Spectrum of Engineering Sciences
ISSN (e) 3007-3138 (p) 3007-312X Volume 4, Issue 3, 2026

SHAPING NEXT GENERATION 6G WIRELESS NETWORKS THROUGH METASURFACE BASED RECONFIGURABLE ANTENNAS: RECENT ADVANCES, INNOVATIVE TECHNOLOGIES, DESIGN CHALLENGES AND FUTURE DIRECTIONS

Iftikhar Hussain[*1], Amanullah[2], Syeda Abeeda Zahra Naqvi[3], Naseer Ahmad[4], Engr. Muhammad Faisal Shehzad[5], Dr. Kashif Ahmad[6]

*[*1]Department of Electrical Engineering, University of Gujrat, Gujrat, Pakistan*
[2,3,5]Department of Telecommunication Engineering, University of Engineering and Technology, Taxila, Pakistan
[4]Faculty of Computing and Technology, IQRA University H9 Campus, Islamabad, Pakistan
[6]Department of Computer Science, Auckland University of Technology (AUT)
Auckland 1010, New Zealand

[*1]iftikhar.hussain@uog.edu.pk, [2]amanullahsasoli99@gmail.com, [3]naqvihaya81@gmail.com, [4]naseer.ahmad@iqraisb.edu.pk, [5]faisal.shehzad@uettaxila.edu.pk, [6]kashifahmad224@gmail.com

DOI: https://doi.org/10.5281/zenodo.24303216

Keywords
Metasurface Based Reconfigurable Antennas, 6G Wireless Networks, Programmable Metasurfaces, Adaptive Beamforming, Reconfigurable Intelligent Surfaces, Artificial Intelligence Optimization.

Article History
Received: 20 January 2026
Accepted: 05 March 2026
Published: 19 March 2026

Copyright @Author
Corresponding Author: *
Iftikhar Hussain

Abstract

The rapid advancement of sixth-generation (6G) wireless communication systems requires intelligent and adaptive antenna technologies capable of supporting ultra-high data rates, massive connectivity, low latency, and dynamic spectrum utilization. Traditional antenna architectures face major limitations due to fixed radiation characteristics and limited flexibility. In response, metasurface-based reconfigurable antennas have emerged as a promising solution, enabling dynamic beam steering, polarization control, frequency reconfiguration, and radiation pattern synthesis within compact and low-profile structures. This paper presents a comprehensive review of recent developments in metasurface-based reconfigurable antennas for 6G wireless networks. It discusses fundamental design principles, reconfiguration techniques, and enabling technologies, including PIN diodes, varactors, MEMS switches, liquid crystals, and graphene-based tunable materials. The review also examines important mathematical modeling and signal processing approaches such as phase modulation, adaptive beamforming, and reflection coefficient optimization for programmable electromagnetic environments. Furthermore, emerging innovations including programmable metasurfaces, artificial intelligence-assisted optimization, and software-defined electromagnetic control are analyzed for their potential in adaptive wireless systems. Finally, key challenges and future research directions are discussed, highlighting AI-driven antenna intelligence, terahertz integration, RIS-assisted communication, and smart electromagnetic ecosystems for next-generation 6G applications.

Nomenclature

Abbreviation	Full Form	Abbreviation	Full Form
6G	Sixth Generation Wireless Communication	RIS	Reconfigurable Intelligent Surface
MIMO	Multiple-Input Multiple-Output	THz	Terahertz
EM	Electromagnetic	RF	Radio Frequency
AI	Artificial Intelligence	ML	Machine Learning
RL	Reinforcement Learning	DL	Deep Learning
DNN	Deep Neural Network	CNN	Convolutional Neural Network
GNN	Graph Neural Network	SNR	Signal-to-Noise Ratio
SINR	Signal-to-Interference-plus-Noise Ratio	SLL	Side Lobe Level
ISAC	Integrated Sensing and Communication	XR	Extended Reality
IoE	Internet of Everything	SDN	Software Defined Networking
NFV	Network Function Virtualization	MPC	Model Predictive Control
FEM	Finite Element Method	PCB	Printed Circuit Board
MEMS	Micro-Electro-Mechanical Systems	PIN	Positive-Intrinsic-Negative Diode
CST	Computer Simulation Technology	HFSS	High Frequency Structure Simulator

1- Introduction:

The requirements of the near-zero latency communication, intelligent network adaptability, massive connectivity and ultra-high data rate communication, facilitate the acceleration of the ongoing development of wireless communication technology towards 6th generation (6G) systems. A paradigm shift in design and operation of wireless infrastructure is required to support new applications, including holographic communications, extended reality, autonomous transportation and Internet of Everything. The spectral efficiency and connectivity of the fifth generation networks has been improved a lot. The hardware architectures, in particular the traditional antenna systems, however have a limitation because of the static radiation characteristics and low adaptability to dynamic propagation environment [1]. Such limitations hinder their ability to meet the varied and demanding needs of future 6G applications. To tackle these challenges, reconfigurable antennas with metasurface are proposed as a viable paradigm to attain intelligent and programmable wireless environment. Metasurfaces are optimised 2D surfaces consisting of sub-wavelength unit cells which provide unprecedented control over the propagation of electromagnetic waves in terms of its phase, amplitude, polarisation and direction [2]. Metasurface antennas are different from fixed geometry, pre-radiation pattern antennas as it is possible to design the antenna to show off the desired radiation pattern. They can dynamically and real time control their electromagnetic response using integrated tunable elements and smart materials. This capability offers significant opportunities for implementation of state of the art functionalities like dynamic beam steering, frequency reconfiguration, polarisation switching and spatial wave front shaping to be implemented in compact light weight and energy efficient architectures. In recent years, these technologies have been used in tandem with novel communication paradigms, like reconfigurable intelligent surfaces (RIS), holographic multiple-input multiple-output system, and terahertz (THz) communication system [3]. Such progress has transformed metasurfaces into active EM components which can be leveraged to design wireless channels and improve signal propagation. In addition, the use of advanced signal processing methods like adaptive beamforming, channel

estimation, sparse signal reconstruction and using artificial intelligence for optimization has greatly enhanced the efficiency and intelligence of metasurface-based communication systems. It's a fundamental ingredient of the fully adaptive and self-optimizing 6G. But still, there are some challenges which prevent metasurface based reconfigurable antenna from being widely used [4]. They involve considerations such as fabrication complexity, switching loss, power inefficiency and mutual coupling in dense configurations and challenges associated with real time control for large scale deployments. However, the current research is somewhat disjointed and the methodologies are not comparable, either revolving around the antenna design, material innovation or signal processing techniques, from which only half baked solutions result, resulting in a difficult antennae scaling and implementation in practical 6G applications. To summarise, they are presented in the coming Table 1, showing the merits of metasurface based approach.

Table 1: Comparison between Conventional Antennas and Metasurface-Based Reconfigurable Antennas for 6G Systems [5].

Feature	Conventional Antennas	Metasurface-Based Reconfigurable Antennas
Radiation Pattern	Fixed	Dynamically reconfigurable
Beam Steering	Mechanical/Electrical (limited)	Real-time adaptive beam steering
Frequency Agility	Narrowband or limited multiband	Wideband and tunable
Polarization Control	Static	Dynamically switchable
Size and Profile	Bulky structures	Compact and low-profile
Signal Processing Integration	Limited	Strong integration with AI and optimization
Adaptability to Environment	Low	High (programmable response)
Suitability for 6G	Limited	Highly suitable

Building upon these insights, this review offers several key contributions beyond conventional narrative surveys:

- It provides a unified and structured analysis of metasurface-based reconfigurable antennas by integrating electromagnetic principles, reconfiguration mechanisms, and signal processing frameworks within a single cohesive perspective.
- It presents a quantitative comparative evaluation of existing approaches based on key performance metrics such as gain, efficiency, bandwidth, energy consumption, and scalability.
- It incorporates advanced mathematical modeling and optimization techniques, highlighting the role of phase control, beamforming, and RIS-assisted channel modeling in modern wireless systems.
- It explores the application of AI/ML techniques, including reinforcement learning and deep learning, for real-time and intelligent metasurface optimization.
- It identifies critical design challenges and outlines future research directions toward smart electromagnetic environments and fully programmable 6G wireless networks.

The paper concludes with a focused and comprehensive review of metasurface-based reconfigurable antennas for next-generation 6G wireless networks, with special emphasis on signal processing aspects. The review provides a systematic account of basic principles, enabling technologies and recent advances, and gives a critical assessment of performance trade-offs and design challenges. To summarize, this paper is intended to provide a clear roadmap for future research and development and to position

metasurface-based reconfigurable antennas as a key technique to realize intelligent, adaptive, and high-performance 6G wireless communication systems.

2- Review Methodology:

The detailed and systematic methodology presented in the review enables the high detailed coverage, deep analysis, and proved high technical relevance for metasurface-based Reconfigurable Antennas for future 6G wireless communication. The goal of this direction is, in addition to summarizing the current research, to critique, compare and synthesize the knowledge in various fields including electromagnetic design, reconfiguration technologies, integration of signal processing and intelligent wireless environments. Clear and transparent methodology provides for the possibility of reproducibility, credibility and the needs of high impact journals such as Signal Processing. Several scientific databases were mined to collect the literature and were considered of high quality and well-known, namely: IEEE Xplore, ScienceDirect, SpringerLink and Scopus databases. The remaining titles and abstracts were then subjected to a first round screening after de-duplication, which resulted in around 150 studies to be further assessed. Then, a strict filtering was performed at the second stage according to inclusion criteria: technical relevance, novelty, experimental validation, mathematical rigour and contribution to the field. Technical depth was low, techniques were outdated, or they were not relevant to 6G systems studies. Hence, a final sample of around 70-90 selected research articles of good quality were selected for detailed analysis [7]. The literature chosen was organised into a number of key thematic areas for synthesising. These include (i) metasurface fundamentals, (ii) electromagnetic control techniques, (iii) reconfiguration and enabling materials, (iv) Mathematical modelling and integration with signal processing, (v) RIS and programmable architectures, (vi) THz and holographic MIMO systems and (vii) AI/ML-based optimisation techniques. This classification scheme gives an overview of the field and shows the interrelations between the various research areas [8]. It also allows the comparison by grouping similar approaches and showing the performance trade-offs. The review is conducted in an analytical framework of a mixture of qualitative and quantitative evaluation. Qualitative analysis involves concepts, design methods and system architectures. Performance parameters like gain, radiation efficiency, bandwidth, switching speed, energy consumption and scalability are related to quantitative analysis. We study mathematical models and optimisation frameworks in detail to get more insight in the behaviour of the system and the design constraints. Comparative tables are also used to compare the strengths and weaknesses of the various approaches, and provide a summary of the main results that is clear and concise. This methodology is important for identification of research gaps and emerging trends. The limitations of existing studies (e.g., fabrication complexity, switching losses, real time control, and scalability) identified in this review, indicate areas for further investigation. Emerging directions are pointed out, such as: AI-driven autonomous metasurfaces, integration THz, smart electromagnetic environment and optimisation via digital twin [9]. The methodology of a systematic review used in this study is presented in figure 1 and involves the identification of literature, screening, eligibility assessment, categorisation and final analysis The proposed methodology ensures a transparent, comprehensive and high quality review process. In this work, we present a robust and meaningful review of the metasurface-based reconfigurable antennas and their potential to impact future 6G wireless communication systems by incorporating systematic literature selection, organized categorization, and comprehensive analytical assessment.

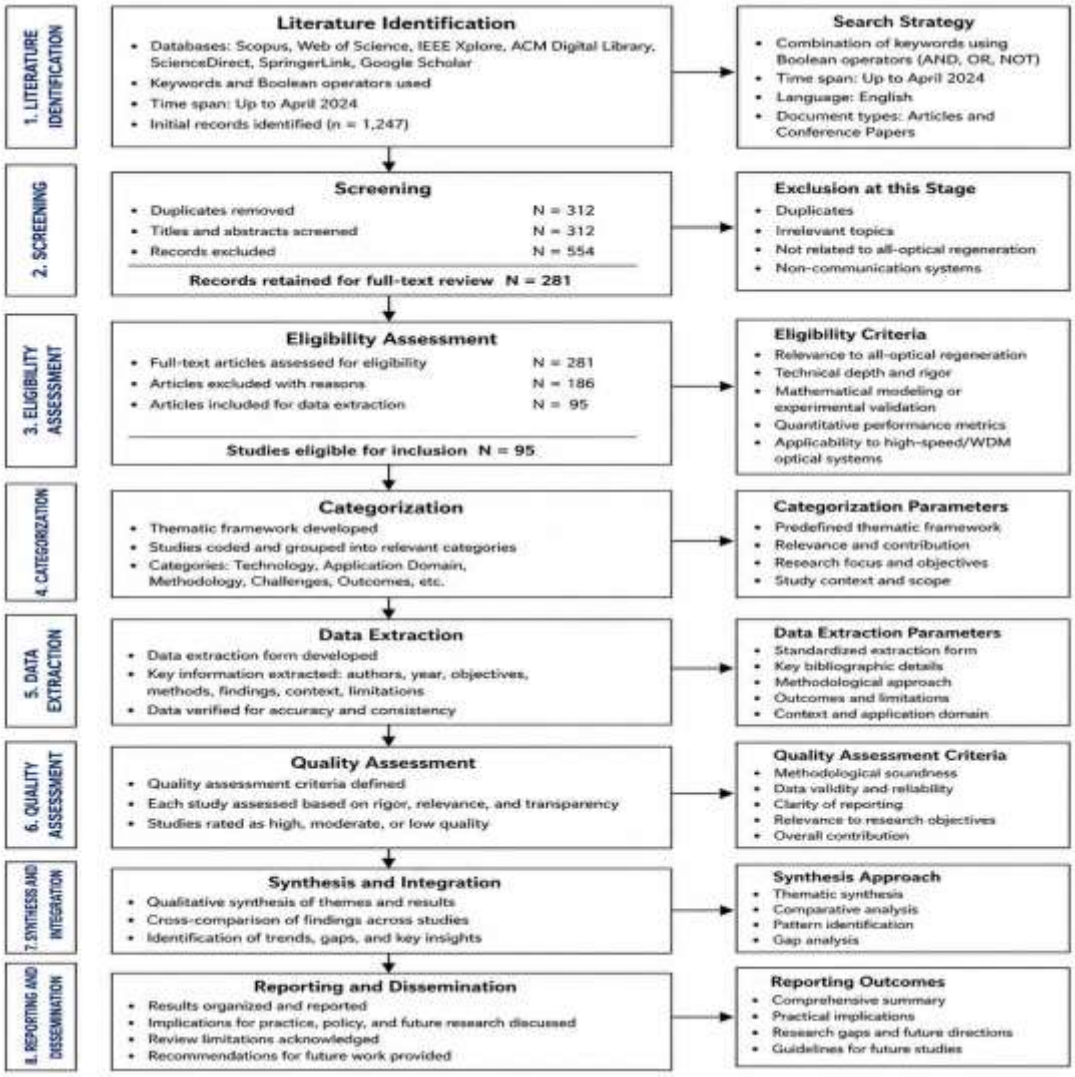


Figure 1: Systematic Review Methodology Framework

3- Fundamentals of Metasurface-Based Reconfigurable Antennas:

The reconfigurable antennas using metasurface are complex electromagnetic devices made of sub-wavelength unit cells and seek to achieve precise and flexible control of impinging waves. Unlike conventional antennas with fixed geometrical configurations, the metasurfaces provide a unique opportunity of dynamic control of electromagnetic responses through incorporation of tunable elements such as PIN diodes, varactors, MEMS switches and emerging smart materials. These structures act by tailoring the boundary conditions of the electromagnetic fields locally and allow for a real time tuning of the main electromagnetic wave properties like phase, amplitude and polarisation. Hence, the metasurface antennas possess several interesting properties, including adaptive beam steering, frequency reconfiguration and polarisation switching in small and low-profile configurations, which are highly beneficial for future 6G wireless communications [10]. The smooth cooperation with advanced signal processing algorithms also provides a starting point for their contribution to the programmable and intelligent communication environments.

