Al-Furat Journal of Innovations in Electronics and Computer Engineering (FJIECE)
ISSN -2708-3985

Comprehensive Review of Holographic Antenna Beamforming for Next Generation (6G) Wireless Communications

Sarmad Muneer Abdulhussein [1*], Asaad. S. Daghal [1]

[1]Al-Furat Al-Awsat Technical University, Engineering Technical College Najaf, Departmentof Communications Techniques Engineering, 54003, Iraq. E-mail: ma.sarmad@atu.edu.iq , ad466kent@atu.edu.iq,
*Corresponding author E-mail: ma.sarmad@atu.edu.iq

Article's Information

Received: 28.01.2026
Accepted: 25.02.2026
Published: 31.03.2026

Keywords:
HBF, 6G Wireless Communications
Beam Steering
THz Communications

Abstract

Holographic beamforming antennas help in increasing the capacity and spectral efficiency of wireless networks while reducing interference by employing advanced signal processing techniques for adaptive beamforming patterns. Hence, these antennas can be effectively used in 5G and future communication systems. This review presents the state-of-the-art technology for holographic beamforming antennas and identify its uniqueness compared with conventional beamforming technology. The uniqueness of this technology is its capacity for controlling electromagnetic waves. The review will also look into the main principles and advantages of this technology and its future prospects. The study reviews existing literature to compare holographic beamforming technology with other technologies, such as conventional phased arrays and massive MIMO to identify its specific advantages and disadvantages. The advantages of high-frequency communications using holographic beamforming can be attributed to its precise capabilities resulting from its flexible design, simple hardware requirements, and beam steering capabilities. Empirical studies on holographic beamforming antennas identified specific advantages to include its flexible beam control system, reduced power requirements, and accurate tracking capabilities to reduce delay times for communications. The realization of holographic beamforming systems depends on resolving three main obstacles, which include high frequency propagation loss, fabrication constraints, and energy efficiency concerns. Future investigators need to concentrate on antenna optimization while developing improved fabrication methods and smart control systems to improve performance and scalability for practical 6G applications. The complete realization of holographic beamforming potential in next generation wireless communications depends on resolving the existing challenges.

https://doi.org/10.46649/fjiece.v5.1.4a.31.3.2026
*Corresponding author: ma.sarmad@atu.edu.iq

1. INTRODUCTION

The main purpose of 5G and 6G network design is to achieve high throughput, low latency, small scale, spectrum, and energy efficiency. Meanwhile, the key objectives for 6G technology consist of incorporating AI and wireless communications, while 5G tech is all about generating higher frequencies

ATU-FJIECE, Volume: 05, Issue: 01, 03, 31, 2026, © 2020 FJIECE, All Rights Reserved

Al-Furat Journal of Innovations in Electronics and Computer Engineering (FJIECE)
ISSN -2708-3985

and more advanced MIMO technologies [1],[2]. Holographic beamforming antennas and their role in wireless communications are among the most recent trends of interest for researchers in this field [3]. This paper gives insightful information for academics and engineers who are working on antenna technologies of 6G to help share knowledge by describing the current developments in technology and literature. Another advantage of this review paper is that it will contribute to the reader's understanding of the most recent progress and developments in applying holographic beamforming antennas to materialize 6G vision. In the first place, we deliver holographic beamforming antennas basics theories and principles in this review study. After that, a detailed review of the most up to date progress in holographic beamforming technology and possible applications for 6G wireless networks is presented [4],[5].

This technology can potentially be a good candidate for 6G wireless communication because it produces a precise 3D radiation pattern. It can be directed electronically, giving flexibility in providing varied services at different frequencies in the future network [6]. Holographic beamforming antenna integration is an ongoing endeavour in both present and future wireless communication systems, though the technology is promisingly expected to rule the future [7]. When used by radio frequency signals, holographic beamforming generates a 3D electromagnetic wave front that can be directed in three-dimensional space. With the aid of this advanced antenna design, the angular, spatial, and frequency diversities of the electromagnetic field can be maximized, thus further increasing tracking precision and decreasing the communication delay of wireless communications [8].

On the other hand, the large size of the antenna can be supported by holographic arrays that would imitate emission signals at different frequencies through a single aperture. As a result, in the 6G technology age, this technology will likely be extremely beneficial for millimeter wave communications, IoT, and bigger MIMO systems. The THz frequency band range (0. 1-10 THz) is one of the techniques 6G will adapt to [9]. Nevertheless, great propagation loss and energy absorption in such frequency ranges can impede the progress of 6G development. In addition, THz frequency antenna technology research is considered a new field. New studies suggest that holographic beamforming antennas may play an important role in 6G wireless communication networks. Holographic beamforming will be an effective go to antenna technology for future 6G wireless communications. Sixth generation (6G) networks are being designed and tested at present and will be operational in some high tech countries by 2030[10],[11]. Potential solutions are explored to improve wireless communication systems as more wireless devices emerge, and the demand for higher bandwidths grows.

1.1. OVERVIEW

This article discusses using holographic beamforming in 6G wireless communication antennas to create an intelligent and autonomous system for future 6G mobile communication. Traditionally, phased array systems have been preferred for 5G communication. These systems use arrays of antennas at both the transmitter and receiver and utilize constructive interference to focus the energy into a narrow beam, known as beamforming. There are various issues related to beamforming technologies, including complex circuit designs, high power requirements, and high costs [12],[13]. The present paper aims to discuss various aspects of beamforming technologies, including different types of beamforming, sub-types of beamforming, different waveforms, requirements, issues, and applications of beamforming technologies. Holographic beamforming has been found to be a successful approach over traditional beamforming technologies by utilizing holographically generated amplitude distributions across the apertures of the beamformer array. Holographic beamforming is different from traditional beamforming technologies, where multiple beams can be generated by holographic beamforming technologies without incorporating complex phase shift modules within each of the antennas of the beamformer array [14]. This is possible by utilizing different sub-array excitations that have different characteristics, enabling radiation beams from different directions

ATU-FJIECE, Volume: 05, Issue: 01, 03, 31, 2026, © 2020 FJIECE, All Rights Reserved

to pass through the large aperture array of beamformer technologies. The present paper aims to discuss the operational mechanism of holographic beamformer technologies, including its ability to optimize a complex field that is implemented across the beamformer array aperture. The advantages and limitations of holographic beamforming technology are explored, discussing how a conventional antenna can evolve into its beamforming system if it has sufficient independent and programmable transceivers. However, this approach requires a robust solution for the antenna's design and comes with added complexity and power consumption. Recent advances in electronics and materials, holographic beamforming antennas have become more applicable due to technological developments. The article presents a comparison of modern technologies in the fields of electronics and materials and different approaches to implementing holographic beamforming antennas.

2. EVOLUTION OF WIRELESS COMMUNICATION TECHNOLOGIES: FROM 1G TO 6G

The first wireless communication network generation appeared in 1980, and currently, there are five generations, and they appear every ten years [15],[16]. Table 1 lists the main aspects of the five generations of mobile technology, 1G to 5G. All the generations have succeeded in reducing latency, faster data transfer rates, and adding more frequency bands. The world is changing from wired to the wireless world (WWWW). So far, 1G was the first generation that introduced analog communication systems in 1980; 2G was the second generation that introduced digital worlds in 1990; 3G with the CDMA technique was introduced in 2000; and 4G and 4G LTE (long term evolution) were introduced in 2010 that offered IP-based services with higher data rates and multimedia facilities [8]. In the past five years, cellular networks have become substantially advanced; thus, the applications of data driven, for instance, multiplayer services, multimedia and high definition streaming media have been made possible. Consequently, the total number of mobile users and the volume of data traffic have increased exponentially [17].

Table 1. Important indicators of the 1G–5G mobile wireless communications evolution [10]

Specifications	1G	2G	3G	4G	5G
Period	1980-1990	1990-2000	2000-2010	2010-2020	2020-2030
Data rate	2.4 kbps	64 kbps	2 Mbps	100–1000 Mbps	≈ 20 Gbps
Bandwidth	150 kHz	5-20 MHz	25 MHz	100 MHz	1-2 GHz
Highest spectral efficiency	1 bps/ HZ	0.5 bps/ HZ	2.5 bps/Hz	15 bps/Hz	30 bps/Hz
Network mobility support	Up to 15 m/hr	Up to 50 km/hr	Up to 150 km/hr	Up to 350 km/hr	Up to 500 km/hr
Multiplexing	FDMA	TDMA,CDMA	CDMA	CDMA,OFDM	OFDM,BDMA
Main network	PSTN	PSTN	Packet	Internet	Internet
Switching	Circuit	Circuit, Packet	Packet	All Packet	All Packet
Features	Voice	Voice,SMS	Voice,data	Video	VoIP,ultra HD

As of January 2020, there were 7. 75 billion smartphone users, and each user consumes 10 GB of data on average annually. Because of the increasing number of record requests for streaming video, data traffic would be 82 GB per user per year, almost half of the global mobile data traffic[17].

Currently, the 5G network is increasingly becoming an actual reality. The 5G network can support radios for wireless local area network (LAN), personal area network (PAN), and wide area network (WAN) bands. 5G networks can accommodate the numerous data hungry applications, combine spectrum, and enable high definition (HD) video streaming. Thus, the 5G network can achieve the fastest throughput, exceeding LTE-A by more than 10 times its maximum data rate of approximately 20 Gb/s. Moreover, the advanced multiple access technique, namely, beam division multiple access (BDMA), can be applied in a 5G network to

ATU-FJIECE, Volume: 05, Issue: 01, 03, 31, 2026, © 2020 FJIECE, All Rights Reserved

increase the system capacity. Users can be assigned an orthogonal beam through this multiplexing based on their location [18]. Smart devices and mobile apps have been contributing to the growth of Internet of Everything (IoE) networks. IoE networks have categories like autonomous vehicles, drones, aircraft, healthcare, and intelligence systems that use data transmission with a very low latency time frame and short delay times. This type of IoE network will demand a spread out network of sensors and computing accuracy that might not be possible through only the 5G networks. Secondly, the kind of data rate that is capable of 5G networks is not to offer something that matches the exponential growth of data traffic in our digital sphere [19]. Although the experience with 6G is anticipated in a few years, significant research efforts will be required to meet the new, imminent problems of 6G's key performance factors [20].

