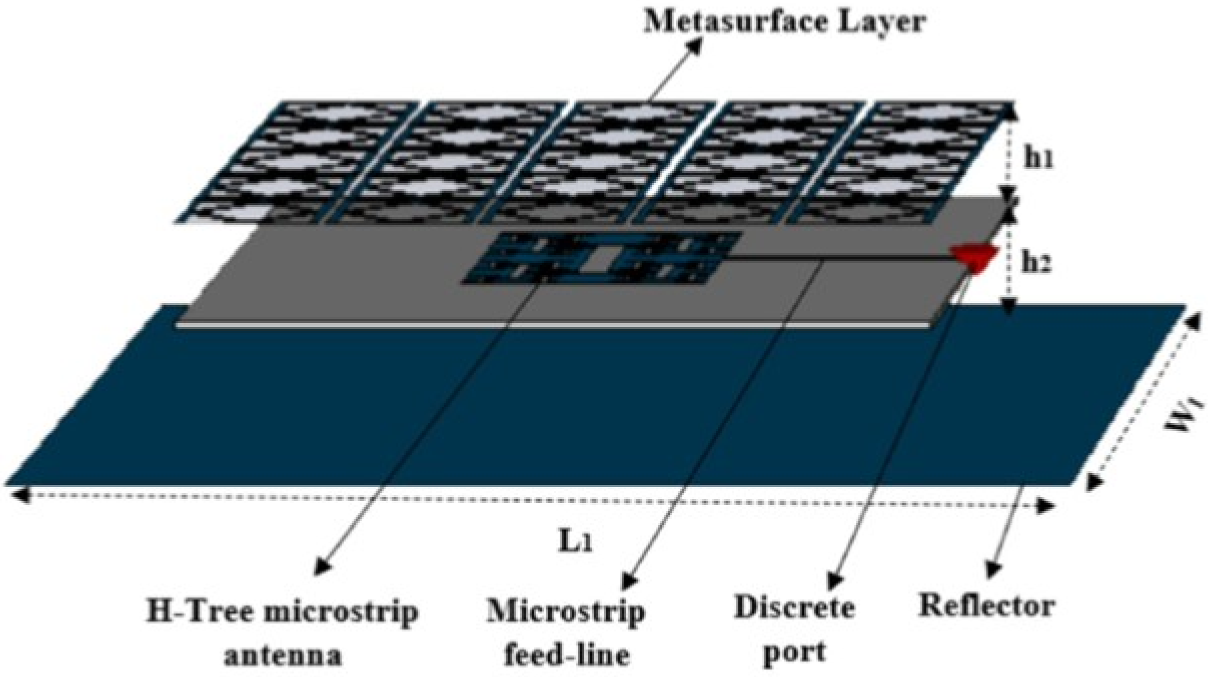


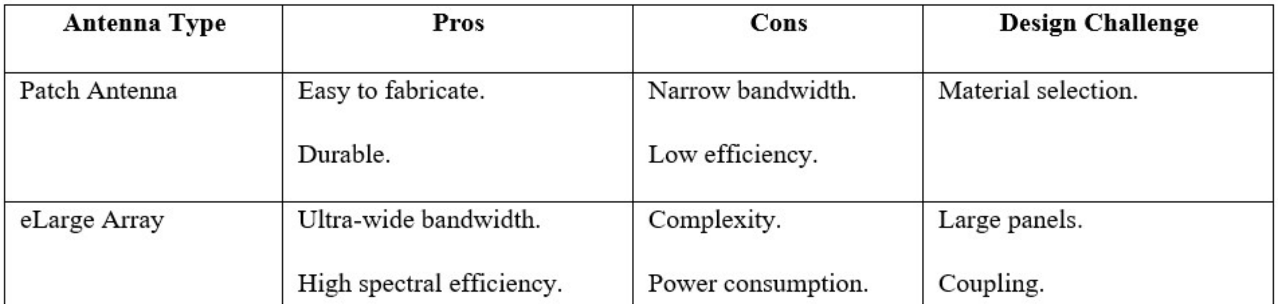
Figure 10 Photonic-controlled metasurface antenna for 6G.[50]

A high gain circularly polarized antenna with a μ negative MM slab and near-zero refractive index was proposed by Ghzaoui et al.[48] To achieve high gain and circular polarization, the antenna used a substrate-integrated waveguide (SIW) approach loaded with a compact square split ring resonator combined with a hexagonal-shaped structure as a unit cell. The antenna was simulated over a wide frequency range of 100 to 280 GHz, recording a peak gain of 11.3 dBi at 223 GHz. Although high gain and good cross-polarization were achieved, the antenna was not reconfigurable.