3.1- Electromagnetic Control Mechanisms (Phase, Amplitude, Polarization):

The fundamental principle of reconfigurable antennas using metasurfaces is that the properties of an electromagnetic wave can be accurately controlled at the unit-cell level, primarily by controlling the phase, amplitude and polarization. Unlike traditional radiating structures, metasurfaces are made of engineered elements which are smaller than the wavelength and can be dynamically modified through integrated electronic devices or smart materials [11]. By doing so, the interactions of the waves at the interface can be controlled locally and this metasurface can be regarded as a programmable boundary for electromagnetic propagation. Such a high granularity is needed in the realization of the envisioned adaptive and intelligent wireless communication systems for the next generation 6G networks. A key function for metasurface operation is the phase control, which is directly related to the direction and shape of the radiated or reflected wavefront. This spatially varying phase shifts across the metasurface aperture can be designed to realize constructive and destructive interference pattern for beam steering, beam focusing, and wave front shaping [12]. Is usually accomplished with dynamically tunable elements, such as PIN diodes, varactors, or tunable materials, within the individual unit cells which change the phase of the reflected or transmitted wave (usually 0 - 360 degrees). Metasurfaces can more accurately modulate the radiation patterns and reduce the undesired interference by selectively attenuating or enhancing the amplitude response of the individual unit cells [14]. The amplitude control is typically implemented in practice by means of biasing circuits or by tuning the materials, changing the effective conductivity or loss properties of the unit cells. Additionally, another challenging issue in electromagnetic manipulation by antennas incorporated with metasurface is the control of polarisation. It is a question of playing with the direction and nature of the electric field vector, allowing the transition between linear, circular and elliptical polarisation states. This is typically achieved with anisotropic geometries of the unit-cell and reconfigurable elements responding to the orthogonal field components [15]. The robustness of communication and the spectral efficiency in multipath environment are improved by dynamic polarization control. These electromagnetic control mechanisms are summarised in Table 2 and a brief comparison of the practical parameter range is performed.

Table 2: Simplified Electromagnetic Control Mechanisms with Practical Ranges [16]**.**

Mechanism	Main Function	Typical Range / Values	Common Implementation	Key Benefit
Phase Control	Beam steering, wavefront shaping	0° – 360° phase shift	PIN diodes, varactors	Dynamic directional control
Amplitude Control	Power tuning, sidelobe suppression	0 – 1 (normalized amplitude)	Resistive tuning, material loss control	Improved radiation efficiency
Polarization Control	Field orientation control	Linear / Circular / Elliptical	Anisotropic unit cells	Enhanced link reliability

Metasurface antennas can be dynamically reconfigured using advanced signal processing techniques, such as adaptive beamforming and AI-based optimisation to adapt to different channel conditions and network requirements. Metasurface unit-cells (as shown in Fig. 2) can control the electromagnetic wave in various ways such as phase based beam steering, amplitude based radiation shaping and polarization manipulation.

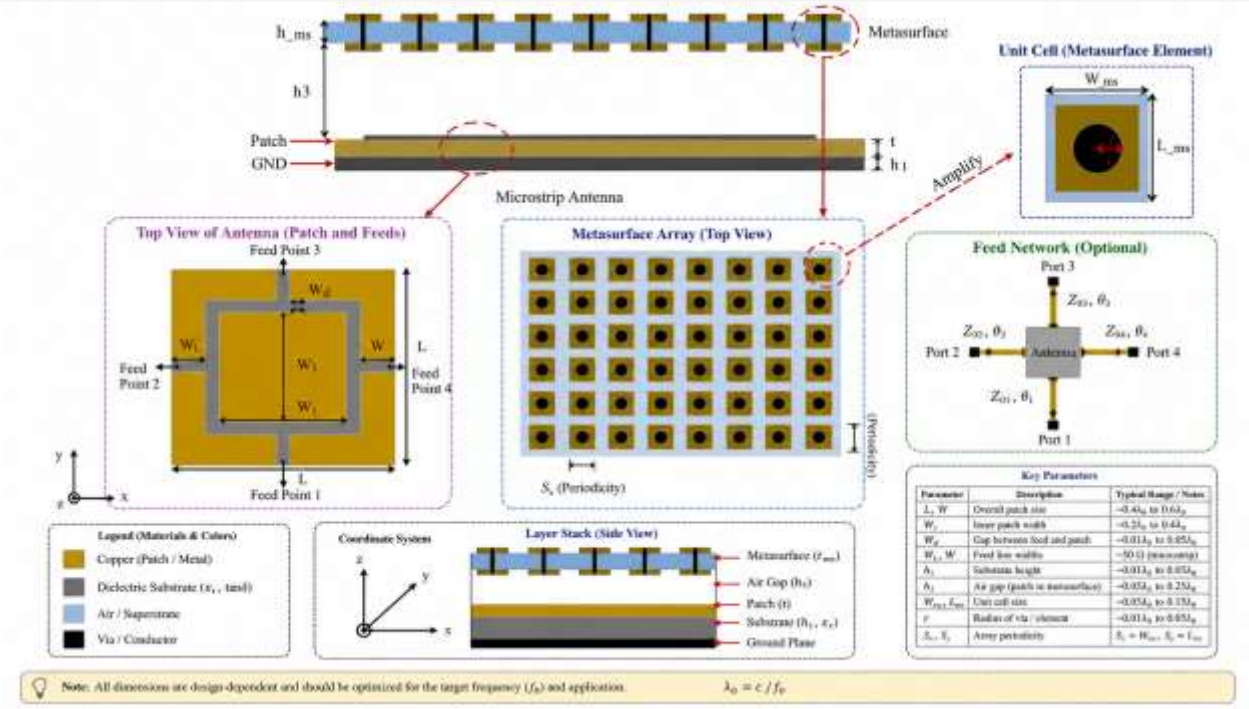


Figure 2: Electromagnetic Control Mechanisms in Metasurface-Based Antennas [17].

This simultaneous control of phase, amplitude and polarization is a highly versatile and highly efficient dynamic manipulation of the electromagnetic fields, and is well suited for reconfigurable antennas using metasurfaces. The synergy with EM design and intelligent control will facilitate the realization of smart and autonomous wireless environments in future communication networks and boost the efficiency and scalability of the system.

3.2- Reconfiguration Principles:

The dynamic tuning of the electromagnetic responses in real-time by tuning the physical or electrical properties of the unit cells is what is known as reconfiguration in metasurface-based antennas. This capability makes metasurfaces more than just passive radiating surfaces and enable dynamic and programmable intelligent 6G wireless platforms. While traditional antennas have fixed antennas geometry, reconfigurable metasurfaces are composed of tunable elements and smart materials, which provide continuous or discrete tuning of the electromagnetic response [18]. These changes allow features such as frequency tuning, beam steering, polarisation switching and radiation pattern reconfiguration without the need to move mechanical components. Electrical reconfiguration, given its fast response time, ease of integration and compatibility with existing electronic systems is the most popular approach. This method uses PIN diodes, varactor diodes and MEMS switches as active components that are embedded within the metasurface unit cells. The external bias voltages can be used to dynamically control the effective impedance of each unit cell and thereby further modify the phase, amplitude or polarization of the reflected or transmitted waves [19]. PIN diodes can be used to switch between pre-defined states, while varactors can be used to switch the capacitance continuously, which can provide a smoother control of the electromagnetic responses. MEMS based approaches offer advantages of high accuracy and low insertion loss, but can be more complicated to fabricate and slower to switch than purely electronic approaches.

Another important paradigm is material-based reconfiguration, where the metasurface's electromagnetic properties are tuned using the

intrinsic properties of advanced materials. For example, the permittivity of liquid crystals depends on voltage, which enables continuous control of wave propagation [20]. Graphene and other 2D materials have also drawn much attention for terahertz (THz) applications because of their tunable conductivity and high-frequency response . A phase-change material example is vanadium dioxide (VO 2) which can be switched between different electromagnetic states by changing the temperature or by using an electrical stimulus. These material driven methods offer enhanced flexibility and are particularly suitable for high frequency and compact metasurface designs. Mechanical reconfiguration is less common in modern designs, but consists of physically changing the metasurface's geometry or structure to achieve desired electromagnetic responses. This can be done either by micro-actuators or by compliant substrates that deform under external forces [21]. Mechanical methods are typically slow in response and not very suitable for real-time adaptive communication systems, but they provide large tuning ranges and high reliability. The main features and practical issues of these reconfiguration approaches are summarized in Table 3.

Table 3: Reconfiguration Techniques in Metasurface-Based Antennas.

Technique	Control Method	Typical Speed	Tuning Type	Advantages	Limitations
Electrical (PIN/Varactor/MEMS)	Bias voltage control	Fast (ns–µs)	Discrete / Continuous	High speed, easy integration	Power consumption, circuit complexity
Material-Based (Graphene, LC, VO_2)	Material property tuning	Medium (µs–ms)	Continuous	Suitable for THz, compact design	Fabrication challenges
Mechanical	Physical structure change	Slow (ms–s)	Continuous	Large tuning range, stable	Slow response, bulky

Depending on the requirements of the application (operating frequency, response time, power usage, system complexity, etc.), it is possible to use one of these reconfiguration mechanisms. Extremely fast adaptability and intelligence of control is a key requirement for 6G systems, making electrical and material-based reconfiguration methods particularly attractive because they can be used to achieve real time operation and integration with signal processing frameworks. In addition, multi-reconfiguration mechanisms are increasingly being used in modern metasurface systems to provide hybrid functionality which can be reconfigurable simultaneously in phase, amplitude and polarisation. This multi-dimensional adaptiveness can be realized by applying sophisticated signal processing techniques such as optimization methods and machine learning models for dynamic adaptation of control parameters, depending on the environmental conditions and user demands [22]. Reconfigurable metasurfaces are thus identified as smart surfaces for self-optimization and autonomous operation of electromagnetic systems.

4- Taxonomy of Metasurface-Based Reconfigurable Antennas:

To gain a better understanding of the wide range of functionality that they are capable of, their design approach, and possible applications in the future 6G wireless systems, the metasurface based reconfigurable antennas can be systematically categorized. The metasurface antennas can be classified mainly according to their electromagnetic control capabilities and reconfigurability level [23] which is different from

the traditional antenna classes that categorize the antennas mainly according to their geometry or frequency [24]. In order to gain insight into the function of these advanced antennas in the context of adaptive, efficient and intelligent wireless communication scenarios, such a structured taxonomy is required.

4.1- Functional Reconfigurability:

The main electromagnetic properties like operating frequency, radiation direction and polarisation state can be dynamically changed in metasurface-based antenna design, which is the key aspect of functional reconfigurability. This flexibility is realised through tunable unit-cell structures combined with electronic components or smart materials, which allow the antenna behaviour to be altered in real-time according to different communication requirements [25]. Exploiting localised control at the metasurface level, these antennas can react intelligently to variations in channel conditions, user mobility and spectrum availability, making them highly suitable for next generation 6G wireless systems. Metasurface antennas can be dynamically tuned to operate at multiple frequency bands by tuning their resonant features, which provides frequency reconfigurability [26]. This is typically realised by tunable elements such as varactor diodes, PIN diodes or material based approaches that alter the effective permittivity or the geometry of unit cells. This is necessary to facilitate efficient spectrum utilisation, carrier aggregation, and multi-band communication in 6G networks. The metasurface allows for dynamic control of the radiation direction by manipulating the phase gradient over the metasurface, which leads to beam-steering reconfigurability without any mechanical movement. Controlled phase shifts between adjacent unit cells can be used to steer electromagnetic waves to desired angles for adaptive coverage, spatial multiplexing, and high-mobility scenarios [27]. The polarisation reconfiguration enables an on-demand switching among different polarisation states such as linear, circular and elliptical modes. This improves the reliability of communications and permits polarisation diversity in complex propagation environments. For a more insightful perspective, a performance-oriented comparison of functional reconfigurability features in metasurface antennas is presented in Table 4.

Table 4: Performance-Oriented View of Functional Reconfigurability [28].

Feature	Control Dimension	Typical Performance Range	Complexity Level	Response Speed	Practical Impact
Frequency Tuning	Resonant frequency	Multi-band (1–300 GHz / THz emerging)	Medium	Fast	Flexible spectrum usage
Beam Steering	Spatial direction (angle)	±60° to ±90°	High	Very Fast	Dynamic coverage, user tracking
Polarization Switching	Field orientation	Linear ↔ Circular ↔ Elliptical	Medium	Fast	Reliable communication, diversity gain

Functional reconfigurability is inherently multi-dimensional, where each feature contributes uniquely to the overall system performance. Beam steering provides the highest degree of flexibility in spatial control but at the cost of increased design complexity and frequency tuning provides the necessary flexibility in spectrum utilisation. Figure 3 presents functional reconfigurability in metasurface-based antennas, encompassing frequency tuning, beam steering through phase gradients, and polarisation switching for adaptive wireless communication.