Table 2. Comparison between 5G and 6G [19]

Characteristics	5G	6G
Operating frequency (GHz)	3 - 300	upto 1000
Peak data rate (Gbps)	20	1000
user experience rate (Mbps)	100	1000
Spectral efficiency (bps/Hz/m^2)	10	1000
Reliability (packet error rate)	10^{-5}	10^{-9}
Maximum mobility (km/h)	500	1000
Latency (msec)	1	<1
Connection density ($divices/km^2$)	10^6	10^7
Device Services	Secure connectivity	Physical interaction in real-time scenarios
Network Type	SDN, NFV, Slicing	SDN, NFV, Intelligent Cloud, AI-based Slicing,Deep learning
Technology	D2D communication, Ultra-dense Network, Relaying, Small cell access, NOMA	Visible Llight Communication, Quantum Communication, Hybrid access, Haptic technology
Application types	Reliable eMMB, URLLC, mMTC, Hybrid	MBRLLC, mURLLC, HCS, MPS

2.1. IMPORTANCE OF HOLOGRAPHIC BEAMFORMING ANTENNA IN 6G

Recent advancements in wireless technology have raised greater needs for stronger antenna systems in support of ever increasing capacities. Hardware component design with lower power requirements is a crucial requirement in setting up a smart information network all over the world [21]. What is foreseen as the sixth generation (6G) of wireless communications will offer revolutionary wireless mobile communication and high capacity data transfer solutions [22]. Even though an extensive use of phased arrays may increase network capacities through spatial diversity, there exist inherent obstacles within traditional phased arrays that prevent the setting of very demanding goals, as has been formulated for 6G networks. Especially, a powerfull requirement for power amplifiers and phase shifters in an extensive phased array prevents the design of appropriate beamforming circuits. The high power and high cost requirements of comprehensive phased arrays make them economically unfeasible at higher operating frequencies of massive MIMO systems, therefore posing a major obstacle to their advancements [23]. It is important to promptly devise more advanced antenna technologies in order to satisfy the escalating data requirements of the forthcoming 6G and subsequent wireless communication eras [24]. Fortunately, metamaterial has undergone rapid advancements due to their capability to programmable and adjustable nature, resulting in the establishment of a software-adaptable paradigm for antennas [25]. The recently created RHS, comprising numerous metamaterial radiation components, offers significant potential in

ATU-FJIECE, Volume: 05, Issue: 01, 03, 31, 2026, © 2020 FJIECE, All Rights Reserved

Al-Furat Journal of Innovations in Electronics and Computer Engineering (FJIECE)
ISSN -2708-3985

addressing the limitations of current antenna technologies [26]. The RHS has the capability to operate as a transmit/receive antenna that is seamlessly integrated with the transceiver in order to produce beams oriented in specific directions through the utilization of the holographic principle [11]. More precisely, the electromagnetic wave, referred to as the reference wave, which is generated by the RHS feed, travels across the metasurface and emits energy from the radiation elements due to the efficient configuration of the RHS, which is established on printed circuit board (PCB) technology. Relying on the holographic interference principle, the RHS employs a metamaterial to form a holographic pattern on its surface[27]. The holographic pattern captures the interference between the reference wave and the target object wave. Each element can adjust the amplitude of the reference wave electronically to generate directed beams based on the holographic pattern [28]. As a result, the system can provide dynamic beamforming without the need for complex phase shifting circuits or bulky mechanical moving hardware. This technique is known as holographic beamforming. The holographic antenna is a type of low-power planar structure that has gained recent attention due to the reduced cost of its manufacturing as well as the ability to perform multi-beam steering. Its design is based on the use of the meta-patch technique to form a hologram on the surface. This allows the recording of the interference between the object wave and the reference wave based on the interference principle. The hologram is then used to convert the reference signal to the required radiation pattern [29].

3. TECHNICAL FOUNDATIONS OF HOLOGRAPHIC ANTENNAS

The beamforming process is essentially a signal processing technique which aims to decrease the angular range by using precision guided antennas to send radio signals in certain directions [30]. Utilizing a Software Defined Antenna (SDA) with a low C-SWaP (Cost, Size, Weight, and Power) architecture, HBF is a novel technique that is substantially [8]. The RF signals from the radio travel to the rear of the antenna, scattering over its front and then altering in accordance with the beam shape and direction. This beamforming technique is based on the use of a hologram to achieve beam steering through the antenna [31], as shown in Figure 1.

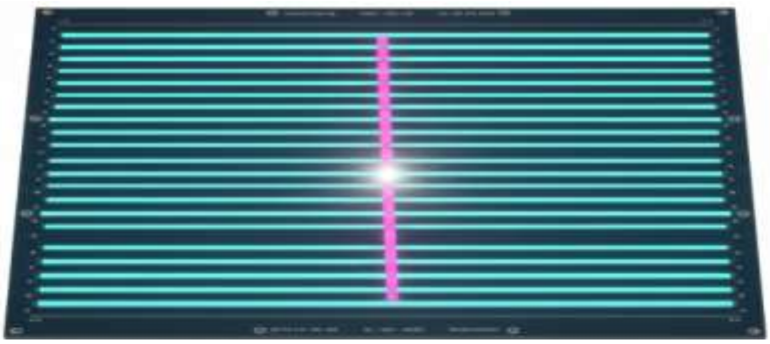

Fig. 1. HBF reference wave distribution network [32]

It generally consists of two steps, as illustrates in Figure 2. The holographic training is the first stage of the entire process. The holographic communication refers to the next stage. As illustrated in Figure 2, a signal from a radio frequency source is directed to a beam splitter. The beam splitter splits the signal into two waves. The first wave is directed to the reflecting object. This is the object wave. The reference wave is sent with other signals that do not reach the reflecting object. The reference wave is sent to a photographic plate. Depending on the signal received on the photographic plate, the reference wave is converted to the required beam for the reflecting object [4]. HBFA offers several advantages over conventional beamforming

ATU-FJIECE, Volume: 05, Issue: 01, 03, 31, 2026, © 2020 FJIECE, All Rights Reserved

methods. It creates focused energy beams with precision in specific directions, allowing for more efficient use of available bandwidth. It is suitable for a wide range of wireless systems as it dynamically generates and directs beams, unlike traditional antenna technologies. This feature helps in adapting to changing environmental conditions and also in operating at low power levels in order to save power and extend the life of batteries in wireless devices. However, the use of beam steering methods for the creation of a tightly focused directional energy beam may mitigate interference caused by neighboring wireless communications. Conformal holographic antennas, made thin and lightweight, can be easily embedded into different designs, such as wearables and IoT systems. Despite the great prospects that holographic beamforming and antennas (HBFA) as a newly emerging technology poses, there exist a number of challenges that need to be addressed before the technology can be implemented. These issues include the complexity of the said type of antenna compared to conventional technology, the need for sophisticated signal processing and control methods for creating and directing beams to desired directions of orientation, and the associated high costs because of the manufacturing and installation processes. Furthermore, the HBFA systems conceived are designed for short range communication and are limited by the bandwidth associated with the number of antenna elements and therefore the ability of these systems to support high data rates is restricted [33].

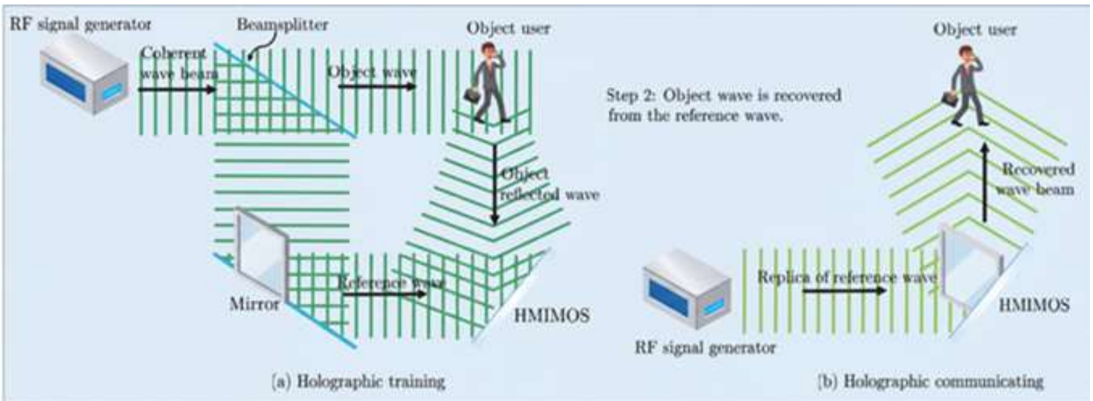

Fig. 2. The two general processes of holographic communication and training [4]

3.1. ELECTROMAGNETIC AND MATHEMATICAL MODEL OF HBF

In terms of the principles of electromagnetics, the notion of holographic beamforming may be defined as the controlled interaction of a guided reference wave with an object wave across a surface or metasurface. The holographic surface is designed in a manner that the launched reference wave is converted to a radiated beam with a specified orientation through a spatial impedance modulation.
a reference wave within the substrate is described as [34]:

$$E_{ref} = Ae^{-jBr} \qquad (1)$$

Where $r = \sqrt{x^2 + y^2}$, and A is the wave amplitude.

To shape transverse EM-mode space waves toward an arbitrary angle, the object wave is defined toward the desired direction [34]

$$E_{obj} = Be^{jk_0(xsin\theta_0 cos\emptyset_0 + ysin\theta_0 sin\emptyset_0)} \qquad (2)$$

ATU-FJIECE, Volume: 05, Issue: 01, 03, 31, 2026, © 2020 FJIECE, All Rights Reserved

47

Al-Furat Journal of Innovations in Electronics and Computer Engineering (FJIECE)
ISSN -2708-3985

where B is the amplitude of the object waves.

The hologram is formed by the interference between the reference and the object waves. In a physical holographic antenna, the interference between the reference and the object waves is manifested by a varying surface impedance or reactance. This is the physical mechanism by which the guided wave is converted into the desired beam.
The surface impedance distribution of holograms can be specified based on reference and object waves as [35]:

$$\eta_{sur} = jX_0\eta_0[1 + MRe\{E_{obj}E_{ref}^{*}\}] \qquad (3)$$

where X_0 and M are the normalized mean and modulation depth of surface reactance relative to the free-space impedance, respectively.