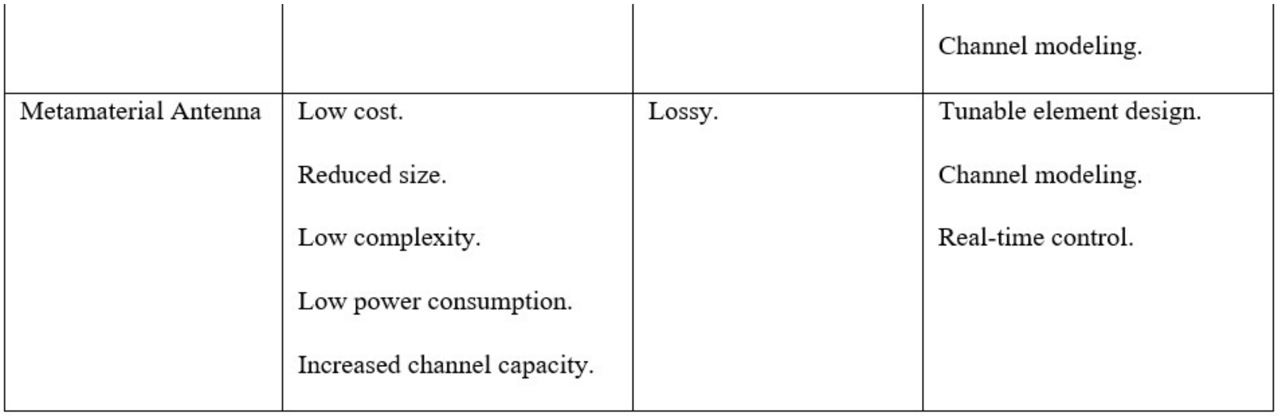
To enhance the gain of many beams emitted from a linear feed antenna array while accounting for multi-layer transmission, a large-aperture metamaterial lens antenna (MLA) was developed by Lee and Kim.[52] The antenna comprised 28 × 28-unit cells fed by a 1.6 dBi dipole antenna. The MLA delivered 14 dBi gain at a resonant frequency of 28 GHz. The high gain obtained was a result of a novel channel model they presented, which considered the radiation pattern, azimuth radiation pattern and meta feed.

A comparison of patch antenna, large array and metamaterial antenna is presented in Table IV.

TABLE IV - A COMPARISON OF PATCH ANTENNA, LARGE ARRAY AND METAMATERIAL ANTENNAS FOR 6G AND FUTURE COMMUNICATION



Antenna Type	Pros	Cons	Design Challenge
Patch Antenna	Easy to fabricate. Durable.	Narrow bandwidth. Low efficiency.	Material selection.
eLarge Array	Ultra-wide bandwidth. High spectral efficiency.	Complexity. Power consumption.	Large panels. Coupling.



			Channel modeling.
Metamaterial Antenna	Low cost. Reduced size. Low complexity. Low power consumption. Increased channel capacity.	Lossy.	Tunable element design. Channel modeling. Real-time control.

RESEARCH DIRECTION

6G and future communication systems will require extremely large bandwidths to deliver the ultra-high data rate promised. An antenna that is highly directional, intelligently reconfigurable and has wide bandwidth is required. The following are promising directions in the design of antennas for 6G and beyond:

1. **Smart Tuning Techniques for Reconfigurable Antennas:** Future work should delve into the development of intelligent tuning techniques specifically tailored for reconfigurable antennas. Smart tuning mechanisms can significantly enhance the adaptability and performance of antennas in dynamic communication scenarios.
2. **Metamaterial Design with Low Index (Permittivity and Permeability):** The development of metamaterials with near-zero index or negative permittivity and permeability is an open area of research as we move toward intelligently reconfigurable surfaces. The design of such materials will mitigate dispersion effects, contributing to enhanced antenna performance in terms of signal propagation and transmission.
3. **Array Coupling and Channel Modeling of emMIMO Antenna:** Investigating the intricacies of array coupling and comprehensive channel modeling for emMIMO antennas holds the potential for optimizing their functionality. Understanding and optimizing these aspects are critical for harnessing their full capabilities.
4. **Bandwidth Optimization Techniques for emMIMO:** Focusing on the optimization of bandwidth for emMIMO antennas is a crucial aspect of future antenna design. Research efforts should explore innovative techniques to maximize the use of available bandwidth, ensuring efficient and high-capacity communication networks.

These proposed directions not only align with the evolving requirements of 6G and future communication systems but also open new avenues for innovation and breakthroughs in antenna design. By addressing these challenges, researchers can contribute to the development of antennas that are not only capable of meeting the demands of future communication systems but also push the boundaries of what is achievable in wireless technology.

CONCLUSION

6G networks seek to provide ultra-high data rates (>100 Gbps), ultra-low latency (< 1 ms), enable ubiquitous broadband connectivity, ultra-high security, ultra-high reliability and achieve intelligent communication. To achieve these goals, the sub-THz and THz frequency spectra are expected to be used. High path loss and atmospheric absorption are critical challenges that have been identified for communication at such high frequencies. To mitigate these challenges, highly directional, ultra-wide bandwidth and intelligently reconfigurable antennas are required. Several types have been proposed and have been categorized into three groups: patch, eLarge array (emMIMO) and metamaterial. This article is meant to serve as a guide for the design and selection of antennas to meet the complex requirements of 6G and future communication.

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