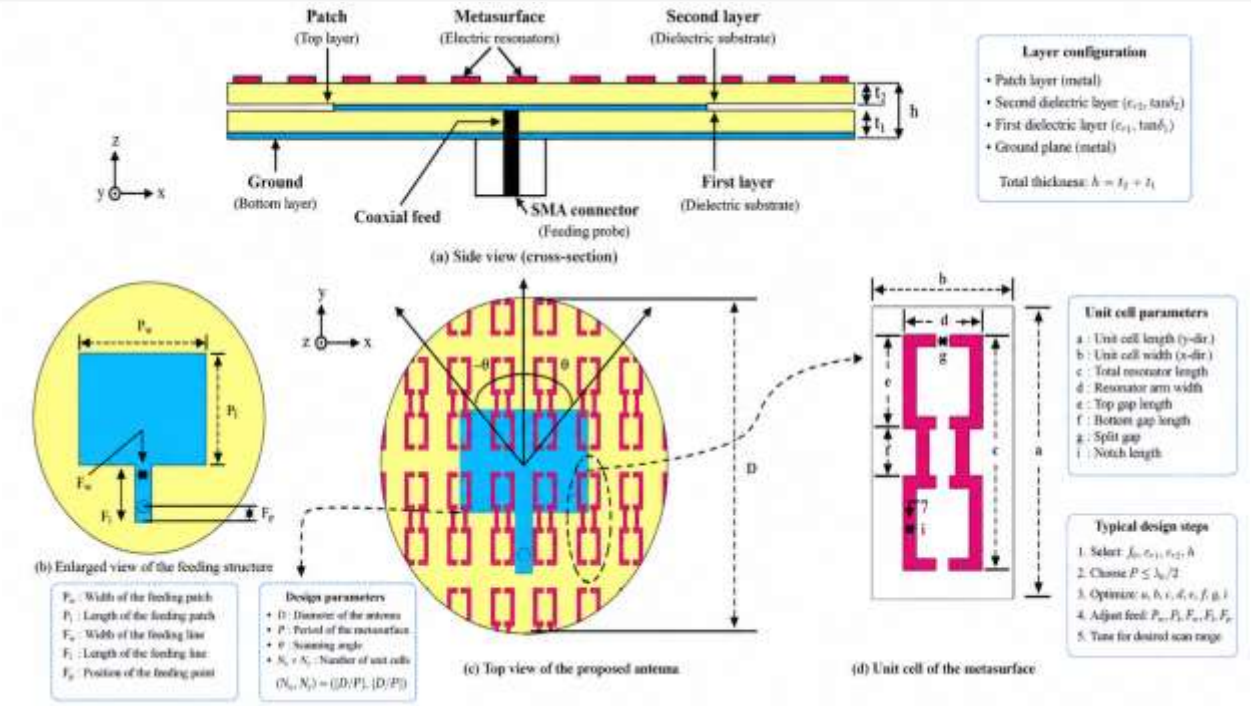


Figure 3: Functional Reconfigurability in Metasurface-Based Antennas [30].

The built-in reconfigurability of an intelligent metasurface-based antenna system is crucial to adaptively deal with various electromagnetic environments, thereby potentially enhancing the system performance, operational efficiency, and design flexibility. Availability of this capability is crucial to meet the demanding characteristics of the next generation 6G wireless networks that include new features such as high data transmission rate, low latency, flexible beam steering and smooth connectivity for various applications.

4.2- Programmable and RIS-Based Architectures:

Among the next steps of metasurface antenna technology is the advancement of programmable metasurfaces and architectures based on the Reconfigurable Intelligent Surface (RIS) towards a paradigm shift that moves from static architectures of electromagnetic structures to full control and software-defined wireless environments. In these architectures, the electromagnetic response of each unit cell of the metasurface can be controlled in real time via external control signals and therefore the propagation parameters of such a metasurface, like its phase, amplitude and polarisation, can be set dynamically. This programmability is usually achieved by embedding the controllers, field-programmable gate arrays (FPGAs) or microcontroller units (MCUs) which can program the metasurface by tuning the active elements which can be PIN diodes or varactors. So, programmable metasurfaces are smart interfaces that can be dynamically reconfigured to facilitate the transmission and reception process between the transmitter and receiver based on the need of the communication and surroundings. In RIS-based systems, the concept is expanded to provide relay arrays of very large metasurfaces in the wireless environment that can actively manipulate the propagation paths. The RIS is passive or semi-passive, which means that it does not need any active radio-frequency chains, and therefore is very energy-efficient compared to traditional relay systems. In complex propagation conditions such as indoor environment or an urban area, the RIS can adaptively adjust the phase rotation of the reflected signals to increase the received signal power, weaken the received

interference and finally optimize the received coverage [31]. Furthermore, with the integration of SDC, the software defined control can enable a seamless integration with the upper layer network functions to enable the applications like dynamic resource allocation, interference management and energy efficient communication [32]. Although the great potential of programmable and RIS-based metasurface systems have been demonstrated, there are still some challenges for their practical implementation. These involve complexity of real time algorithms for control, scalability of the hardware for the large array and synchronization issues and efficient channel estimation in highly dynamic environments. These challenges have to be solved to open the full potential of programmable metasurfaces for 6G networks [33]. Fig. 4. The communication architectures based on programmable metasurface can be categorized as (i) programmable metasurface embedded control unit; (ii) RIS-assisted communication between transmitter and receiver; (iii) software-defined electromagnetic environment with adaptive wireless propagation.

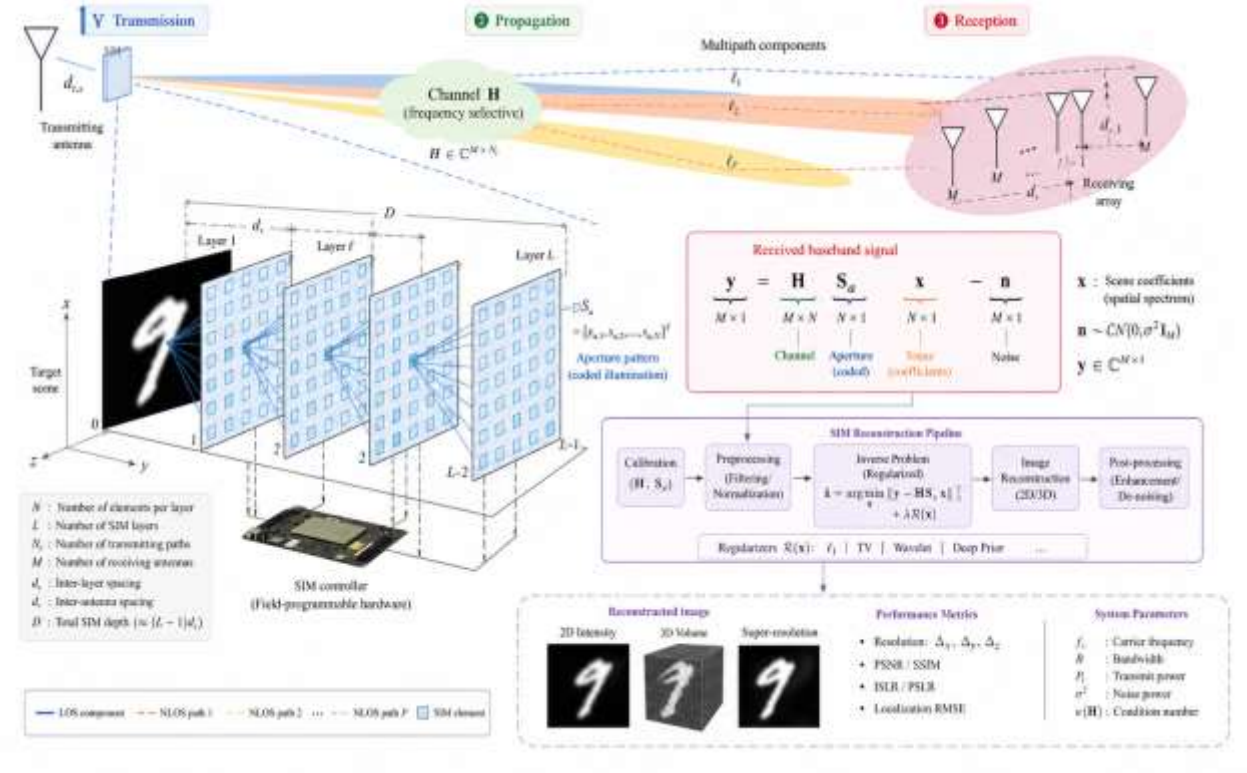


Figure 4: Taxonomy of Programmable and RIS-Based Metasurface Architectures [34]**.**

Programmable and RIS-based architectures are a paradigm shift in wireless communications, as they enable the ability to intelligently, adaptively and energy-efficiently control the electromagnetic environment. Such systems are envisioned to be the backbone of future 6G networks, which are expected to bind and bridge high-level signal processing intelligence and the physical layer hardware.

5- Enabling Materials and Reconfiguration Technologies:

The performance and adaptability of metasurface-based reconfigurable antennas are mainly determined by the materials and reconfiguration technologies used in their unit-cell structures. These enabling components provide physical and electronic mechanisms to dynamically control electromagnetic responses such as phase, amplitude and polarisation. Advances in semiconductor devices, smart materials and micro-

fabrication techniques have greatly improved the functionality of metasurfaces [35], enabling the control of the wave propagation in a real-time and programmable way. In particular, the combination of electronic switching elements, tunable materials and hybrid control has enabled the realisation of highly efficient, compact and intelligent antenna systems for next-generation 6G wireless networks. A good understanding of these enabling technologies is crucial in order to optimise the performance, minimise the losses and achieve scalable and energy efficient metasurface designs.

5.1- PIN Diodes and Switching Circuits:

One of the most popular components to enable reconfigurability in metasurface-based antennas is PIN diodes due to their simplicity, fast switching speed and ease of integration with electronic control circuits. The PIN diode is a type of diode that is composed of p type and n type semiconductors separated by an intrinsic (undoped) layer and thus operates as a variable resistor when it varies bias conditions [36]. When the diode is in the forward bias state it has a low resistance and effectively short circuit the unit cell. On the other hand, in reverse bias it has high resistance and behaves like an open circuit. This switching behaviour enables a discrete control of the electromagnetic responses at the metasurface level and is especially suited to (digital or binary) reconfiguration schemes. In metasurface applications, PIN diodes are usually embedded in unit cells to dynamically change the current distribution and surface impedance. Selective switching of the ON or OFF states of the diodes leads to the possibility of switching the reflection or transmission characteristics of the metasurface and hence controlling the phase, amplitude and polarisation of the electromagnetic waves. This is highly useful for beam steering, frequency shifting and radiation pattern reconfiguration. The spatial phase gradient can be generated by loading an array of unit cells with various ON/OFF states, for example, which can be used for dynamic beam steering without mechanical motion. This is a common setup in the reconfigurable intelligent surfaces (RIS) systems and adaptive antenna arrays (AAs) in 6G communication. Switching circuits are important in the control of the operation of the PIN diodes throughout the metasurface [37]. These circuits contain biasing networks, control lines and driver modules to control the voltage levels applied to each of the diodes or groups of diodes. Using RF chokes, DC blocking capacitors and proper grounding techniques will minimize the parasitic effect of RF signals when using a well designed biasing network [38]. These components separate out RF and DC paths to maintain antenna performance and make efficient control possible. In more advanced versions, the metasurface is reconfigurable in real time and programmable, using microcontroller, field-programmable gate array, or digital control unit to adjust the metasurface to the varying channel conditions and demand of the users [39]. Table 5 shows the key parameters of PIN diodes for metasurface applications, which will give a broad perspective of the operational features of the PIN diodes.

Table 5: Key Characteristics of PIN Diodes in Metasurface Antennas [40].

Parameter	Typical Value	Role in Metasurface
Switching Speed	1–100 ns	Enables fast real-time reconfiguration
ON-State Resistance	1–5 Ω	Determines insertion loss
OFF-State Resistance	>1 kΩ	Provides signal isolation
Bias Voltage	1–10 V	Controls ON/OFF switching
Operating Frequency	Up to mmWave (~100 GHz)	Suitable for 5G/6G bands

The parameters show that PIN diodes are a good compromise between speed, controllability and cost, making them very promising for practical and scalable metasurface implementations [41]. As an example, the PIN diode based reconfiguration mechanisms, including (i) forward and reverse bias

switching characteristic, (ii) integration into metasurface unit-cell structure, (iii) biasing network design and (iv) beam steering by controlling the diode state, are discussed.