In accordance with aperture antenna theory, the far-field radiation pattern of the holographic aperture can be derived from the tangential aperture field via a Fourier transform relationship. Hence, the beam direction, beam width, and sidelobes are a function of the aperture field distribution [36].

$$E_{far}(r,\theta,\emptyset) \approx \frac{jk_0 e^{-jk_0 r}}{2\pi r}[F_\theta(\theta,\emptyset)\hat{\theta} + F_\emptyset(\theta,\emptyset)\hat{\emptyset} \qquad (4)$$

$$F_\theta(\theta,\emptyset) = \tilde{E}_{ax}cos\emptyset + \tilde{E}_{ay}sin\emptyset \qquad (5)$$

$$F_\emptyset(\theta,\emptyset) = cos\theta(-\tilde{E}_{ax}sin\emptyset + \tilde{E}_{ay}cos\emptyset) \qquad (6)$$

where $\tilde{E}_{ax}$ and $\tilde{E}_{ay}$, respectively, represent the spectrums of E_{ax} and E_{ay} and are defined as

$$\tilde{E}_{ax}(u,v) = \iint_{ap} E_{ax}(x',y')e^{jk_0(ux'+vy')}dx'dy' \qquad (7)$$

$$\tilde{E}_{ay}(u,v) = \iint_{ap} E_{ay}(x',y')e^{jk_0(ux'+vy')}dx'dy' \qquad (8)$$

with $u = sin\theta cos\phi, v = sin\theta sin\phi$ and k_0 as the free-space wavenumber.

The above description provides a clear theoretical rationale for the concept of holographic beamforming (HBF), as the connection between the interaction of the reference/object wave with the aforementioned processes of hologram formation, aperture field, and far-field beam synthesis is established. Accordingly, holographic beamforming can be viewed as a mechanism for the engineering of electromagnetic fields, which is controlled by the spatial modulation imposed on the aperture.

4. HOLOGRAPHIC, MIMO, AND PHASED ARRAY BEAMFORMING COMPARISON

ATU-FJIECE, Volume: 05, Issue: 01, 03, 31, 2026, © 2020 FJIECE, All Rights Reserved

MIMO, phased arrays, and HBF are some of the techniques used in electromagnetic devices to produce beams. Though these categories overlap, they all have their own features and serve different purposes.

1) Holographic Beamforming :

a) Architecture: HBF utilizes a software defined antenna (SDA) which has a unique architectural design that is significantly different from other phased arrays and MIMO solutions. HBF antennas, known as Passive Electronically Steered Antennas (PESAs), are different from traditional phase shifters, as they use the concept of holography in beamforming [13].

b) Cost and Complexity: Cost and complexity of the HBF technology are relatively low compared to the electronically scanned phased arrays (ESPA) technology. This technique uses a closely packed array of antennae, requiring a 2.5 to 3 times increase in the number of antennae, but the necessary controls are very cheap, making it an efficient alternative (as shown in Figure 3) [13].

c) Performance: Holographic Beamforming (HBF) also has the potential to deliver performance capabilities similar to conventional phased arrays, along with benefits of lower cost, compact design, lower weight, and lower power consumption (C-WaP). This helps promote scan angles up to ±80°, thus increasing flexibility with regard to coverage [13].Holographic Beamforming exhibits accurate.

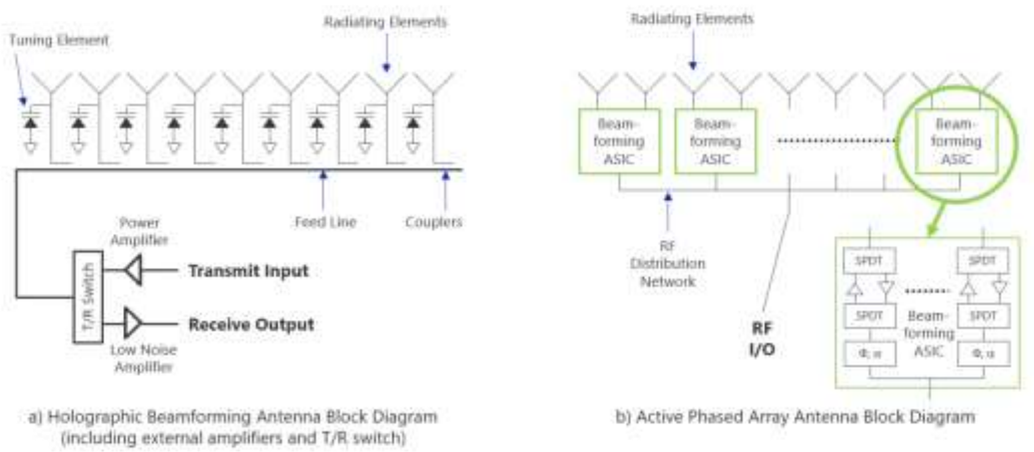

Fig. 3. The two standard procedures for holographic communication and training [13]

beamforming capabilities through the manipulation of signal amplitude and phase at each radiating element, enabling the formation and steering of the beam in two dimensions. This process is often compared to the creation of a hologram, hence the term Holographic Beamforming [37].

d) Power Efficiency: HBF antennas provide a better level of power efficiency by making use of an amplitude control approach to modulate data in interferograms. The control process of these elements is done relative to the phase of the wave of reference, which allows for efficient data transmission into space, thereby optimizing power utilization [32]. Compared to traditional phased arrays, which use multiple amplifiers to control various elements, HBF arrays provide a power

ATU-FJIECE, Volume: 05, Issue: 01, 03, 31, 2026, © 2020 FJIECE, All Rights Reserved

efficient approach to data transmission by using a single amplifier for sending and receiving data in their antennas [13].

2) Massive Multiple Input Multiple Output:

a) Architecture: Massive MIMO refers to the use of a high number of antennas at the BS to serve different users concurrently, aiming at improving the spatial resolution and beamforming optimization capabilities by using planar or three-dimensional arrays, as depicted in reference [13]. Accurate channel estimation depends on the availability of sufficient information about the channel, which requires advanced data processing. Modern beamforming procedures, such as Maximum Ratio Combination and Zero-Forcing, are utilized to ensure proper beam direction towards the target users, thus improving signal quality by preventing interference [38].

b) Cost and Complexity: It is important for designers to measure the cost effectiveness, since the cost increases with the increase of the number of radiating elements in massive MIMO systems, as well as adding complexity to design with increased power consumption owing to the array antenna. A large number of RF chains, with one RF chain required per radiator element array design, as explained in [39]. Signal processing play cirucial tasks to alleviate some complexity of beamforming [38].

c) Performance: Overall, the system performance, such as efficiency, speed and reliability, are increases in massive MIMO. This achievement in efficiency results from spatial multiplexing, where many users can access the same spectrum. This leads to an increase in system speed resulting from transmitting many data streams at the same time, an aspect that fares well in a highly populated area [40].

d) Power Efficiency: Due to narrow beams in massive MIMO techniques, the energy efficiency is increased drastically. With the benefit of beamforming, the power needed for signal transmission decreases as the number of antennas rises. However, despite the effective transmission of signals, total power usage persists at high levels due to the presence of multiple active RF chains and the intricate demands of signal processing [38].

3) Phased Array Beamforming:

a) Architecture: In a phased array or what knowns as an electronically scanned array, an array of antennas is used excited controlled through a computer to provide radio frequency beams in various directions without moving the physical location of the antennas. In the conventional phased array, RF source is responsible for providing the phase relationship to all other antennas, resulting in interference between beams generated by the individual antennas. This results in a desired beam direction, which can be modifiy the changing the phase relationship between the antenna elements. Phase shifters are used to electronicly control the phase relationship between different antenna elements [41]. Figure 4 illustrats how modifying the signal phase of in each antenna can steer the effective beam in the desired direction for a linear array. As a result, each antenna in the array has its own independent adjustments in phase and amplitude to produce the desired radiation pattern [42].

b) Cost and Complexity: Due to the requirement for numerous active components in each antenna element, such as amplifiers and phase shifters, phased array beamforming is considered more costly

ATU-FJIECE, Volume: 05, Issue: 01, 03, 31, 2026, © 2020 FJIECE, All Rights Reserved

Al-Furat Journal of Innovations in Electronics and Computer Engineering (FJIECE)
ISSN -2708-3985

and intricate [32]. Figure 5 shows a tiny 4 x 4 array with patch antennas as radiators. The most challenging designs lie at higher frequencies since the half wavelength spacing, reducing the size of each unit cell. Also, there is another aspect during the construction of the antenna, where numerous chalinging appears during the array design. These challenges encompass various aspects such as the arrangement of control lines, implementation of pulsed circuitry, conduct of power supply, thermal regulation, and environmental factors. The emphasis in the industry at present lies in the implementation of arrays with low profile, in other words, arrays with reduced volume and weight [42].

c) Performance: Phased-array antennas are known for their high gain and directive beam patterns, thus making them appropriate for applications that require strong beam concentration and significant signal intensities. Phased arrays often have a scan range of approximately ±60°, which can limit their coverage flexibility when compared to HBF[13].

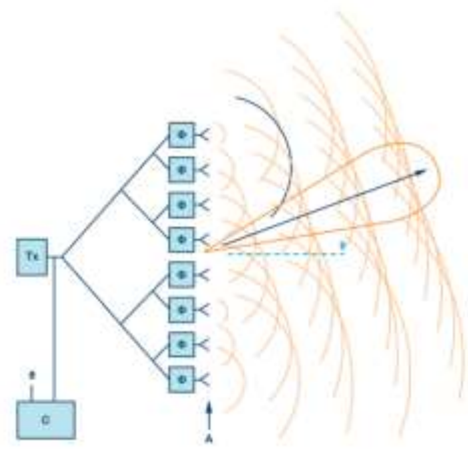

Fig. 4. Phased array elements diagram [42]

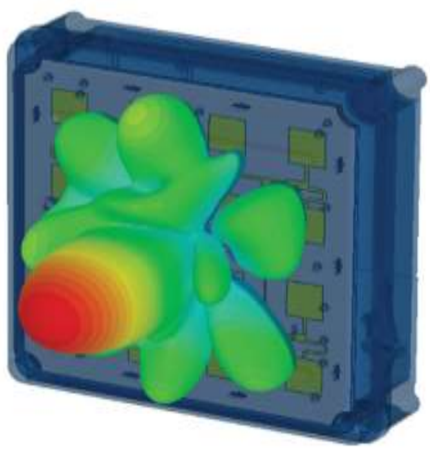

Fig. 5. 4 x 4 element array's radiation pattern [42].

To summarize the main differences among these technologies a comparative overview is presented in Table

ATU-FJIECE, Volume: 05, Issue: 01, 03, 31, 2026, © 2020 FJIECE, All Rights Reserved

Al-Furat Journal of Innovations in Electronics and Computer Engineering (FJIECE)
ISSN -2708-3985

3.

Table 3. Comparative Summary of Holographic Beamforming, Massive MIMO, and Phased-Array Beamforming

Metric	Holographic Beamforming	Phased Array Beamforming	Massive MIMO
RF architecture	Uses feed-line/tuning-element based control; does not require phase shifters in the same way as ESPA	Passive phased array can use a single RF source with phase shifters; active phased array uses one TR module per element	One RF chain per antenna element
Amplifier requirement	Typically one amplifier for transmission and one for reception	Requires many active devices including phase shifters/amplifiers/attenuators per array architecture	Large number of RF/baseband chains increases power use
Cost / power trend	Lower cost and energy consumption than ESPA	Higher cost, size, weight, and power consumption	Higher cost/complexity and power due to many RF chains
Beamforming mechanism	Holographic control of amplitude/phase through hologram/feed-line modulation	Electronic phase shifting across array elements	Digital/precoded multi-stream beamforming with many antennas
Hardware scaling issue	Promising low-CSWaP architecture	Challenging at high frequencies because of dense electronics and thermal/control routing	Very large arrays become difficult because spacing and RF-chain scaling increase size/complexity

5. HOLOGRAPHIC BASED ANTENNAS

5.1. HOLOGRAPHIC BASED LEAKY WAVE ANTENNAS

The inception of the leaky antenna prototype dates back to 1940, when Hansen introduced a longitudinal slot in one of the side walls of a rectangular waveguide [43]. The radiation patterns of LWAs exhibit scanning characteristics that are dependent on the frequency. Categorically, leaky wave antennas can be segmented into three main classes: periodic (slow-wave), uniform (fast-wave), and substrate integrated waveguide (SIW) or composite right/left-handed (CRLH) constructions [35]. Fast-wave antenna radiation works similarly to travelling wave radiation, where radiation travels constantly along the antenna [36]. Researchers are depending more and more on tunable materials to regulate the antenna beam. Ferroelectric, optoelectronic, temperature varying, and LC materials are examples of commonly tunable materials [44]. These substances function as the leaky wave antenna's transmission medium, and their properties allow for the control of the antenna beam's direction and range [45]. At present, LC materials are becoming more popular due to their ability to be utilized in millimeter waves and higher frequency bands. They are also increasingly being integrated with leaky wave antennas to accomplish fixed frequency beam scanning [46]. Antennas inspired by holography are a form of pseudoperiodic antennas. Essentially, a hologram is an interference pattern created by reference and object waves, containing embedded amplitude and phase information of the waves. The holographic approach may be applied to build various sorts of reflected or transmitting arrays and LWAs [36]. The surface wave (SW) is the most commonly utilized reference wave in the development of LWAs [47]. In Figure 6, you can see the complete structure of a leaky wave holographic antenna, which comprises pseudo periodic patches printed on the grounded dielectric [48]. The holographic LWA is represented by the calculated scatterer pattern on the substrate. By superimposing the phase lines of E_{ref} with the E_{obj} map on the supporting substrate, a phase line pattern is

ATU-FJIECE, Volume: 05, Issue: 01, 03, 31, 2026, © 2020 FJIECE, All Rights Reserved

generated. These phase lines can be captured by printing a series of metallic scatterers on the substrate, following the interferogram pattern [49].

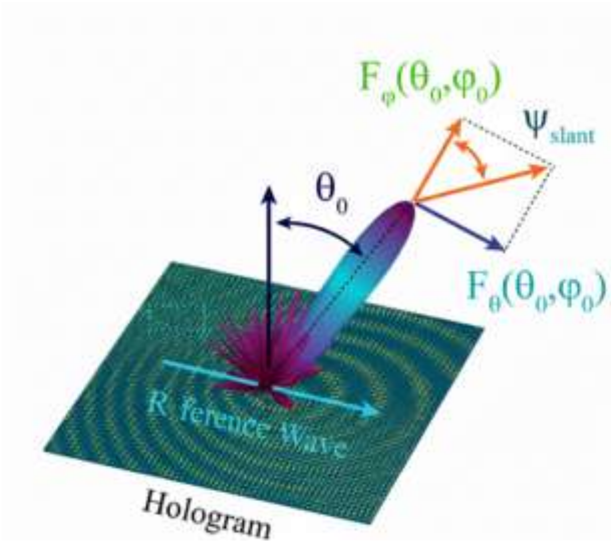

Fig. 6. Schematic representation of a leaky wave hologram with arbitrary polarization and a pencil beam directed at an angle $\theta = \theta_0$ [48]

The main mode of holographic LWAs, which includes grounded unit cells, is the TM mode [50]. Metal strips, Hertzian dipoles, and metasurfaces are options that have garnered attention, particularly the third option, due to its precise sampling, polarization control, and flexibility.Nevertheless, continuous metal strips remain to play a key role in the design of contemporary HLWA structures [51],[52]. In comparison to the other two options, the main advantage of continuous metal strips is related to the simplicity of the analytical process, and the performance, which is related to the achievable gain and directional accuracy, is comparable to, or even better than, metasurfaces and dipole scatterers [27].

5.2. HOLOGRAPHIC BASED REFLECTORS

The traditional methodology in designing an Electromagnetic (EM) reflector is based on geometrical optics, where the reflecting ray satisfies Snell's law. By manipulating the geometrical configuration of the reflecting body, it is possible to design such an EM system so that all reflecting rays converge at one point, thus producing a focal point. Another methodology is through an array of resonant elements, most commonly in the form of patch antennas, placed in an arrangement known as a reflectarray [53].In this case scenario, the desired phase distribution will be replicated on the reflective surface. The achievement of this result can be accomplished by adjusting the reactive loads on respective patches or by adjusting the geometric dimensions (rotation angle) of the elements [54]. Surface waves (SWs) have traditionally been used for the design of different electromagnetic (EM) devices such as leaky-wave antennas, electromagnetic band gaps, electromagnetic lenses, etc. In addition to this, recently, there was a renewed trend towards utilizing surface waves for artificial surfaces used for reflection. In other words, when a substrate sheet is subjected to a packet of waves, a surface wave will appear on its interface. The surface waves can then be sampled via interactions that are scattered. Constructive leakage can then occur towards the direction of interest via an arrangement of sub-wavelength elements on its structure, usually printed patches [55]. In this direction, it can be said that control of macroscopic electromagnetic properties on artificial surfaces, as

ATU-FJIECE, Volume: 05, Issue: 01, 03, 31, 2026, © 2020 FJIECE, All Rights Reserved

Al-Furat Journal of Innovations in Electronics and Computer Engineering (FJIECE)
ISSN -2708-3985

represented by the metasurface, is crucial to this area of science [56]. In the last few years, one of the most prominent trends observed was on holographic antennas. The reasons for this include miniaturization, weight reduction, cost-effectiveness, simplicity of design, as well as the potential to reap substantial benefits from its use [57]. Two prevalent categories of holographic antennas were identified, specifically the reflected and transmitted types. It is worth noting that both of these categories are afflicted by significant scattered wave losses [57],[58]. Space waves are produced and used as reference waves employing different antennas in holographic based reflect or transmit array antennas [35]. The radiation pattern's preferred direction experiences a null at the same time that the forward and backward modes propagate simultaneously. Researchers have used the strategy of establishing a 180º phase difference between neighbouring hologram surfaces or utilizing a reflector in the antenna structure to counteract this detrimental effect [58],[59]. By determining the position and magnitude of their surface distortions and then making the necessary corrections, reflector antennas may operate more efficiently. Because of their achievable accuracy and ease of implementation, microwave holographic techniques are finding wide usage as practical tools for completing this task. Using a reference antenna and an illuminating source, these techniques measure the complex (amplitude and phase) far-field (or Fresnelfield) pattern of the reflector antenna. Radio, satellite, or terrestrial sources could be this source. Next, to identify the surface distortion, the Fourier transform relationship between the distant field and a function associated with the induced current is used [55]. The details of previous research on antennas based on holography are presented in Table 4.

Table 4. Comprehensive analysis of antennas based on holography.

Ref.	Date	antenna type	frequency band(s)	key innovation	Main objective of research
[60]	2020	Flat-panel holographic metasurface antenna	X-band (10 GHz)	Phase-shifter-free holographic beamforming with integrated flat-panel feed	Develop holographic beamforming metasurface antenna for CubeSat platforms, Simplify hardware architecture and power consumption metrics for beam synthesis, and Achieve high-fidelity beam control with flat-panel system layout.
[49]	2020	Fully printed bidirectional holographic leaky-wave antenna (HLWA)	mmWave, 30 GHz (25.9-32.7 GHz)	Continuous metallic strips + Vivaldi SWL for wideband bidirectional frequency scanning	Design a wideband bidirectional holographic-based leaky wave antenna in mmW, and Investigate the frequency scanning property of the designed HLWA.
[4]	2020	HMIMOS / reconfigurable intelligent metasurface	mmWave to THz	Programmable holographic MIMO surface for smart 6G wave shaping and environment control	Investigate HMIMOS wireless communication technology for future 6G networks, and Highlight HMIMOS hardware, functionalities, applications, and potential challenges.
[61]	2021	Phased array telescope / low-frequency aperture array	50-350 MHz (tested at 149 MHz)	Self-reference holographic calibration without a separate reference antenna	Demonstrate holographic technique for phased array telescope calibration, and Measure complex aperture illumination pattern for SKA-Low prototype station.
[62]	2021	Large intelligent surface (LIS) / reconfigurable intelligent surface (RIS)	mmWave to THz	Holographic localization using intelligent surfaces by exploiting near-field EM phase/wavefront information	Envision holographic localization for future wireless positioning with intelligent surfaces, Address challenges and unsolved issues in holographic localization for 6G networks, and Explore joint communication and localization design for diverse applications in 6G.
[63]	2021	Holographic reconfigurable intelligent surface (RIS) /	THz band	Holographic RIS beam-pattern modeling with closed-loop dual-sparsity channel	Analyze holographic RISs for THz massive MIMO systems, Derive beam pattern of holographic RIS, and propose beamforming designs.