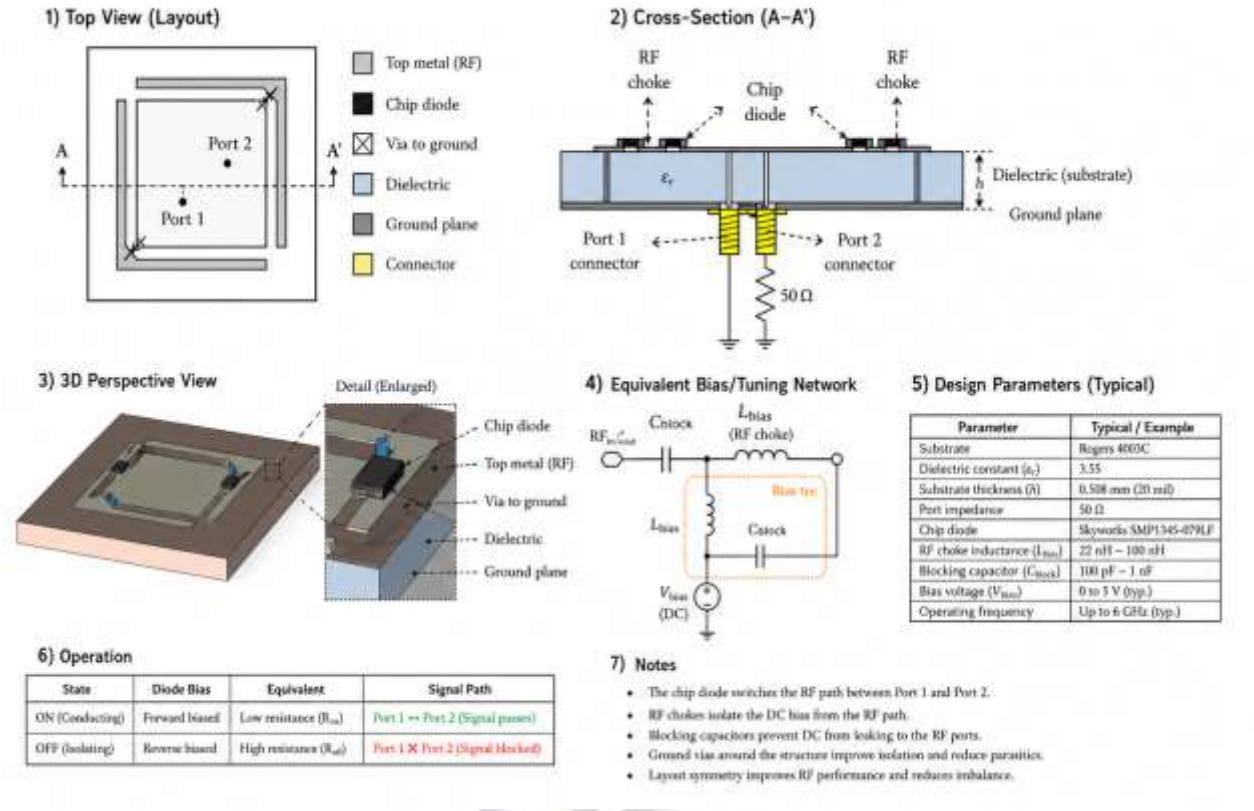


Figure 5: PIN Diode-Based Reconfiguration in Metasurface Antennas [42].

Some of the key enablers for reconfigurable metasurface based antennas are the use of PIN diodes with dedicated switching and biasing networks to achieve high speed and discrete control of the electromagnetic response. They are able to switch from conductive to non-conductive and vice versa under forward and reverse bias, enabling efficient modulation of the phase distribution and current flow in the metasurface. Thus they can offer functionalities like beam steering, polarisation control and frequency tunability, that are crucial to meet the complex and dynamic requirements of the next generation 6G wireless communication scenarios.

5.2- Varactor-Based Tunable Designs:

Varactor diodes provide a key function for continuous (analogue) reconfiguration in metasurface-based antennas in addition to the function of switching provided by PIN diodes. The junction capacitance is varied by applying a reverse-bias voltage, using a varactor (voltage controlled capacitor). This tunable capacitance is directly used to modify the effective impedance of a metasurface unit cell, thus allowing the resonance, phase and, to a lesser extent, amplitude to be smoothly tuned. In this way, the use of varactor-loaded metasurfaces can enable fine-tuning of the electromagnetic responses, particularly beneficial for accurate beamforming, frequency agility, and adaptive wavefront shaping in 6G systems [43]. The varactor-based tuning leads to a more gradual evolution of the radiation pattern and to a lower quantisation error than a binary PIN-diode control, which is advantageous for high-resolution beam steering and sidelobe control. From the circuit perspective, the varactor-based metasurface needs to be well-designed, so

that the RF and DC paths can be separated with low loss. RF chokes (inductors) prevent the flow of RF currents into the DC lines and DC blocking capacitors prevent leakage of bias voltages into the RF lines. The layout should minimise parasitics (series resistance, package inductance) since they directly affect the quality factor (Q) of the varactor and thus the insertion loss and tuning range. The parasitic effects and series resistance are more dominant at higher frequencies (mmWave/THz) and device selection and layout optimisation are important. The designs based on the varactors are extensively employed for beam steering, frequency tuning and reconfigurable filters/absorbers in metasurface antennas [44]. The main beam can then be dynamically steered with high angular resolution, by imposing a controlled phase gradient with the voltage profiles across the array. Furthermore, the continuous tuning enables adaptive matching to and real-time compensation of environment variations. The practical features and design considerations of the varactor-based tunable metasurface antennas are summarised briefly in Table 6.

Table 6: Varactor-Based Tuning Characteristics in Metasurface Antennas [45].

Parameter	Typical Range / Value	Design Implication	Impact on Performance
Capacitance Range	~0.1–5 pF	Sets tuning span of resonance/phase	Wider tuning → broader frequency agility
Bias Voltage	~1–20 V (reverse bias)	Controls capacitance continuously	Fine, analog control of phase
Phase Tuning	Up to ~360° (design-dependent)	Requires proper unit-cell geometry	Smooth beam steering, low quantization error
Quality Factor (Q)	~30–200 (freq.-dependent)	Limited by series resistance/parasitics	Higher Q → lower loss, better efficiency
Operating Frequency	RF to mmWave (THz emerging)	Parasitics critical at high f	Performance degrades if parasitics high

Unlike discrete switching, the varactor-based tuning allows for smoother transitions in radiation characteristics and improved beam quality, at the cost of paying careful attention to losses and linearity. Figure 6. Varactor-based tuning in metasurface antennas. (a) Voltage-controlled variation of capacitance. (b) A varactor diode in a unit-cell. (c) Continuous tuning for phase-gradient beam steering. (d) RF and DC biasing networks with chokes and blocking capacitors.These values emphasise the fact that varactors offer high-resolution, continuous control, making them perfect for applications where precision and adaptability are key. Unlike discrete switching, the varactor-based tuning allows for smoother transitions in radiation characteristics and improved beam quality, at the cost of paying careful attention to losses and linearity. Fig. 6. Metasurface antenna tuning using varactors with voltage-controlled capacitance variation, unit-cell integration, phase-gradient beam steering with continuous tuning, and RF/DC biasing networks with chokes and blocking capacitors.

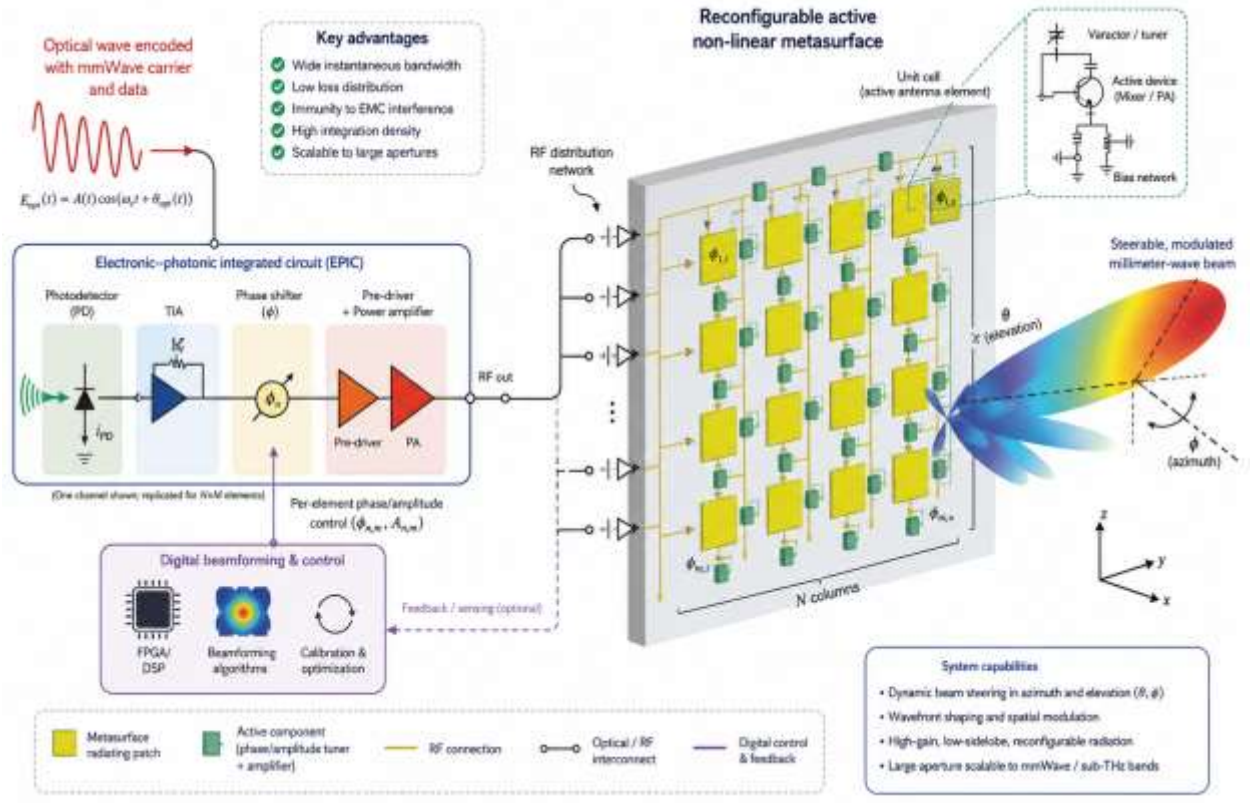


Figure 6: Varactor-Based Tunable Metasurface Design and Operation [46].

Varactor-based tunable designs offer a promising approach to achieve continuous high-resolution reconfiguration for metasurface antennas. Their capability to enable smooth phase and frequency control makes them very attractive for adaptive beamforming, dynamic spectrum use and the smart wireless environments predicted for 6G systems, provided that judicious exploitation of losses and non-linearities is achieved through optimised design.

5.3- MEMS-Based Reconfiguration:

The use of Micro-Electro-Mechanical Systems (MEMS) for reconfiguration provides a very efficient and accurate way to control dynamically the electromagnetic properties of metasurface-based antennas, particularly in applications where low loss and high linearity are required. MEMS devices work by changing electrical connections or structural arrangements at the microscale using mechanisms such as electrostatic, thermal or piezoelectric actuation. In metasurface implementations, MEMS switches are embedded in the unit cells to change the current paths, capacitance or inductance, and thus allow controlled variation in reflection, transmission and phase responses. This enables metasurfaces to implement functionalities such as beam steering, frequency tuning and radiation pattern reconfiguration with high accuracy and repeatability. One of the most important advantages of MEMS-based reconfiguration is the very low insertion loss and high isolation compared to the semiconductor-based alternatives such as PIN diodes and varactors. However, the use of MEMS-based reconfiguration also has some limitations that need to be carefully considered when designing practical implementations. MEMS devices have typically a slower switching speed (microseconds to milliseconds) which can be a limiting factor in their applications in highly dynamic real-time systems [47]. Moreover, the manufacturing process of MEMS components is more complicated and costly requiring the use of

specialised microfabrication techniques. Reliability issues including mechanical wear, stiction, and environmental sensitivity may also influence long-term performance [48]. Despite these challenges, MEMS technology still evolves and presents promising solutions for high performance metasurface antennas where efficiency and signal quality are the priorities.

5.4- Liquid Crystals and Smart Materials:

The intrinsic ability of liquid crystals and smart materials to change their electromagnetic properties under the action of external stimuli can be used to make metasurface-based antennas reconfigurable in an advanced and highly flexible way. In particular liquid crystals are characterised by a voltage dependent permittivity which allows to continuously tune the effective dielectric constant by the application of an electric field. Such a feature allows for continuous and analogue control of the phase, frequency and polarisation responses of the metasurface unit cells, which makes the liquid crystal based designs particularly suitable for applications, where high resolution and gradual adaptation is desired, such as adaptive beam steering and tunable frequency operation in 6G systems [49]. The introduction of liquid crystal layers within or beneath the metasurface structure offers an active means of controlling the wave propagation without significantly increasing the complexity of the structure. Besides liquid crystals, a broader class of smart materials has emerged as possible candidates for reconfigurable metasurface applications: phase-change materials, ferroelectrics and tunable dielectrics. Materials like vanadium dioxide (VO 2) can undergo a reversible phase transition from an insulator to a metal by means of thermal or electrical stimulus, which allows for an ultrafast switching of the electromagnetic properties. Similarly, ferroelectric materials offer electric-field-controlled permittivity tuning, which offers additional degrees of freedom for antenna reconfiguration. They can be tuned continuously and discretely based on their physical properties and excitation techniques, thus supporting a wide range of functionalities from frequency agility to polarisation control [50]. The advantages of using liquid crystals and smart materials are many, including compact integration, less reliance on complex biasing circuitry, high frequency operation, especially in the millimetre wave and terahertz regions. However, these methods have some drawbacks including relatively slower response time compared to the all-electronic switching, the susceptibility to environmental factors (e.g., temperature) and the challenges in the material fabrication. However, improvements in material science and nanofabrication continue to enhance their performance and reliability.

5.5- Graphene and THz-Enabled Materials:

Graphene and other terahertz (THz) enabled materials have emerged as highly promising enablers for next generation metasurface based reconfigurable antennas especially in the context of ultra-high frequency 6G communication systems. Graphene is a two dimensional material consisting of a single layer of carbon atoms in a hexagonal lattice. It possesses unique electrical and optical properties such as tunable surface conductivity, high carrier mobility and a strong interaction with electromagnetic waves in the THz regime [51]. These properties make graphene very suitable for dynamic tuning of the electromagnetic responses (e.g. phase, amplitude and frequency) at very high frequencies. The Fermi level of graphene can be tuned by an external bias voltage or chemical doping, which changes its conductivity and allows for real-time reconfiguration of metasurface unit cells. In metasurface antenna designs, graphene is typically used as a conductive layer or patterned into meta-atoms for tunable resonance and wave manipulation [52]. Unlike conventional semiconductor devices, the tuning in graphene is continuous and ultra-fast, without the need for cumbersome biasing circuits. This allows for compact and light weight structures for high resolution beam steering, frequency tuning and adaptive filtering.

Table 7: Comparison of Graphene and THz-Enabled Materials for Metasurface Applications [54].