ATU-FJIECE, Volume: 05, Issue: 01, 03, 31, 2026, © 2020 FJIECE, All Rights Reserved

		ultra-dense RIS		estimation for THz massive MIMO	
[29]	2021	Reconfigurable holographic surface (RHS)	10 GHz	Amplitude-controlled holographic beamforming for multi-user communications without phase shifters	Develop RHS for multibeam steering with low power consumption, and Propose amplitude-controlled algorithm for sum rate maximization in communication systems
[35]	2021	Axially-modulated conformal leaky-wave holographic antenna	18 GHz	Variable modulation index for sidelobe-level reduction	Decrease the sidelobe level of conformal LWAs using holographic techniques, and Modify holographic relation with variable modulation index for antenna performance enhancement.
[34]	2021	Holographic-based leaky-wave structures (1D/2D LWA)	Microwave to terahertz	Comprehensive tutorial/design framework with technical comparison of metal-strip, dipole-scatterer, and metasurface implementations	Investigate holographic-based leaky-wave structures for advanced electromagnetic applications, Explore methods for controlling polarization using scalar impedance , and design holographic structures for multiple beams and radar-cross-section impedance surfaces
[53]	2022	Holographic-based metasurface reflector	Sub-6 GHz, 3.5 GHz	Systematic dispersion-based design for dual-beam holographic reflector	Develop a method for regulating artificial impedance surface response effectively, and propose a practical approach to manipulate surface waves for reflector design.
[7]	2022	Reconfigurable holographic surface (RHS) / metamaterial antenna	Not specified	Amplitude-controlled holographic beamforming for integrated sensing and communication (ISAC)	Propose holographic beamforming for integrated sensing and communication optimization,and Advance ISAC system with a BS, radar targets, and communication users.
[8]	2022	Software-defined antenna (SDA) / passive electronically steered holographic beamforming antenna	mmWave	Hologram-based beam steering with low C-SWaP and without discrete phase shifters	Introduce Holographic Beamforming for high-speed network in 5G communication, and Discuss dynamic beamforming technique using Software Defined Antenna (SDA).
[64]	2022	3D-printed hollow rectangular waveguide-fed holographic beamforming antenna	10-10.5 GHz	Additive manufacturing of a holographic slot-waveguide antenna using conductive polymer with copper electroplating	Design and fabricate 3D printed holographic beamforming antennas for RF systems, Explore 3D printing for metasurface antennas to enable rapid prototyping, demonstrate the design of holographic beamforming antennas operating near 10 GHz, and investigate the application of 3D printing for complex electromagnetic structures.
[65]	2022	Graphene holographic impedance surface antenna	THz band	DC-bias tunable graphene patches for reconfigurable beam scanning, polarization control, and conformal operation	Design tunable THz graphene holographic antennas for wireless communication applications, and Explore graphene's conductivity manipulation for reconfigurable and conformal antenna designs.
[66]	2022	Holographic transmitarray antenna	12 GHz	Reactance/susceptance-based holographic transmitarray design	Design holographic transmitarrays based on susceptance distribution for X-band antennas, Present single and dual linearly polarized pencil

ATU-FJIECE, Volume: 05, Issue: 01, 03, 31, 2026, © 2020 FJIECE, All Rights Reserved

		(linearly polarized)		for single- and multi-beam radiation without optimization algorithms	beams at X-band, achieve high gain bandwidth and aperture efficiency in antenna design, improve radiation efficiency using subwavelength elements with holographic technique, and validate holographic TA design process with simulations and measurements.
[37]	2023	Reconfigurable holographic surface (RHS) / metasurface-based antenna	12 GHz	Amplitude-controlled holographic beamforming with series-fed tunable metamaterial elements	Investigate RHS-enabled holographic radio for 6G communications,and verify RHS potential for ultra-massive MIMO and wireless SLAM.
[67]	2023	Stacked intelligent metasurfaces (SIM) / HMIMO transceiver	28 GHz	Multi-layer metasurface wave-domain precoding/combining with reduced RF chains	Implement HMIMO communications using Stacked Intelligent Metasurfaces for spatial gains, and Optimize channel fitting and capacity scaling laws for SIM-assisted HMIMO.
[68]	2023	Reconfigurable holographic surface (RHS) / metasurface-based antenna	12 GHz	Practical low-power amplitude-controlled holographic beamforming with prototype implementation	Investigate RHS-enabled holographic radio for 6G networks, Develop holographic beamforming optimization algorithm for beampattern gain maximization, and Study hardware design of RHS elements with controllable radiation amplitudes.
[69]	2023	Holographic MIMO (HMIMO) with holographic grid array (HGA) / RHS grids	28 GHz	AI-based integrated sensing, localization, and communication using VAE + GRU for dense-location-based holographic beamforming and power allocation	Propose AI framework for holographic MIMO-enabled wireless network optimization, and Develop integrated sensing, localization, and communication framework utilizing artificial intelligence.
[70]	2023	Reconfigurable holographic surface (RHS) / planar metamaterial antenna	12 GHz	Low-power holographic ISAC using amplitude-tunable RHS without phase shifters, validated by hardware prototype	Introduce holographic ISAC with reconfigurable holographic surfaces for low power consumption, Propose a holographic beamforming scheme for ISAC with high directive gain, and Discuss future research directions and key challenges related to holographic ISAC.
[71]	2023	Reconfigurable holographic surface (RHS) / metamaterial-based antenna	20 GHz	Holographic beamforming for LEO satellites with minimum-element analysis versus phased arrays	Analyze minimum RHS elements for sum rate exceeding PA, and Develop holographic beamforming algorithm for real-domain amplitude constraints.
[36]	2023	Conformal leaky-wave holographic antenna (CLWA)	10 GHz	Flat-topped beam synthesis using AFE + holographic principle + transformation optics (TO)	Develop a beam shaping method for CLWAs using optimization techniques, and Synthesize a flat-topped pattern in single-curvature conformal leaky-wave antennas.
[72]	2023	Holographic surface / lossless dense antenna array	Not specified	Mutual-coupling-aware beamforming analysis for densely packed holographic surfaces	Quantify mutual coupling in holographic surfaces for beamforming enhancement, Develop a general model for mutual coupling in lossless antenna arrays, and Optimize beamforming design by considering mutual coupling among radiating elements.
[44]	2023	Liquid-crystal-based	34.7 GHz	First SIW-ML + LC-etched CSRR design	Propose LC-based ML antenna unit for improved beam-scanning performance,and

ATU-FJIECE, Volume: 05, Issue: 01, 03, 31, 2026, © 2020 FJIECE, All Rights Reserved

		holographic metasurface leaky-wave antenna		for fixed-frequency beam scanning	Combine LC materials, discrete weighting, and multibeam theory for innovation.
[73]	2023	Reconfigurable holographic surface (RHS)-enabled radar / dual Tx-Rx RHSs	30 GHz	Joint waveform and amplitude optimization for multi-target detection using amplitude-controlled RHSs	Investigate multi-target detection using reconfigurable holographic surfaces (RHSs), and Develop a radar system for adaptive multi-target detection with RHSs.
[5]	2024	HMIMO surface / nearly continuous reconfigurable metasurface aperture	mmWave, THz, and visible-light bands	HMIMO framework covering physical design, EM-domain theory, channel modeling, and beamforming	Present comprehensive overview of HMIMO communications paradigm, and Address fundamental limits and technical challenges in HMIMO technology.
[57]	2024	Planar holographic metasurface leaky-wave multi-beam antenna	28 GHz	Tensor-free multi-beam design with tailorable gain, phase, and polarization using a single source and no hologram partitioning	Design holographic leaky-wave antennas with tailorable beams and polarization control, Achieve multiple beams at the same frequency without partitioning hologram and Validate designs through simulations and measurements on fabricated prototypes.
[74]	2024	Holographic MIMO with holographic uniform planar array (UPA)	Not specified	Near-field holographic ISAC framework with spherical-wave modeling and closed-form performance analysis	Propose near-field ISAC framework for enhanced sensing and communications performance, and Analyze downlink and uplink scenarios with spatially correlated Rayleigh fading.
[75]	2024	Holographic MIMO with a uniform linear array of closely spaced half-wavelength dipoles	3.5 GHz	Multiport-theory-based physically consistent analysis of mutual coupling and uplink/downlink duality in Holographic MIMO	Derive consistent uplink/downlink models for multi-user Holographic MIMO communications, and Investigate spectral efficiency advantages of closely spaced antennas in MIMO systems.
[76]	2024	HMIMO-enabled base station with holographic grid array (HGA) / reconfigurable holographic surface (RHS)	28 GHz	AI-based cell-free HMIMO-ISAC using VAE sensing + Transformer power allocation through grid activation	Propose AI-based HMIMO-empowered CF network with ISAC for power allocation,and Maximize sensing utility function for energy efficiency and cross-correlation.
[77]	2024	3D holographic antenna array / superdirective holographic array	1.6 GHz	Electromagnetic hybrid beamforming (EHB) combining analog excitation-current control and digital precoding for programmable superdirective beams with mutual-coupling awareness	Propose an EHB scheme for holographic communications with superdirective beamforming gain, investigate electromagnetic channel model and beamforming algorithms to enhance spectral efficiency, and Attain programmable spatial patterns and flat beamforming gain for multiple beams.

ATU-FJIECE, Volume: 05, Issue: 01, 03, 31, 2026, © 2020 FJIECE, All Rights Reserved

[78]	2024	Beamforming microstrip patch antenna array	24-61.5 GHz	Comprehensive review and comparison of analog, digital, hybrid, and switched beamforming techniques for 5G/6G microstrip patch arrays	Analyze beamforming techniques for 5G/6G networks, and compare various beamforming methods for wireless communication systems.
[50]	2024	Metal-only SSPP holographic leaky-wave antenna	18 GHz	Dielectric-free metal-only holographic LWA based on spoof surface plasmon polaritons (SSPP) for beam scanning	Develop a metal-only holographic leaky-wave antenna with high efficiency, and utilize SSPP structures for antenna design with linear polarization.
[79]	2025	Holographic metasurface antenna (HMA)	24 GHz	PCB-fabricated metasurface for dynamic beam steering with reduced sidelobes	Design, fabricate, and validate a high-gain HMA for high-frequency applications
[80]	2025	Reconfigurable multibeam holographic antenna based on liquid-crystal technology	36 GHz	LC-based single-source independent multibeam control	Low-power multibeam steering for LEO satellite applications
[81]	2025	Space-time holographic metasurface antenna (HMA)	24.5 GHz	Spatiotemporal heterodyne holography for full amplitude–phase–frequency reconstruction	Multifrequency beamforming and 2D/3D holographic imaging using a single programmable metasurface
[82]	2025	Optically transparent holographic display antenna (HDA)	27.5–28.35 GHz	Transparent holographic metasurface with 1×4 SWLA and lossless bonding-free component-separated structure for beam steering	High-gain beam-steerable display antenna for 5G smartphones with reduced beam distortion
[83]	2025	quasi-HLWA	22–32 GHz	3D-printed 2D beamforming using a Rotman lens + quasi-HLWA with a 25° tapered transition	Realize a passive 2D-scanning antenna with azimuth frequency scanning and elevation port-switching beam steering

6. APPLICATIONS OF HOLOGRAPHIC ANTENNA IN 6G

To enable a smart networking system for the upcoming sixth generation (6G) wireless networks, new methods are required to offer reduced power usage, more cost effective devices, and enhanced device integration to guarantee extensive connectivity and high data rates [69],[76]. Massive multiple input multiple output (mMIMO) technology has the potential to support a significant number of antennas, offering spatial diversity. However, its capability to control phased arrays is limited, and it cannot meet the requirements of the 6G network [76]. As a result, new approaches are needed to deliver enhanced services, including power savings, energy efficiency, and extensive connectivity, to meet the increasing demand for

ATU-FJIECE, Volume: 05, Issue: 01, 03, 31, 2026, © 2020 FJIECE, All Rights Reserved

Al-Furat Journal of Innovations in Electronics and Computer Engineering (FJIECE)
ISSN -2708-3985

multimedia applications and data services [63]. The concept of holographic MIMO (HMIMO) is an innovative solution that effectively enables an energy efficient intelligent networking system [56]. Holographic multiple input multiple output (HMIMO) communications offer a revolutionary method for manipulating the electromagnetic (EM) field with unparalleled flexibility, showing great promise for enhancing next generation wireless networks [5],[84]. HMIMO schemes are based on transceiver apertures that are spatially continuous and have an almost infinite number of antennas with very small element spacing. A practical way to implement HMIMO schemes is to use intelligent metasurfaces made from advanced metamaterials and micro electromechanical systems [14]. To provide more insight into the HMIMO concept and its potential for 6G, we can describe HMIMO communications as accurately reconstructing three-dimensional (3D) target scenes using communication ends equipped with holographic type radios and EM-domain signal processing. At the same time, the aim is to enable three-dimensional dynamic wireless interactions between humans, objects, and their surroundings. Holographic Massive MIMO (HMIMO) communication can be achieved by using HMIMO surfaces, which enable the control of electromagnetic waves [5]. In terms of the anticipated changes within the broader framework of the paradigm shift, we foresee a broad range of possible application scenarios for HMIMO in the new 6G networks, as shown in Figure 7. The proposed vision for the new wireless communication network spans different domains, including space, air, land, and sea. This communication network would cover different HMIMO deployment topologies, in which the HMIMO technology acts as active transceivers as well as passive reflectors.

Fig. 7. Possibility of future communication using holographic technology, enabled by HMIMO surfaces [5]

In different situations, these case scenarios could be implemented in smart cities, mountainous areas, forests, desert areas, as well as sea environments. For example, in outdoor communication systems for smart cities, HMIMO surfaces could be placed on building walls as base stations (BSs) and passive relays for data transfer and User Equipment (UE) location detection in offices, residential areas, institutions, and industries [85],[86]. In addition, these surfaces could also be used as tools for providing satellite communications systems. As such, the multi-use capabilities of HMIMO offer tremendous opportunities for the transformation of wireless communications in challenging and demanding environments [5].

The overall wireless network, as shown in Figure 7, consists of holographic MIMO surfaces placed at appropriate locations on different platforms, such as satellite solar panels, aircraft bodies/wings, airships, and aerial vehicles. These surfaces not only promote better communication and sensing but also achieve

ATU-FJIECE, Volume: 05, Issue: 01, 03, 31, 2026, © 2020 FJIECE, All Rights Reserved

cost and power savings. Satellite systems with HMIMO technology can also be used as a means to monitor distant areas and control desertification. In addition, there is potential for better physical layer security from HMIMO technology [87],[88].

In addition to these theoretical analyses, a number of experimental implementations for holographic beamforming systems based on holographic technology and metasurfaces have been presented in the literature, which confirm the practical viability of holographic technology for wireless communication systems. For instance, a number of prototypes for metasurface antennas consisting of a number of sub-wavelength elements have been experimentally implemented for enabling beam steering capabilities along with high-gain radiation patterns for millimeter-wave bands, which confirm the capabilities of holographic beamforming technology for manipulating electromagnetic waves with high accuracy levels [14]. In addition, the practical implementation of holographic MIMO wireless communication systems has also been explored by means of experimental testbeds for wireless communications in the microwave band, where high data rates along with significant enhancement in signals for extended transmission distances have been achieved for wireless communications in real-time [5]. Moreover, a number of prototypes for holographic radio systems based on holographic technology have also been implemented for confirming the capabilities of holographic technology for point-to-point wireless communications, where both transmission and reception beam patterns have been experimentally implemented for holographic radio systems [29]. Therefore, from these experimentally implemented holographic beamforming systems, it is clear that holographic technology is not a mere theoretical technology but has the capabilities for being implemented for future wireless communication systems, including the prospective 6th generation wireless networks.

7. CONCLUSION AND OUTLOOK

The review article discusses the most recent developments in holographic beamforming antennas that are utilized in wireless communication networks, as well as in 6G technology. One of the major benefits of holographic beamforming technology, as well as that utilized in these wireless communication networks, lies in the ability of holographic antennas to improve data transfer rates, beamsteering resolution, and spectrum efficiency. The ability of holographic antennas to control electromagnetic waves makes it an integral part of future wireless communication technologies, including 6G, as it can be utilized in various contexts, including smart city technologies as well as satellite communication technologies.

To provide a clearer roadmap for future work, the main open challenges and research directions are summarized below.

1) Technological challenges: One key aim is the realization of holographic antenna systems that can be seamlessly integrated into existing or future wireless systems without requiring significant hardware complexity. Some key challenges include channel estimation, calibration, mutual coupling, synchronization, and efficient control for large continuous or quasi-continuous apertures. Some promising directions include channel estimation using model-driven methods, calibration using adaptation mechanisms, efficient control systems, and hardware-software co-design for holographic antenna systems.

2) Advanced materials: Further progress in this direction depends on the availability of tunable materials with low losses, wide bandwidth, phase control, and reliable long-term performance. Although materials like liquid crystals, graphene, and metamaterials are still promising in this direction, their implementation is still dependent on factors like manufacturability, environmental robustness, biasing complexity, and cost. Hence, in the coming years, more attention must be given to low-loss tunable materials, design with

ATU-FJIECE, Volume: 05, Issue: 01, 03, 31, 2026, © 2020 FJIECE, All Rights Reserved

manufacturing in mind, and experimental verification of prototypes with balanced performance and implementation complexity.

3) Artificial intelligence algorithms: Real-time beam steering, tracking of users, and allocation of resources can be made possible by artificial intelligence. However, for the practical implementation of beamforming, especially for massive antenna arrays, certain challenges need to be considered. Some of the challenges are related to latency, scalability, computational complexity, robustness, and interpretability. Some promising directions for addressing the challenges are related to lightweight learning models, physics-informed artificial intelligence, adaptation mechanisms, and joint optimization of beamforming and network resources.

4) Integration with 6G Networks: The major challenge is related to the smooth integration of holographic beamforming antennas into the overall framework of 6G technology, including massive MIMO technology, reconfigurable intelligent surfaces, integrated sensing and communication, cell-free technology, and space-air-ground-sea networks. This is mainly due to various issues related to channel modeling, signaling, protocol differences, and cross-layer requirements. In this regard, future work should focus on developing integrated system architectures, effective signaling protocols, and cross-layer optimization approaches for effective integration of this technology into future systems.

5) Security and Privacy: This technology allows for highly directive and adaptive transmissions, thus extending security concerns beyond traditional encryption techniques. Some of the open issues include security in the physical layer, secure control of programmable surfaces, robustness in the face of adversarial manipulations, as well as privacy concerns in localization and sensing. Some of the possible remedies include joint beamforming and secrecy, privacy-aware learning, as well as quantum-resistant security for 6G environments.

6) Applications and Use Cases: The potential exists for holographic antennas to be utilized in various application scenarios such as telemedicine, augmented reality, industrial internet of things, and autonomous vehicle systems. The application scenarios need further investigation in future studies. The implementation of this technology in various sectors will depend upon its scalability.

In conclusion, it is safe to say that the future of 6G wireless communications holds a great deal of promise concerning the development and application of holographic beamforming antennas; however, it is necessary to continue to conduct Research and Development to overcome the current limitations and potential disadvantages to this type of technology to unlock its potential and its associated solutions to ensure the future of reliable and secure 6G communications systems.

REFERENCES

[1] Haque, M. A., Ahmad, S., Abboud, A. J., Hossain, M. A., Kumar, K., Haque, S., Sonal, D., Rahman, M., Marisennayya, S., 6G wireless communication networks: Challenges and potential solution, *International Journal of Business Data Communications and Networking (IJBDCN)*, 19, 1, 2024.

[2] Charu, M., Kumar, A., Upadhyay, A., Chauhan, P., A 6G network: Future of nations? Challenges in 6G communications, *Tuijin Jishu/Journal of Propulsion Technology*, 44, 2023, 2023.

[3] Zhu, F., Wang, X., Huang, C., Alhammadi, A., Chen, H., Zhang, Z., Yuen, C., Debbah, M., Beamforming inferring by conditional WGAN-GP for holographic antenna arrays, *IEEE Wireless Communications Letters*, 13, 2023, 2024.

ATU-FJIECE, Volume: 05, Issue: 01, 03, 31, 2026, © 2020 FJIECE, All Rights Reserved

[4] Huang, C., Hu, S., Alexandropoulos, G. C., Zappone, A., Yuen, C., Zhang, R., Di Renzo, M., Debbah, M., Holographic MIMO surfaces for 6G wireless networks: Opportunities, challenges, and trends, *IEEE Wireless Communications*, 27, 118, 2020.