Material Type	Switching Speed	Loss Level	Cost Level	Operating Frequency
Graphene	Ultra-fast (ps–ns)	Low–Moderate	High	THz range (0.1–10 THz)
Black Phosphorus	Fast (ns–µs)	Moderate	High	THz / IR
TMDs (e.g., MoS_2)	Fast (ns–µs)	Moderate	Medium–High	THz / Optical
Liquid Crystals	Slow (ms)	Low	Medium	GHz–THz
MEMS	Moderate (µs–ms)	Very Low	Medium	RF–THz

The comparison in Table 7 indicates that graphene has the fastest switching speed and thus good prospects for THz applications, making graphene a promising candidate for ultra-high-frequency reconfigurable metasurfaces. However, for practical implementations the materials have to be selected considering the trade-offs in cost and fabrication complexity. Figure 7 shows an example of a graphene-based metasurface antenna, which showcases the tunability of conductivity by tuning the Fermi level, the application of THz enabled materials in the unit cells, and beam steering by dynamic electromagnetic control.

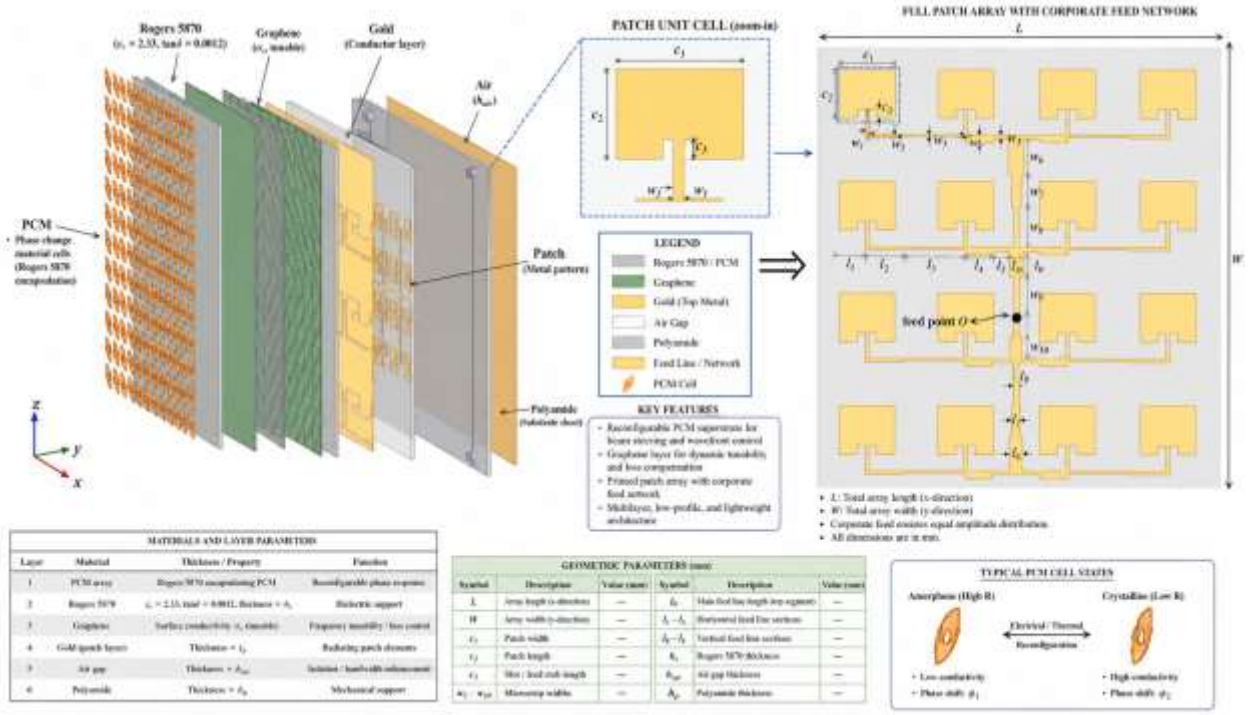


Figure 7: Graphene-Based and THz-Enabled Metasurface Antennas [56].

Graphene and terahertz (THz)-enabled materials are revolutionizing metasurface antenna technology, offering unprecedented capabilities for ultra-fast, high-frequency, and highly efficient electromagnetic control. These materials have excellent electrical and tunable surface conductivity properties, which enable the dynamic control of electromagnetic waves on the subwavelength scale, with functions such as real-time beam steering, frequency agility and polarization control. Smooth integration into reconfigurable metasurface architectures is predicted to be a key factor in the development of intelligent, high-capacity and ultra-low-latency 6G wireless communication systems.

6- Mathematical Modeling and Signal Processing Integration:

The mathematical modeling and signal processing is the heart of the realization of intelligent operation and performance optimization of metasurface-based reconfigurable antennas (MS-RAs) in 6G wireless systems. The possibility of manipulating electromagnetic waves through the physical structure of metasurfaces offers the ability to implement the metasurface in practical and adaptive communication, and it is the mathematical frameworks and signal processing algorithms that enable this ability. Precise control of the propagation of a wave requires accurate models of the relationship between the unit-cell parameters and electromagnetic responses, such as phase, amplitude and polarization.

6.1- Phase Modulation and Reflection Coefficient Modeling:

The mathematical foundation of metasurface-based reconfigurable antenna systems is modeling of phase modulation and reflection coefficients. Such models determine the interaction of electromagnetic waves with the designed unit cells and the desired wavefront transformations. Each metasurface element can be considered as a controllable scatterer with a complex reflection coefficient, which contains both the amplitude and phase information of the reflected signal. Spatially engineering these coefficients over the metasurface aperture enables the synthesis of arbitrary wavefronts for beam steering, focusing and multi-beam generation, enabling highly adaptive wireless communication systems.

$$\Gamma(x,y) = A(x,y)e^{j\phi(x,y)}$$

The reflection coefficient $\Gamma(x,y)$ depends on the local surface impedance and is derived from electromagnetic boundary conditions as [57]:

$$\Gamma(x,y) = \frac{Z_s(x,y) - Z_0}{Z_s(x,y) + Z_0}$$

where $Z_s(x,y)$ represents the tunable surface impedance of the metasurface unit cell and Z_0 is the intrinsic impedance of free space. The surface impedance can further be modeled using an equivalent RLC representation:

$$Z_s(x,y) = R(x,y) + j\omega L(x,y) + \frac{1}{j\omega C(x,y)}$$

which emphasises the effect of tunable resistance, inductance and capacitance on electromagnetic behaviour. In order to steer the beam a spatial phase gradient on the metasurface has to be applied. According to the generalised Snell's law [58]:

$$\sin\theta_r - \sin\theta_i = \frac{\lambda}{2\pi}\frac{d\phi(x)}{dx}$$

For two-dimensional metasurfaces, the phase gradient extends as:

$$\nabla\phi(x,y) = \left(\frac{\partial\phi}{\partial x}, \frac{\partial\phi}{\partial y}\right) \sin\theta_r\cos\phi_r - \sin\theta_i\cos\phi_i = \frac{\lambda}{2\pi}\frac{\partial\phi}{\partial x} \sin\theta_r\sin\phi_r - \sin\theta_i\sin\phi_i = \frac{\lambda}{2\pi}\frac{\partial\phi}{\partial y}$$

These expressions allow for full beam steering and wavefront control in 2D. For discrete metasurfaces, the phase quantisation is defined as:

$$\phi_n = \frac{2\pi}{2^b}(n-1), \quad n = 1,2,\ldots,2^b$$

where b represents the number of quantization bits. The quantization error is given by:

$$\epsilon_\phi = \phi_{\text{ideal}} - \phi_{\text{quantized}}$$

which directly affect the beamforming accuracy and the sidelobe performance. An extended array formulation [59] is used to model the total reflected electromagnetic field:

$$E_r(\theta,\phi) = \sum_{m=1}^{M}\sum_{n=1}^{N} A_{m,n}\, e^{j\phi_{m,n}} e^{jk(x_m\sin\theta\cos\phi + y_n\sin\theta\sin\phi)}$$

This formulation captures spatial interference, beam shaping, and radiation synthesis. For RIS-assisted communication systems, the cascaded channel model is expressed as:

$$y = \mathbf{h}_r^T \mathbf{\Phi} \mathbf{G} \mathbf{x} + n$$

with the reflection matrix:

$$\mathbf{\Phi} = \mathrm{diag}\left(A_1 e^{j\phi_1}, A_2 e^{j\phi_2}, \ldots, A_N e^{j\phi_N}\right)$$

The received signal power is given by:

$$P_r = |\mathbf{h}_r^T \mathbf{\Phi} \mathbf{G} \mathbf{x}|^2$$

The optimization of phase configuration can be formulated as:

$$\max_{\{\phi_n\}} \left| \sum_{n=1}^{N} h_{r,n}\, g_n e^{j\phi_n} \right|^2$$

For joint amplitude-phase optimization:

$$\max_{\{A_n, \phi_n\}} \left| \sum_{n=1}^{N} A_n\, h_{r,n} g_n e^{j\phi_n} \right|^2$$

subject to:

$$0 \le A_n \le 1, \quad \phi_n \in [0, 2\pi]$$

In multi-user scenarios, the optimization extends to spectral efficiency maximization [60]:

$$\max_{\mathbf{\Phi}} \sum_{k=1}^{K} \log_2 \left(1 + \frac{\left|\mathbf{h}_{r,k}^T \mathbf{\Phi} \mathbf{G} \mathbf{w}_k\right|^2}{\sum_{i \ne k} \left|\mathbf{h}_{r,k}^T \mathbf{\Phi} \mathbf{G} \mathbf{w}_i\right|^2 + \sigma^2} \right)$$

Phase modulation and reflection coefficient modelling offer a rigorous and comprehensive mathematical framework that combines electromagnetic theory, array processing and optimisation techniques. These models pave the way for accurate, adaptive and intelligent control of electromagnetic wave propagation, which is an important basis for the realisation of high performance metasurface-based communication systems in future 6G wireless networks.

6.2- Radiation Pattern Synthesis and Optimization:

The practical realisation of metasurface-based reconfigurable antennas relies heavily on the synthesis and optimisation of their radiation pattern describing the spatial distribution of the electromagnetic energy to meet particular communication requirements. Individual metasurface unit cells can jointly control the amplitude and phase responses, to engineer highly directive beams, suppress sidelobes, nulls towards interferers and multi-beam patterns for multi-user scenarios [61]. Instead of conventional antenna arrays, metasurfaces afford continuous or finely quantised manipulation at subwavelength scale, granting greater flexibility for radiation characteristic shaping in complicated propagation environments. The synthesised far-field pattern of a metasurface can be expressed by a generalised array factor for continuous or quasi-continuous apertures [62]:

$$E(\theta, \phi) = \iint_{\mathcal{A}} A(x, y)\, e^{j\phi(x,y)}\, e^{jk\,(x \sin\theta\cos\phi + y \sin\theta \sin\phi)}\, dx\, dy$$

where $A(x, y)$ and $\phi(x, y)$ represent the spatial amplitude and phase distributions over the metasurface aperture $\mathcal{A}$, and $k = 2\pi/\lambda$ is the wave number.

$$E(\theta, \phi) = \iint_{\mathcal{A}} A(x, y) e^{j\phi(x,y)} e^{jk(x \sin\theta\cos\phi + y \sin\theta \sin\phi)} dx dy$$

Radiation pattern synthesis can be formulated as an optimization problem where the objective is to match a desired far-field response $E_d(\theta, \phi)$. A commonly used formulation minimizes the mean squared error between the synthesized and desired patterns:

$$\min_{A,\phi} \int_{\Omega} |E(\theta,\phi) - E_d(\theta,\phi)|^2 \, d\Omega$$

subject to practical constraints on amplitude and phase:

$$0 \le A(x,y) \le 1, \quad \phi(x,y) \in [0,2\pi]$$

In many practical designs, phase-only optimization is preferred due to hardware simplicity, leading to:

$$\min_{\phi} \int_{\Omega} |E(\theta,\phi) - E_d(\theta,\phi)|^2 \, d\Omega$$

Such problems are usually solved by iterative techniques such as Gerchberg-Saxton algorithm, alternating projection method or convex relaxation approach. Additional constraints are imposed for discrete metasurfaces with quantised phase levels [63]:

$$\phi_n \in \left\{0, \frac{2\pi}{2^b}, \frac{2\cdot 2\pi}{2^b}, \ldots, \frac{(2^b-1)2\pi}{2^b}\right\}$$

introduces non-convexity and requires more sophisticated optimization techniques such as genetic algorithms, particle swarm optimization, or deep learning-based solvers. Another important goal in radiation synthesis is the minimization of the sidelobe level (SLL) which can be expressed as:

$$\min_{\phi} \max_{\theta \in \Theta_s} |E(\theta,\phi)|$$

where Θ_s denotes sidelobe regions. Similarly, null steering toward interference directions θ_i is achieved by enforcing:

$$E(\theta_i,\phi) = 0$$

These formulations can accurately suppress the interference and improve the signal-to-interference-plus-noise ratio (SINR). The design of RIS-assisted systems is closely tied to the channel-aware optimization of radiation pattern. The metasurface configuration is optimized to maximize the received power or the spectral efficiency. The goal for a given user can be expressed as

$$\max_{\mathbf{\Phi}} |\mathbf{h}_r^T \mathbf{\Phi} \mathbf{G} \mathbf{x}|^2$$

For multi-user scenarios, weighted sum-rate maximization is often considered [64]:

$$\max_{\mathbf{\Phi}} \sum_{k=1}^{K} w_k \log_2\left(1 + \frac{\left|\mathbf{h}_{r,k}^T \mathbf{\Phi} \mathbf{G} \mathbf{w}_k\right|^2}{\sum_{i \ne k} \left|\mathbf{h}_{r,k}^T \mathbf{\Phi} \mathbf{G} \mathbf{w}_i\right|^2 + \sigma^2}\right)$$

$$\max_{\mathbf{\Phi}} \sum_{k=1}^{K} w_k \log_2\left(1 + \frac{\left|\mathbf{h}_{r,k}^T \mathbf{\Phi} \mathbf{G} \mathbf{w}_k\right|^2}{\sum_{i \ne k} \left|\mathbf{h}_{r,k}^T \mathbf{\Phi} \mathbf{G} \mathbf{w}_i\right|^2 + \sigma^2}\right)$$

Design and optimization of radiation patterns for metasurface-based antennas is based on the combination of electromagnetic field modeling with advanced signal processing and optimization techniques. This integration enables accurate beam control, improved energy efficiency and adaptive interference management paving the way for intelligent and high performance 6G wireless communication systems.