[5] Gong, T., Gavriilidis, P., Ji, R., Huang, C., Alexandropoulos, G. C., Wei, L., Zhang, Z., Debbah, M., Poor, H. V., Yuen, C., Holographic MIMO communications: Theoretical foundations, enabling technologies, and future directions, *IEEE Communications Surveys & Tutorials*, 26, 196, 2023.

[6] Huo, Y., Dong, X., Ferdinand, N., Distributed reconfigurable intelligent surfaces for energy-efficient indoor terahertz wireless communications, *IEEE Internet of Things Journal*, 10, 2728, 2022.

[7] Zhang, H., Zhang, H., Di, B., Di Renzo, M., Han, Z., Poor, H. V., Song, L., Holographic integrated sensing and communication, *IEEE Journal on Selected Areas in Communications*, 40, 2114, 2022.

[8] Borse, I., Patil, H., Holographic Beamforming for High-Speed Network in 5G Communication, *International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies*, 13, 1, 2022.

[9] Pant, R., Malviya, L., THz antennas design, developments, challenges, and applications: A review, *International Journal of Communication Systems*, 36, e5474, 2023.

[10] Jiang, W., Zhou, Q., He, J., Habibi, M. A., Melnyk, S., El-Absi, M., Han, B. et al., Terahertz communications and sensing for 6G and beyond: A comprehensive review, *IEEE Communications Surveys & Tutorials*, 26, 2326, 2024.

[11] Di, B., Reconfigurable holographic metasurface aided wideband OFDM communications against beam squint, *IEEE Transactions on Vehicular Technology*, 70, 5099, 2021.

[12] Brilhante, D. S., Manjarres, J. C., Moreira, R., Veiga, L. O., Rezende, J. F., Müller, F., Klautau, A., Mendes, L. L., Figueiredo, F. A. P., A literature survey on AI-aided beamforming and beam management for 5G and 6G systems, *Sensors*, 23, 4359, 2023.

[13] Staff, P., *Holographic beam forming and phased arrays*, Pivotal Commware, Inc., Kirkland, WA, USA, 68-73, 2019.

[14] An, J., Yuen, C., Huang, C., Debbah, M., Poor, H. V., Hanzo, L., A tutorial on holographic MIMO communications—Part III: Open opportunities and challenges, *IEEE Communications Letters*, 27, 1674, 2023.

[15] del Peral-Rosado, J. A., Raulefs, R., López-Salcedo, J. A., Seco-Granados, G., Survey of cellular mobile radio localization methods: From 1G to 5G, *IEEE Communications Surveys & Tutorials*, 20, 1124, 2017.

[16] Onoe, S., 1.3 Evolution of 5G mobile technology toward 1 2020 and beyond, *2016 IEEE International Solid-State Circuits Conference (ISSCC)*, 23, 2016.

[17] Solyman, A. A., Yahya, H. A. L. I. T., Evolution of wireless communication networks: from 1G to 6G and future perspective, *International Journal of Electrical and Computer Engineering*, 12, 2022.

[18] Wang, C.-X., Haider, F., Gao, X., You, X.-H., Yang, Y., Yuan, D., Aggoune, H. M., Haas, H., Fletcher, S., Hepsaydir, E., Cellular architecture and key technologies for 5G wireless communication networks, *IEEE Communications Magazine*, 52, 122, 2014.

[19] Alsabah, M., Naser, M. A., Mahmmod, B. M., Abdulhussain, S. H., Eissa, M. R., Al-Baidhani, A., Noordin, N. K., Sait, S. M., Al-Utaibi, K. A., Hashim, F., 6G wireless communications networks: A comprehensive survey, *IEEE Access*, 9, 148191, 2021.

[20] Asghar, M. Z., Memon, S. A., Hämäläinen, J., Evolution of wireless communication to 6G: Potential applications and research directions, *Sustainability*, 14, 6356, 2022.

[21] Zhang, S., Liu, J., Guo, H., Qi, M., Kato, N., Envisioning device-to-device communications in 6G, *IEEE Network*, 34, 86, 2020.

[22] Zhang, S., Zhang, H., Di, B., Song, L., Cellular UAV-to-X communications: Design and optimization for multi-UAV networks, *IEEE Transactions on Wireless Communications*, 18, 1346, 2019.

ATU-FJIECE, Volume: 05, Issue: 01, 03, 31, 2026, © 2020 FJIECE, All Rights Reserved

Al-Furat Journal of Innovations in Electronics and Computer Engineering (FJIECE)
ISSN -2708-3985

[23] Wang, D., Zhang, Y., Wei, H., You, X., Gao, X., Wang, J., An overview of transmission theory and techniques of large-scale antenna systems for 5G wireless communications, *Science China Information Sciences*, 59, 081301, 2016.
[24] Di, B., Zhang, H., Song, L., Li, Y., Han, Z., Poor, H. V., Hybrid beamforming for reconfigurable intelligent surface based multi-user communications: Achievable rates with limited discrete phase shifts, *IEEE Journal on Selected Areas in Communications*, 38, 1809, 2020.
[25] Guo, Y., Qin, Z., Liu, Y., Al-Dhahir, N., Intelligent reflecting surface aided multiple access over fading channels, *IEEE Transactions on Communications*, 69, 2015, 2020.
[26] Sleasman, T., Imani, M. F., Xu, W., Hunt, J., Driscoll, T., Reynolds, M. S., Smith, D. R., Waveguide-fed tunable metamaterial element for dynamic apertures, *IEEE Antennas and Wireless Propagation Letters*, 15,
[27] Fong, B. H., Colburn, J. S., Ottusch, J. J., Visher, J. L., Sievenpiper, D. F., Scalar and tensor holographic artificial impedance surfaces, *IEEE Transactions on Antennas and Propagation*, 58, 3212, 2010.
[28] Smith, D. R., Yurduseven, O., Mancera, L. P., Bowen, P., Kundtz, N. B., Analysis of a waveguide-fed metasurface antenna, *Physical Review Applied*, 8, 054048, 2017.
[29] eng, R., Di, B., Zhang, H., Tan, Y., Song, L., Reconfigurable holographic surface: Holographic beamforming for metasurface-aided wireless communications, *IEEE Transactions on Vehicular Technology*, 70, 6255, 2021.
[30] Qadir, Z., Le, K. N., Saeed, N., Munawar, H. S., Towards 6G Internet of Things: Recent advances, use cases, and open challenges, *ICT Express*, 9, 296, 2023.
[31] Elmeadawy, S., Shubair, R. M., Enabling technologies for 6G future wireless communications: Opportunities and challenges, *arXiv preprint arXiv:2002.06068*, 2020.
[32] Black, E. J., Holographic beam forming and MIMO, *Pivotal Commware*, 12, 1, 2017.
[33] https://www.rfwireless-world.com/Terminology/Advantages-and-disadvantages-of-Holographic-beamforming-antenna.html.
[34] Araghi, A., Khalily, M., Xiao, P., Tafazolli, R., Holographic-based leaky-wave structures: Transformation of guided waves to leaky waves, *IEEE Microwave Magazine*, 22, 49, 2021.
[35] Chaychi Zadeh, M. A., Komjani, N., Improved performance of an axially-modulated conformal leaky-wave holographic antenna through using variable modulation index, *Journal of Electromagnetic Waves and Applications*, 35, 2020, 2021.
[36] Zadeh, M. A. C., Komjani, N., Flat-topped radiation pattern synthesis of a conformal leaky-wave holographic antenna, *IEEE Transactions on Antennas and Propagation*, 71, 4045, 2023.
[37] Deng, R., Zhang, Y., Zhang, H., Di, B., Zhang, H., Song, L., Reconfigurable holographic surface: A new paradigm to implement holographic radio, *IEEE Vehicular Technology Magazine*, 18, 20, 2023.
[38] An, J., Yuen, C., Huang, C., Debbah, M., Poor, H. V., Hanzo, L., A tutorial on holographic MIMO communications—Part I: Channel modeling and channel estimation, *IEEE Communications Letters*, 27, 1664, 2023.
[39] Yoo, I., Smith, D. R., Holographic metasurface antennas for uplink massive MIMO systems, *arXiv preprint arXiv:2108.12513*, 2021.
[40] Taruna, S., Kaur, I., Performance analysis of MIMO for various antenna configurations, *2013 International Conference on Green Computing, Communication and Conservation of Energy (ICGCE)*, 90, 2013.
[41] Bharadwaj, P. M., Kathavathe, A. R., Hegde, R., Kumar, S., MIMO versus phased array antenna systems for 5G mobile communication systems, *Perspectives in Communication, Embedded-systems and Signal-processing-PiCES*, 4, 64, 2020.
[42] Benson, K., Phased array beamforming ICs simplify antenna design, *Analog Dialogue*, 53, 10, 2019.