6.3- Adaptive Beamforming Techniques:

To take full advantage of metasurface-based reconfigurable antennas, adaptive beamforming is essential because they have the capacity to dynamically adjust the radiation patterns according to the dynamic channel conditions, user mobility, and interference environment. Unlike fixed beamforming techniques, adaptive beamforming adapts the phase and/or amplitude of the metasurface unit cells over time to optimize a performance metric like the signal-to-noise ratio (SNR), the signal-to-interference-plus-noise ratio (SINR), or the system capacity [65]. In metasurface and RIS-assisted systems, beamforming is extended beyond the traditional antenna arrays by incorporating the programmable electromagnetic environments, enabling the joint optimization of the transmitter, metasurface and receiver. The received signal of a metasurface-assisted system can be modeled as:

$$y = \mathbf{h}_r^T \mathbf{\Phi G w} s + n$$

where $\mathbf{w}$ is the transmit beamforming vector, $\mathbf{G}$ is the channel from transmitter to metasurface, $\mathbf{h}_r$ is the channel from metasurface to receiver, and $\mathbf{\Phi}$ represents the metasurface reflection matrix. Adaptive beamforming aims to jointly optimize $\mathbf{w}$ and $\mathbf{\Phi}$ to maximize system performance.

$$y = \mathbf{h}_r^T \mathbf{\Phi G w} s + n$$

A common objective in adaptive beamforming is SINR maximization, which can be expressed as [66]:

$$\max_{\mathbf{w},\mathbf{\Phi}} \frac{|\mathbf{h}_r^T \mathbf{\Phi G w}|^2}{\sum_{i \neq k} \left|\mathbf{h}_{r,i}^T \mathbf{\Phi G w}_i\right|^2 + \sigma^2}$$

This problem is inherently non-convex due to the coupling between w and Φ, and is generally solved by iterative methods such as alternating optimization where one variable is optimized by fixing the other variable. Adaptive beamforming can be generally classified as classical, optimization-based and learning-based methods. Classical techniques such as Minimum Variance Distortionless Response (MVDR) and Least Mean Squares (LMS) are based on the statistical properties of the received signals [67]. For example, the MVDR beamformer minimizes the output power subject to a distortionless response in the look direction:

$$\min_{\mathbf{w}} \mathbf{w}^H \mathbf{R} \mathbf{w} \quad \text{s.t.} \quad \mathbf{w}^H \mathbf{a}(\theta_0) = 1$$

where $\mathbf{R}$ is the covariance matrix of the received signal and $\mathbf{a}(\theta_0)$ is the steering vector.

$$\min_{\mathbf{w}} \mathbf{w}^H \mathbf{R} \mathbf{w} \text{ s.t. } \mathbf{w}^H \mathbf{a}(\theta_0) = 1$$

Optimization-based approaches extend these formulations to metasurface systems by incorporating constraints on phase shifts:

$$\phi_n \in [0, 2\pi], \quad \left|\Phi_{n,n}\right| = 1$$

These approaches are often based on convex relaxations, semidefinite programming (SDP) or gradient-based optimizations to find near optimal solutions. Recently, machine learning and artificial intelligence (AI) based beamforming techniques have received considerable attention. These approaches learn optimal beamforming strategies directly from the environment based on data-driven models such as deep neural networks (DNNs) and reinforcement learning (RL). For instance, reinforcement learning can iteratively update the metasurface phase configurations according to reward signals, e.g., received power and SINR, which allows real-time adaptation without explicitly modeling the channel [68]. The achievable rate for such systems can be written as:

$$R = \log_2\left(1 + \frac{|\mathbf{h}_r^T \mathbf{\Phi G w}|^2}{\sigma^2}\right)$$

$$R = \log_2\left(1 + \frac{|\mathbf{h}_r^T \mathbf{\Phi G w}|^2}{\sigma^2}\right)$$

Adaptive beamforming methods provide a powerful framework for dynamically optimizing communication systems with metasurfaces. The techniques include electromagnetic control with advanced signal processing and AI-based algorithms for intelligent beam adaptation, enhanced interference management and increased spectral efficiency, all of which are essential for the future 6G wireless networks.

6.4- Channel Modeling in RIS-Assisted Systems:

Channel modeling for reconfigurable intelligent surface (RIS)-assisted systems is of great importance in the analysis and optimization of the performance of metasurface-enabled wireless communication. Different from the conventional wireless channels, the RIS-aided propagation process involves an extra controllable reflection stage, where the transmitted signal interacts with a programmable metasurface before arriving at the receiver [69]. This leads to a cascaded channel structure that combines the transmitter-to-RIS

channel and the RIS-to-receiver channel, so that the signal propagation characteristics including phase, amplitude, and direction can be flexibly manipulated. The received signal at the baseband equivalent in a RIS-aided system can be expressed as:

$$y = \mathbf{h}_r^T \mathbf{\Phi} \mathbf{G} \mathbf{x} + \mathbf{h}_d^T \mathbf{x} + n$$

where $\mathbf{G} \in \mathbb{C}^{N \times M}$ represents the channel matrix between the transmitter and RIS, $\mathbf{h}_r \in \mathbb{C}^{N \times 1}$ denotes the channel between RIS and receiver, and $\mathbf{h}_d$ is the direct channel between transmitter and receiver. The matrix $\mathbf{\Phi}$ is the RIS reflection matrix controlling phase shifts of each element, and n represents additive noise.

$$y = \mathbf{h}_r^T \mathbf{\Phi} \mathbf{G} \mathbf{x} + \mathbf{h}_d^T \mathbf{x} + n$$

The RIS reflection matrix is typically modeled as a diagonal matrix:

$$\mathbf{\Phi} = \mathrm{diag}\left(e^{j\phi_1}, e^{j\phi_2}, \ldots, e^{j\phi_N}\right)$$

where each phase shift $\phi_n \in [0, 2\pi]$ is independently controlled. In practical systems, amplitude control may also be considered:

$$\mathbf{\Phi} = \mathrm{diag}\left(A_1 e^{j\phi_1}, A_2 e^{j\phi_2}, \ldots, A_N e^{j\phi_N}\right)$$

The cascaded RIS channel can be compactly represented as:

$$\mathbf{H}_{\mathrm{RIS}} = \mathbf{h}_r^T \mathbf{\Phi} \mathbf{G}$$

which reveals the multiplicative coupling between propagation channels and RIS control. For realistic propagation environments, RIS-assisted channels are typically modeled by geometric or stochastic channel models. The channel in a geometric model with L propagation paths can be written as [70]:

$\mathbf{G} = \sum_{l=1}^{L} \alpha_l \, \mathbf{a}_{\mathrm{RIS}}\left(\theta_l^{\mathrm{RIS}}\right) \mathbf{a}_{\mathrm{Tx}}^H\left(\theta_l^{\mathrm{Tx}}\right)$ $\mathbf{h}_r = \sum_{k=1}^{K} \beta_k \, \mathbf{a}_{\mathrm{RIS}}\left(\theta_k^{\mathrm{Rx}}\right)$

where α_l and β_k are complex path gains, and $\mathbf{a}(\cdot)$ represents array response vectors. This formulation captures the spatial characteristics of RIS-assisted propagation.

$$\mathbf{G} = \sum_{l=1}^{L} \alpha_l \, \mathbf{a}_{\mathrm{RIS}}\left(\theta_l^{\mathrm{RIS}}\right) \mathbf{a}_{\mathrm{Tx}}^H\left(\theta_l^{\mathrm{Tx}}\right)$$

Under many scenarios, in particular for mmWave and THz bands, the RIS channels are often characterized by low-rank and sparse structures that can be exploited by compressed sensing and sparse recovery techniques for efficient channel estimation. The model of the received signal for estimation can be written as [71]:

$$\mathbf{y} = \mathbf{X}\mathbf{H}_{\mathrm{RIS}} + \mathbf{n}$$

where $\mathbf{X}$ is the pilot matrix. Accurate estimation of $\mathbf{H}_{\mathrm{RIS}}$ is challenging due to the passive nature of RIS elements, which lack RF chains. The achievable rate in RIS-assisted systems is given by:

$$R = \log_2\left(1 + \frac{|\mathbf{h}_r^T \mathbf{\Phi} \mathbf{G} \mathbf{w}|^2}{\sigma^2}\right)$$

$$R = \log_2\left(1 + \frac{|\mathbf{h}_r^T \mathbf{\Phi} \mathbf{G} \mathbf{w}|^2}{\sigma^2}\right)$$

One of the most widely used optimization problem for RIS-assisted channels is the maximization of the received power or spectral efficiency over the transmit beamforming vector and RIS phase shifts. This results in very non-convex optimization problems, for which alternating optimization, semidefinite relaxation and deep learning based approaches are usually used. Moreover, the channel model should account for practical limitations like phase noise, finite-phase quantization of the RIS elements, mutual coupling among the RIS elements and hardware non-idealities. These are all important factors to consider when dealing with real world performance and would be a part of more advanced models that would be used to design a system.

6.5- AI/ML-Based Optimization for Metasurfaces (Reinforcement Learning and Deep Learning):
With the recent progress in artificial intelligence and machine learning, it is a promising direction to optimize reconfigurable antennas based on metasurfaces, especially in the complex and

dynamic wireless systems for 6G technologies. On the other hand, AI/ML enabled approaches can provide data-driven optimization, where metasurfaces can be trained to optimize their configuration directly from measurements of their environs, and adapt their lattice configuration with minimal latency as the environment changes [72]. For this type of reconfigurable antennas, large-scale reconfigurable intelligent surface systems with potentially very large number of controllable elements are particularly advantageous. One of the most promising approaches to optimizing metasurfaces is reinforcement learning that allows the learning of an intelligent agent, which interacts with the environment, to reach an optimal control policy. In this approach, the metasurface controller is employed here as an agent, taking an observation of the system state and making an appropriate action towards it, such as varying phase shifts or amplitude values of the RIS elements. Next, the performance measure like received signal power, SINR and system capacity is given as a reward signal by the environment. The RL agent is trained to get a reward by learning a policy to maximise the average reward over a period of time, and the policy is not only adaptively trained, but also real-time, without such explicit model knowledge of the channel. For example, popular RL methods, like Q-learning, Deep Q-Networks and Policy Gradient methods have been applied successfully in beamforming and phase optimization problems for RIS [73]. Deep learning-based approaches improve the optimization ability by employing neural networks to mimic complex nonlinear mappings from the channel states of the input to the optimal metasurface configurations. In supervised learning, classical optimisation algorithms are used to prepare data sets with labels, and then train a neural network using the data sets. This can be used to make quick inferences when deployed. Alternatively, performance objectives can be directly optimized by unsupervised and self-supervised learning methods without the need of labeled data [74]. With the aim of efficient prediction of optimal phase distributions, spatial correlations between metasurface elements are modeled using deep neural networks, convolutional neural networks and graph neural networks. These models can greatly reduce the complexity of computation and make real-time decisions in large scale RIS systems. RL and DL has also been used together in hybrid learning approaches, which apply DL to solve high-dimensional optimization problems using reinforcement learning. Figure 8 shows a comprehensive picture of the signal processing chain in RIS-assisted systems, and the paths of the electromagnetic signals from the transmitter, controlled reflection and manipulation on the RIS to the receiver. In this case, there are AI/ML based optimization modules which can be expressed as reinforcement learning and deep learning algorithm to constantly monitor CSI and SPIs.

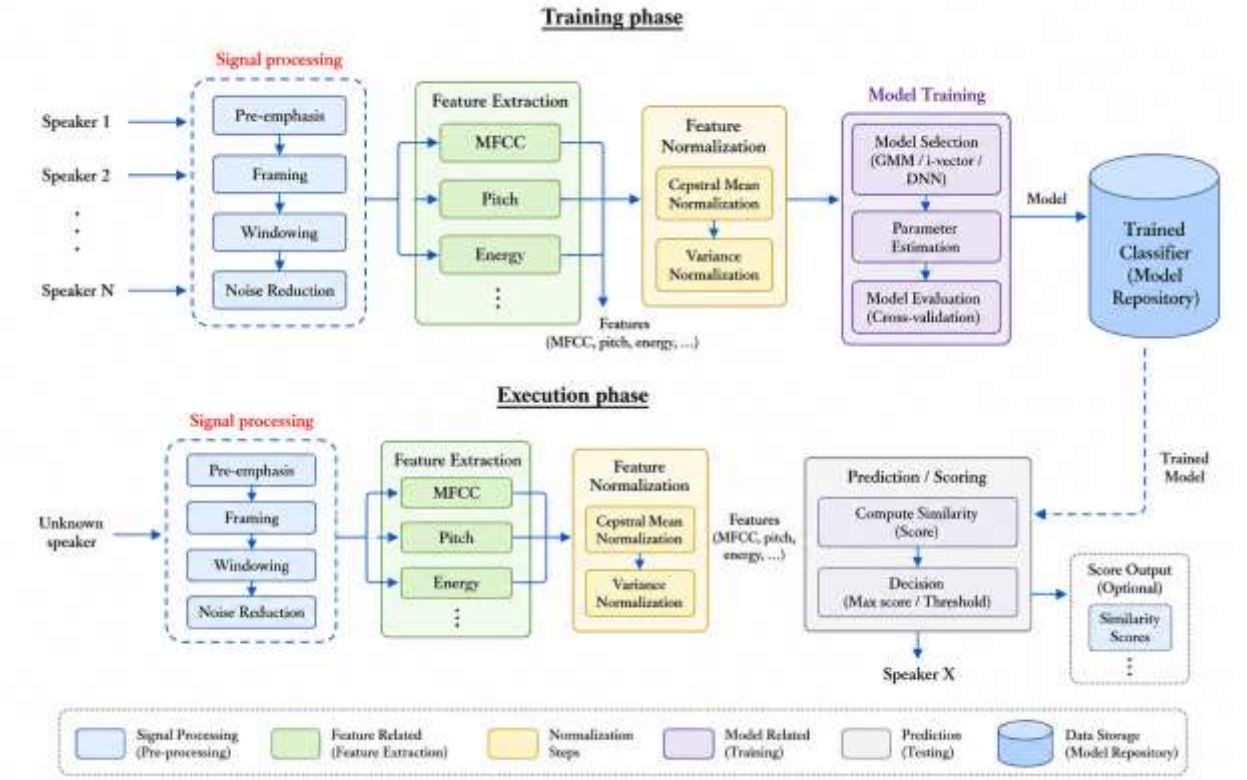


Figure 8: Signal Processing Pipeline for RIS-Based Systems with AI/ML Optimization [76]

For intelligent metasurface control, the optimization techniques based on AI/ML like reinforcement learning and deep learning provide a transformative paradigm. These approaches could enhance the efficiency and feasibility of metasurface-based communication systems, offering significant potential for improved performance and usability. With the increasing intelligence and autonomy of 6G networks, the future of wireless communication is likely to be significantly influenced by AI optimization of metasurfaces.

7- Recent Advances in Metasurface Antennas:

The advent of smart, adaptive and high performance wireless communication systems in the last few years has witnessed tremendous developments on the metasurface based antenna technologies. To date, these advances have allowed metasurfaces to function not only as passive electromagnetic devices, but also to take on the roles of platforms for the active and in situ control of wave propagation. Together with the use of advanced signal processing, materials and fabrications have paved the way for e.g., dynamic beam steering, frequency agility, polarization control and environment-aware communication [77]. Furthermore, the combination of metasurfaces with new technologies like artificial intelligence, terahertz communication and software-defined networking has drastically increased the applicability in a plethora of 6G use cases. The results demonstrate that metasurfaces antennas are an important technology approach for future wireless systems.

7.1- RIS and Intelligent Reflecting Surfaces:

One of the greatest advancements in metasurface-based antenna systems is Reconfigurable Intelligent Surfaces (RIS) or so-called intelligent reflecting surfaces. RIS is comprised of large configuration of low cost passive or semi-passive elements to dynamically manipulate the components of the wireless signal propagation to

control the signal transmission property [78]. RIS can reflect impinging signals with programmable phase shifts, while the traditional relay system will transmit and amplify; moreover, only RIS can reflect impinging signals. Unlike the traditional relay systems, in which signals must be actively transmitted and amplified, RIS can reflect impinging signals and adjust the propagation phase in different ways, allowing signals to be transmitted with low energy per unit propagation. This allows RIS to increase the signal without the use of additional power-consuming equipment, resulting in greater coverage, range and interference cancellation. The idea of RIS-aided communication systems is based on transforming the wireless channel into a controllable channel, with the propagation environment being a part of the communication design [79]. RIS can be used intelligently to manipulate the phase shift of its constituent elements to send the signal to the desired user, thereby providing the desired user(s) with favourable propagation pathways even when signal propagation and reception is problematic, such as when the RF transmission line is obstructed by non-line-of-sight conditions [80]. Furthermore, using techniques of artificial intelligence, RIS adapts its operation in real time based on various channel conditions, ranging from the mobility and location of the users, to the varying requirements of the network, leading to autonomous and intelligent wireless environments. The suite of capabilities lets the wireless propagation through RIS to become programmable and optimized rather than random, a key requirement in the development of smart electromagnetic environment. Table 8 shows a brief comparison for the essential features to illustrate the benefits and properties of RIS technology over traditional technologies.

Table 8: RIS vs Conventional Wireless Technologies [81]

Feature	Traditional Relay Systems	Massive MIMO	RIS-Based Systems
Power Consumption	High (active RF chains)	High	Very Low (passive elements)
Signal Processing Complexity	Moderate	High	Moderate–High
Hardware Cost	High	Very High	Low
Channel Control	Limited	Partial	Full environment control
Energy Efficiency	Moderate	Low–Moderate	High
Suitability for 6G	Limited	Moderate	Excellent

The energy efficiency and low power consumption, along with a full control of the wireless environment enable the creation of a wireless environment where no other system can match, making RIS systems extremely suitable for the future 6G applications. Though the massive MIMO system has strong beamforming capabilities, the RIS can also control the environment and boosts into the technologies. The concept of RIS using the communication scenario is shown in Figure 9 wherein the signal transmitted by the base station is captured and intelligently reflected by the RIS with proper phase shifts. The RIS diverts the propagation paths, and focuses the reflected waves on the user to greatly improve the signal quality and reception. This adaptive control of the wireless environment enables more efficient communication in non-line-of-sight scenarios, and enables the performance requirements for the advanced 6G systems.

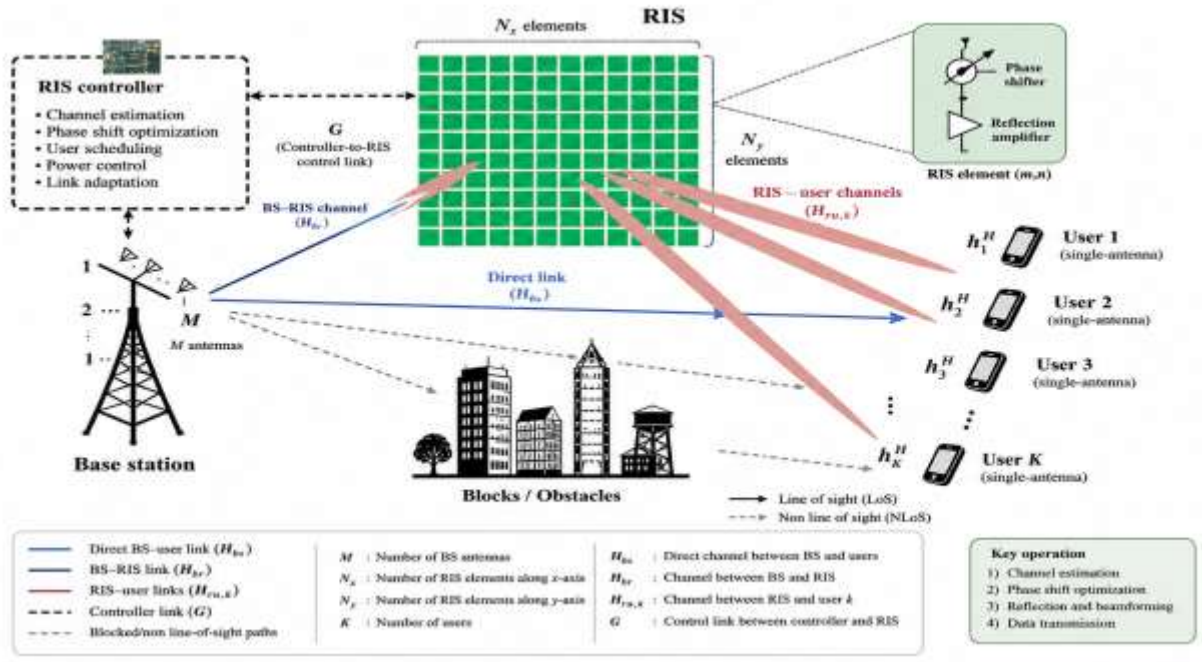


Figure 9: RIS-Assisted Wireless Communication System [82].

In addition, the discrete phaseshift, finite fringe lengths, imperfections of the hardware, and mutual coupling between handles need to be considered in the system design. But these challenges are being gradually resolved as continously evolving designs of metasurfaces, optimization algorithms, and control algorithms based on AI develop, respectively. A new era of wireless communications, with programmable and energy-efficient electromagnetic environments, is now ushered in by RIS and intelligent reflecting surfaces. Their integration with advanced signal processing and optimized intelli Technologies makes them key technologies for the next generation of 6G wireless networks.

7.2- THz and Holographic MIMO Systems:

The great breakthrough of the researches about metasurface-based antennas is Terahertz communication as well as holographic multiple-input multiple-output (MIMO) systems that will enable the data rate, spatial resolution and unprecedented control of the electromagnetic field for the future 6G network. The THz systems operate in the frequency spectrum range from 0.1 to 10 THz, and offer tremendous bandwidth that remains unused and can be used for tera-bit/s data transfer. The path loss, molecular absorption and limited propagation range problems limit the use of these systems. To overcome these, the propagation of the signal and the system performance are enhanced by metasurfaces based architectures like RIS and holographic surfaces [84]. In holographic MIMO technologies, the conventional massive MIMO technologies that use ultra-dense continuous or quasi-continuous electromagnetic apertures are extended. In the case of holographic MIMO the MIMO surface is treated as a continuous electromagnetic field, allowing to form the wavefront with a high fidelity and to sum up a high number of spatial degrees of freedom. It offers the benefit of greater beamforming accuracy, greater spectral efficiency, and good performance in near-field communication environments. Recent works have shown that holographic RIS systems can replace the ideal continuous aperture by densely packing sub-wavelength elements, to provide better beam control and channel capacity in comparison to traditional RIS implementations [85].

In THz metasurface systems, the use of advanced materials such as graphene and plasmonic structures can enable high-frequency operation and dynamic tunability. To mitigate the propagation challenges, these systems utilize highly directional beams and adaptive beam tracking. Moreover, THz channels are sparse in angular and delay domains, so efficient signal processing techniques like compressive sensing can be used for channel estimation and beamforming optimization [86]. Recent experimental advances have also shown programmable metasurface-based holographic MIMO systems with multi-channel transmission and enhanced effective degrees of freedom, which highlights the strong potential of the holographic MIMO systems for the next-generation wireless systems. RIS-aided holographic MIMO can further enhance the system capabilities by allowing the programmable manipulation of the electromagnetic environment [87].

Table 9: Comparison of Recent Works in THz and Holographic MIMO Systems [88]

Study / Approach	Technology Focus	Frequency Range	Key Contribution	Performance Gain
Holographic RIS (Wan et al.)	THz Massive MIMO + RIS	THz	Continuous aperture modeling, compressive sensing CE	Improved beam accuracy & reduced pilot overhead
Programmable Digital Coding Metasurface	Holographic MIMO	GHz–mmWave	Multi-channel QPSK transmission	Increased DoF (˜2.16), cost reduction
THz RIS-Based Systems	THz Communication	0.1–10 THz	Sparse channel modeling, adaptive beamforming	High spectral efficiency
Ultra-Dense RIS Arrays	Near-field MIMO	mmWave–THz	Quasi-continuous surface approximation	Enhanced spatial resolution

The recent research trends, as indicated in Table 9, are in the direction of continuous-aperture designs, THz integration, and intelligent signal processing, which altogether enhance the system performance and scalability. In particular, holographic MIMO represents a substantial step beyond conventional massive MIMO, providing fine-grained spatial control and increased degrees of freedom [89]. Figure 10. THz and holographic MIMO systems with continuous metasurface apertures, ultra-dense RIS elements and adaptive beamforming for next generation high frequency communication.

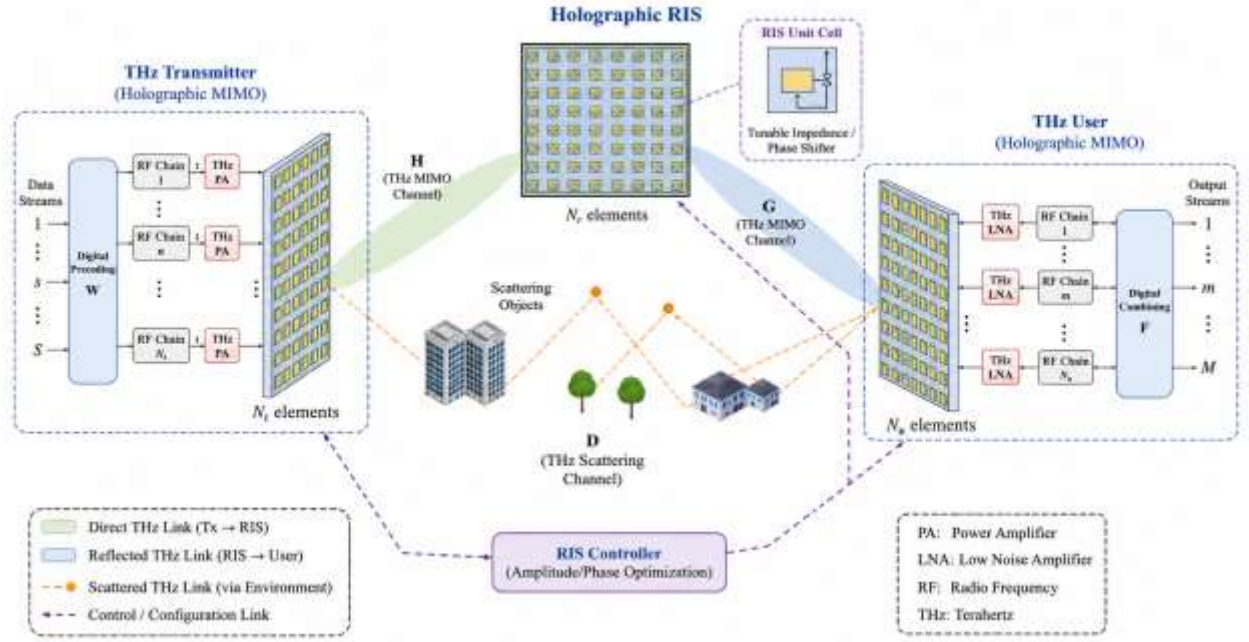


Figure 10: THz and Holographic MIMO-Based RIS Communication System [90].

8- Comparative Analysis of Existing Approaches:

There is a need for an in-depth comparison of reconfigurable antenna technology based on metasurfaces and other reconfigurable technologies to comprehend their performance advantages, trade-offs and potential for applicability in future 6G wireless systems. During the past decade, several reconfiguration techniques have been proposed such as PIN diode switching, varactor tuning, MEMS actuation, liquid crystal and smart material modulation, graphene-based plastic even THz control, and finally RIS reconfiguration architectures providing adaptive electromagnetic functionalities. All these strategies are expected to realize the dynamic manipulation of wave propagation, but quite different in the gain, radiation efficiency, bandwidth, response speed, system complexity, scalability and energy consumption. Thus, a joint evaluation using these major indicators provides good insight of their applicability in practice. Gain, efficiency and bandwidth are still the larger measures of the effectiveness of an antenna for performance. Due to the low insertion loss and high isolation, the MEMS based systems normally have the highest efficiency (80-95%) and gain (10-18 dBi) and are suitable for high frequency and precision applications [91]. For ultra-wide bandwidths (20–50%) and high gains (12–20 dBi), with a particular focus on the terahertz realm for communication applications, these are graphene and THz-enabled metasurfaces. With clever manipulation of the propagation environment, gains of up to 25 dBi and efficiency greater than 90% can be achieved at the system level with RIS-based systems [92]. Variable tuning is based on a varactor, which offers a good compromise with 10-25% continuous tuning and efficiencies up to 90%. PIN diode-based techniques have restricted bandwidth (5–15%), but also offer strong and stable operation, rapid switching characteristic. In contrast, by use of liquid crystal based systems, moderate performance is achieved, but in most cases, these systems have one of the most significant drawbacks: slow response time [93].