ATU-FJIECE, Volume: 05, Issue: 01, 03, 31, 2026, © 2020 FJIECE, All Rights Reserved

[43] Choi, J. H., Itoh, T., Beam-Scanning Leaky-Wave Antennas, in Chen, Z., Liu, D., Nakano, H., Qing, X., Zwick, T. (eds), *Handbook of Antenna Technologies*, Springer, Singapore, 2016.
[44] Hou, S., Fang, S., Wang, Y. et al., A Ka-band Holographic Metasurface Leaky-wave Antenna Based on Liquid Crystal, *Research Square*, 2023.
[45] Damm, C., Maasch, M., Gonzalo, R., Jakoby, R., Tunable composite right/left-handed leaky wave antenna based on a rectangular waveguide using liquid crystals, *2010 IEEE MTT-S International Microwave Symposium*, 13, 2010.
[46] Ma, S., Wang, P.-Y., Meng, F.-Y., Fu, J.-H., Wu, Q., Electronically controlled beam steering leaky wave antenna in nematic liquid crystal technology, I*nternational Journal of RF and Microwave Computer-Aided Engineering*, 30, e22188, 2020.
[47] Martini, E., Maci, S., Modulated metasurfaces for microwave field manipulation: Models, applications, and design procedures, *IEEE Journal of Microwaves*, 2, 44, 2021.
[48] Amini, A., Oraizi, H., High Gain Arbitrarily-Oriented Linearly-Polarized Leaky-Wave Antenna by Tensorial Impedance Surfaces, *2020 50th European Microwave Conference (EuMC)*, 764, 2021.
[49] Araghi, A., Khalily, M., Xiao, P., Tafazolli, R., Holographic-based mmw-wideband bidirectional frequency scanning leaky wave antenna, *2020 14th European Conference on Antennas and Propagation (EuCAP)*, 1, 2020.
[50] Zadeh, M. A. C., Zohrevand, S., Farokhipour, E., Erni, D., Komjani, N., A metal-only holographic leaky-wave antenna based on spoof surface plasmon polaritons, *2024 15th German Microwave Conference (GeMiC)*, 111, 2024.
[51] Rusch, C., Holographic Antennas, in Chen, Z. (eds), *Handbook of Antenna Technologies*, Springer, Singapore, 2015.
[52] Rusch, C., Schäfer, J., Gulan, H., Pahl, P., Zwick, T., Holographic mmW-antennas with TE0 and TM0 surface wave launchers for frequency-scanning FMCW-radars, *IEEE Transactions on Antennas and Propagation*, 63, 1603, 2015.
[53] Araghi, A., Khalily, M., Xiao, P., Wang, F., Tafazolli, R., Systematic design of a holographic-based metasurface reflector in the sub-6 GHz band, *IEEE Antennas and Wireless Propagation Letters*, 21, 1960, 2022.
[54] Sievenpiper, D. F., Schaffner, J. H., Song, H. J., Loo, R. Y., Tangonan, G., Two-dimensional beam steering using an electrically tunable impedance surface, *IEEE Transactions on Antennas and Propagation*, 51, 2713, 2003.
[55] Kuester, E. F., Mohamed, M. A., Piket-May, M., Holloway, C. L., Averaged transition conditions for electromagnetic fields at a metafilm, *IEEE Transactions on Antennas and Propagation*, 51, 2641, 2003.
[56] Sievenpiper, D. F., Artificial impedance surfaces for antennas, *Modern antenna handbook*, 737, 2008.
[57] Weng, C.-K., Tsai, Y.-Z., Vilenskiy, A., Kehn, M. N. M., Tensor-free holographic metasurface leaky-wave multi-beam antennas with tailorable gain and polarization, *Sensors*, 24, 2422, 2024.
[58] Karimipour, M., Komjani, N., Holographic-inspired multibeam reflectarray with linear polarization, *IEEE Transactions on Antennas and Propagation*, 66, 2870, 2018.
[59] Karimipour, M., Komjani, N., Realization of multiple concurrent beams with independent circular polarizations by holographic reflectarray, *IEEE Transactions on Antennas and Propagation*, 66, 4627, 2018.
[60] Yurduseven, O., Podilchak, S., Khalily, M., Towards holographic beam-forming metasurface technology for next generation CubeSats, *2020 International Conference on UK-China Emerging Technologies (UCET)*, 1, 2020.
[61] Kiefner, U., Wayth, R. B., Davidson, D. B., Sokolowski, M., Holographic calibration of phased array telescopes, *Radio Science*, 56, e2020RS007171, 2021.

ATU-FJIECE, Volume: 05, Issue: 01, 03, 31, 2026, © 2020 FJIECE, All Rights Reserved

Al-Furat Journal of Innovations in Electronics and Computer Engineering (FJIECE)
ISSN -2708-3985

[62] Elzanaty, A., Guerra, A., Guidi, F., Dardari, D., Alouini, M.-S., Toward 6G holographic localization: Enabling technologies and perspectives, *IEEE Internet of Things Magazine*, 6, 138, 2023.
[63] Wan, Z., Gao, Z., Gao, F., Di Renzo, M., Alouini, M.-S., Terahertz massive MIMO with holographic reconfigurable intelligent surfaces, *IEEE Transactions on Communications*, 69, 4732, 2021.
[64] Yoo, I., Gollub, J., Ye, S., Gray, A., Yurduseven, O., Deshpande, M. D., Smith, D. R., Hollow Rectangular Waveguide-fed Holographic Beamforming Antenna Additively Manufactured (3D Printed) with Conductive Polymer, *arXiv preprint arXiv:2208.14531*, 2022.
[65] Ren, P., Jiang, L., Li, P., Graphene based tunable terahertz holographic antennas, *IEEE Open Journal of Antennas and Propagation*, 3, 324, 2022.
[66] Salehi, M., Oraizi, H., Holographic transmitarray antenna with linear polarization in X band, *AEU-International Journal of Electronics and Communications*, 146, 154115, 2022.
[67] An, J., Xu, C., Ng, D. W. K., Alexandropoulos, G. C., Huang, C., Yuen, C., Hanzo, L., Stacked intelligent metasurfaces for efficient holographic MIMO communications in 6G, *IEEE Journal on Selected Areas in Communications*, 41, 2380, 2023.
[68] Deng, R., Zhang, Y., Zhang, H., Di, B., Zhang, H., Poor, H. V., Song, L., Reconfigurable holographic surfaces for ultra-massive MIMO in 6G: Practical design, optimization and implementation, *IEEE Journal on Selected Areas in Communications*, 41, 2367, 2023.
[69] Adhikary, A., Munir, M. S., Raha, A. D., Qiao, Y., Han, Z., Hong, C. S., Integrated sensing, localization, and communication in holographic MIMO-enabled wireless network: A deep learning approach, *IEEE Transactions on Network and Service Management*, 21, 789, 2023.
[70] Zhang, H., Zhang, H., Di, B., Song, L., Holographic integrated sensing and communications: Principles, technology, and implementation, IEEE Communications Magazine, 61, 83, 2023.
[71] Hu, X., Deng, R., Di, B., Zhang, H., Song, L., Holographic beamforming for LEO satellites, *IEEE Communications Letters*, 27, 2717, 2023.
[72] Wang, P., Khormuji, M. N., Popovic, B. M., Beamforming performances of holographic surfaces, *IEEE Transactions on Wireless Communications*, 23, 5816, 2023.
[73] Zhang, X., Zhang, H., Deng, R., Liu, L., Di, B., Multi-target detection for reconfigurable holographic surfaces enabled radar, *GLOBECOM 2023-2023 IEEE Global Communications Conference*, 6634, 2023.
[74] Zhao, B., Ouyang, C., Zhang, X., Liu, Y., Performance analysis for near-field ISAC: A holographic MIMO design, arXiv preprint arXiv:2401.14129, 2024.
[75] D'Amico, A. A., Sanguinetti, L., Holographic MIMO communications: What is the benefit of closely spaced antennas?, *IEEE Transactions on Wireless Communications*, 23, 13826, 2024.
[76] Adhikary, A., Raha, A. D., Qiao, Y., Saad, W., Han, Z., Hong, C. S., Holographic MIMO with integrated sensing and communication for energy-efficient cell-free 6G networks, *IEEE Internet of Things Journal*, 11, 30617, 2024.
[77] Ji, R., Huang, C., Chen, X., EI Sha, W., Dai, L., He, J., Zhang, Z., Yuen, C., Debbah, M., Electromagnetic hybrid beamforming for holographic MIMO communications, *IEEE Transactions on Wireless Communications*, 23, 15973, 2024.
[78] Saeed, M. A., Nwajana, A. O., A review of beamforming microstrip patch antenna array for future 5G/6G networks, *Frontiers in Mechanical Engineering*, 9, 1288171, 2024.
[79] Sudhaman, K., Roshan, A., Saritha, M. A., DESIGN, ANALYSIS, AND FABRICATION OF A HOLOGRAPHIC METASURFACE ANTENNA FOR HIGH FREQUENCY APPLICATIONS, *International Journal of Engineering Research and Sustainable Technologies (IJERST)*, 3, 22, 2025.
[80] Yoo, Y., Park, J., Lee, C., Yoon, D. K., Park, S.-O., Reconfigurable multibeam holographic antenna based on liquid-crystal technology for Ka-band LEO satellite application, *IEEE Access*, 13, 27141, 2025.

ATU-FJIECE, Volume: 05, Issue: 01, 03, 31, 2026, © 2020 FJIECE, All Rights Reserved

65

[81] Wu, G.-B., Dai, J. Y., Sun, Y., Shum, K. M., Chan, K. F., Cheng, Q., Cui, T. J., Chan, C. H., A space-time holographic metasurface antenna, *Science Advances*, 11, eadx7090, 2025.
[82] Kim, B., Hwangbo, S., Optically Transparent Holographic Display Antenna: High Gain, Beam Steering, and Lossless Bonding for 5G Millimeter-Wave n261 Band, *IEEE Open Journal of Antennas and Propagation*, 2025.
[83] Tag, A., Ekin, S., Alnuweiri, H., Patterson, A. E., Mohan, M. P., Alphones, A., Henry, H. T. S., Karim, M. F., 3D-Printed mmWave Quasi-Holographic Antenna for 2D Beamforming, *IEEE Open Journal of Antennas and Propagation*, 2025.
[84] An, J., Xu, C., Gan, L., Hanzo, L., Low-complexity channel estimation and passive beamforming for RIS-assisted MIMO systems relying on discrete phase shifts, *IEEE Transactions on Communications*, 70, 1245, 2021.
[85] Shlezinger, N., Dicker, O., Eldar, Y. C., Yoo, I., Imani, M. F., Smith, D. R., Dynamic metasurface antennas for uplink massive MIMO systems, *IEEE Transactions on Communications*, 67, 6829, 2019.
[86] Xu, J., You, L., Alexandropoulos, G. C., Wang, J., Wang, W., Gao, X., Dynamic metasurface antennas for energy efficient uplink massive MIMO communications, *2021 IEEE Global Communications Conference (GLOBECOM)*, 1, 2021.
[87] Alexandropoulos, G. C., Katsanos, K., Wen, M., Da Costa, D. B., Safeguarding MIMO communications with reconfigurable metasurfaces and artificial noise, *ICC 2021-IEEE International Conference on Communications*, 1, 2021.
[88] Alexandropoulos, G. C., Katsanos, K. D., Wen, M., Da Costa, D. B., Counteracting eavesdropper attacks through reconfigurable intelligent surfaces: A new threat model and secrecy rate optimization, *IEEE Open Journal of the Communications Society*, 4, 1285, 2023.

ATU-FJIECE, Volume: 05, Issue: 01, 03, 31, 2026, © 2020 FJIECE, All Rights Reserved

66