The use of electronic techniques (PIN diodes, varactors) is very desirable in terms of complexity and scalability, given that these can be easily incorporated into conventional RF circuit design and fabrication. They can be expanded to moderately large arrays, but the complexity of the

biasing networks increases with the array size. While the performance of MEMS-based system is excellent, it has complex requirements on microfabrication and packaging, which hinder the successful implementation on large deployments [94]. The design of graphene and advanced material based design adds another challenge regarding uniformity of the material, fabrication accuracy and high surface uniformity for the integration. The main advantage of large-scale RIS-based architectures is their passive manner and they are inherently scalable, but sophisticated control algorithms and efficient channel estimation techniques are needed for real-time operation of thousands of elements. Another main consideration for sustainable 6G communication systems is energy efficiency. The RIS based solutions are passive/near passive solutions that result in lower power consumption and are more energy efficient due to their operation without requiring active components and consuming very little power [95] to achieve a substantial gain in the system performance. Another advantage for a MEMS system is that there is very little power used, especially when they are in a steady state, as energy has to be utilised during a switching. The continuous tuning mechanisms result in relatively low power consumption for varactor- and liquid-crystal-based designs. Appendix systems, on the other hand, use the PIN diode system and must have a moderate level of power due to the necessity of constant biasing particularly in the case of large arrays. Graphene based devices can have low electromagnetic energy consumption, but they might require more energy for control and fabrication [96].

The practical feasibility of deployment depends on a combination of cost, reliability, maturity of fabrication and the ability to integrate with the existing communication infrastructure. PIN-diode and varactor based metasurfaces are the most mature technologies currently, widely adopted for their low cost, ease of implementation and compatibility with existing RF systems. MEMS-based solutions are high performing but face challenges in reliability, packaging and manufacturing complexity [97]. Liquid crystal and smart materials based approaches are still actively researched and improvements of response time and environmental stability are ongoing. Graphene and THz-enabled systems are considered as emerging technologies with a huge potential but limited large-scale deployment due to fabrication challenges [98]. Nevertheless, RIS-based systems have recently gained a lot of attention as a practical and scalable solution to enhance wireless networks without requiring re-design of the existing infrastructure, which is highly promising for the near-term 6G deployment.

Table 10: Comparative Evaluation of Metasurface Reconfiguration Techniques

Technique	Gain (dBi)	Efficiency (%)	Bandwidth (%)	Switching Speed	Complexity	Scalability	Energy Consumption
PIN Diodes	6 – 12	60 – 85	5 – 15	1–100 ns	Moderate	High	Moderate
Varactors	7 – 14	65 – 90	10 – 25	10–100 ns	Moderate	High	Low–Moderate
MEMS	10 – 18	80 – 95	15 – 30	1–100 µs	High	Moderate	Very Low
Liquid Crystals	5 – 10	50 – 80	10 – 20	1–10 ms	Low–Moderate	Moderate	Low
Graphene / THz	12 – 20	70 – 95	20 – 50	ps–ns	High	Low–Moderate	Moderate–High
RIS-Based Systems	10 – 25	75 – 98	20 – 60	µs–ms	Moderate–High	Very High	Very Low

The comparison results in Table 10 indicate that no approach is the best for all cases and each technique has its own advantages for the application scenario. High-performance systems like MEMS and graphene-based metasurfaces are highly efficient and broadband, but limited in scalability and cost. On the other hand, PIN diode and varactor based approaches offers practical and scalable solutions with moderate performance trade-offs. RIS-based systems are one of the most promising technologies for future 6G networks due to their unique combination of high efficiency, scalability, and environmental adaptability. Choice of an appropriate metasurface reconfiguration approach should be carefully balanced with respect to performance, complexity, energy efficiency, and deployment feasibility [99]. In future, hybrid and multi-functional designs will be the focus. They integrate multiple technologies to compensate for the limitations. Such approaches will be key to the development of intelligent, adaptive and high-performance metasurface-based communication systems, ultimately leading to the realization of next-generation 6G wireless networks.

9- Design Challenges and Practical Limitations:

The challenges and limitations in designing and implementing metasurface-based reconfigurable antennas and RIS technologies in 6G wireless systems are still many, which have made their large-scale deployment and deployment in the real world difficult. These challenges are due to the complex interrelation of electromagnetic behavior, hardware constraints, material properties and signal processing requirements [100]. This needs to be addressed to overcome this limitation and close the gap to develop communication systems based on these advances in theory. The difficulty in fabrication, particularly for more complex metasurface designs with the incorporation of MEMS components, graphene materials or ultra dense RIS arrays [101] is one of the key challenges. Simple electronic devices, such as PIN diodes and varactors, are generally relatively inexpensive and more easily made with standard PCB methods, but with new innovations, higher resolution patterning, precision material deposition, and more complex nanofabrication processes are on the horizon. This contributes to the fabrication cost and restricts scalability mainly when it comes to integrating thousands of unit cells into a single metasurface [102]. Moreover, uniformity and reliability on large areas may be still difficult, particularly for flexible/flexfilm and large area applications. Other effects of interest that are difficult to overcome are switching losses and nonlinear action of the active and tunable elements [103]. The operation of the RIS based systems are generally passive and hence these systems are energy efficient, however the power consumption of control circuit, biasing networks, and signal processing units attached to them are not ignored [104]. The cost of actively controlling, for each element, thousands of systems (active metasurfaces) may be significant, limiting the efficiency of the systems. In addition, thermal management also becomes extremely relevant in dense systems due to the risk of poor performance and reliability caused by excess heat.

A major difficulty is the mutual coupling and EMI between the neighboring unit cells. If the designs are ultra-dense, the strong coupling effects can alter the desired electromagnetic response of each element, causing deviations from the desired radiation pattern. This phenomenon makes it more difficult for design and modelling because of the lack of independent element assumptions and their respective characteristics. In addition, there may be undesirable coupling effects that may cause interfering effects and impact beamforming accuracy particularly in high frequencies or near field applications [105]. Last but not least, the real-time control and latency are huge challenges for adaptive metasurface systems. The reconfiguration of the phase and amplitude of potentially elements should be fast. This requires not only rapid control algorithms but also a low latency communication between the controller and the metasurface hardware. As passive elements similar to an antenna in RIS systems, channel estimation is also a challenging problem in the RIS-assisted systems, worsening this problem. Although AI/ML techniques are promising solutions, they also

come with added complexity and computational burden in implementation.

10- Future Research Directions:

By creating intelligent, adaptive and fully programmable electromagnetic environments, reconfigurable antennas based on metasurfaces will revolutionize the basics of wireless communication. Future 6G systems will be capable of providing ultra-high data rates and sub-milliseconds latency, as well as seamless integration of communication, sensing and computation, and metasurfaces will gradually become more than just passive wave manipulators and will be autonomous and cognitive. The next wave of innovation will be based on the integrated use of advanced materials, Artificial Intelligence, Terahertz technologies and distributed computing, with the aim of making wireless networks self-optimizing ecosystems [107]. These advances will not only drive better communications performance, but will make possible novel models like environment-aware networking, digital twin-enabled optimization, and fully software-defined wireless architectures.

- **AI-Driven Autonomous Antenna Systems:**

In the future metasurface antennas will be fully independent and have AI features that will allow them to learn, adapt and optimize their electromagnetic response while in operation. The antennas will dynamically tune their phase, amplitude and polarization based on the environment, the user mobility, and the network needs by using reinforcement learning, deep neural networks and federated learning frameworks [108].

- **Terahertz Communication Integration:**

Together with the terahertz (THz) communication technology, metasurface antennas will lead to an unprecedented bandwidth and data rate, paving the way for data transmission on terabit-per-second wireless links. Future studies will focus on the realization of low losses and high efficiencies THz metasurfaces based on the use of advanced materials such as plasmonic nanostructures and graphene [109]. Ultra-directional beamforming or adaptive beam tracking with signal enhancement from RIS can be utilized to overcome some of the challenges of high propagation loss and limited coverage [110]. By combining the THz communication and metasurface technology, it would be important in various applications, such as holographic communication, high resolution sensing and immersive virtual reality, etc.

- **Smart Electromagnetic Environments:**

Another very promising research trajectory for 6G is the concept of smart electromagnetic environments, that is, information is transmitted over a smart and programmable medium. Using large scale RIS in an indoor or outdoor deployment, one can dynamically control wireless channels for enhanced signal coverage, reduced interference and improved energy efficiency [111].

- **Towards Fully Programmable Wireless Networks:**

The ultimate goal of future wireless systems is to realize completely programmable networks with software-defined interfaces for hardware and the propagation environment. In this paradigm, metasurfaces will be used in combination with software-defined networking and network function virtualization frameworks [112]. It will enable reconfiguration of the network resources and adaptive spectrum management and seamless integration of communication, sensing and computing functions. As new applications continue to emerge including integrated sensing and communication, extended reality, and intelligent transportation systems [113], fully programmable wireless networks will be able to support these applications. In the future, the 6G smart electromagnetic environment is expected to be truly exciting, as the reconfigurable intelligent surface, artificial intelligence control, edge computing, digital twin and programmable wireless infrastructure will all work together to create adaptive and intelligent wireless communication (Figure 11).

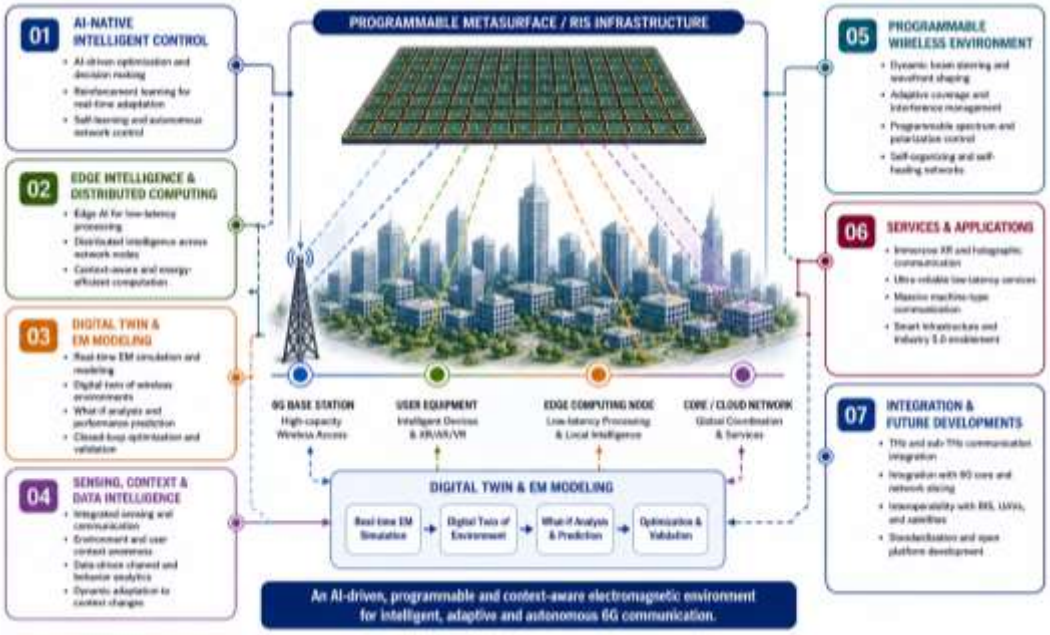


Figure 11: Future 6G Smart Electromagnetic Environment Architecture [114].

Current research trends for reconfigurable antennas with metasurfaces focus on intelligence, programmability and integration with new technologies. The fusion of AI, THz communications, smart environment and digital twin paradigms for next generation metasurface systems will set the ground for a paradigm shift towards fully autonomous and adaptive wireless networks, which will be the technological backbone of 6G and beyond.

11- Public Datasets and Open-Source Platforms for Metasurface and RIS Systems:

The advent of public data sets and open-source platforms it has become more simple to create metasurface based reconfigurable antenna and reconfigurable antenna communication systems. Publicly available data sets and open-source platforms have enabled the design of publicly used reconfigurable antennas and reconfigurable antenna communication systems such as those capable of beam forming for public use with metasurface-based technology. The reproducible research, algorithm benchmarking and quick prototyping of smart wireless systems constitute a crucial aspect of these resources [115]. Standardized datasets, and simulation environments, are significant in terms of being able to validate theoretical models and to provide a fair comparison between different methodologies. To address the complexities of electromagnetic behaviour and large-scale optimisation, public datasets are utilized in 6G research when simulating the performance of the system in real-world situations, where adaptability is key, due to the use of Artificial Intelligence. The popular DeepMIMO Dataset, for instance, is a popular choice for RIS and mmWave simulations, and contains ray-tracing based channel data for various scenarios [116]. Similarly, the Wireless Dataset used to validate the high-frequency propagation model is data from real-world measurements in urban and indoor environments that is provided at NYU. These datasets enable lower cost experiments, and good fidelity of the evaluated system. Targeted design, analysis and optimization of metasurface systems can in turn be facilitated by open-source platforms and simulation platforms. Modelling of the RIS assisted communication systems can be performed using a numerical computing environment such as MATLAB and simulation tools such as SimRIS Toolbox [117] can be used to simulate their performance. In computer vision, deep learning

algorithms are used and the algorithms are optimized using AI and implemented using computer frameworks such as TensorFlow or PyTorch, the same goes for the reinforcement learning algorithms. In addition, the modelling of the metasurface unit cells and antenna structures can also be achieved by using electromagnetic simulation software like HFSS and CST Studio Suite.

Table 11: Public Datasets and Open-Source Platforms for Metasurface and RIS Research

Resource Type	Name	Application Area	Key Features	Usage in Research
Dataset	DeepMIMO	RIS, mmWave Channels	Ray-tracing based, scalable scenarios	Beamforming, channel modeling
Dataset	NYU Wireless	mmWave/THz Communication	Real-world measurements	Propagation modeling, validation
Simulation Tool	MATLAB / Simulink	Signal Processing & Modeling	Extensive toolboxes, flexible environment	Algorithm development
RIS Tool	SimRIS Toolbox	RIS System Simulation	Channel modeling, phase optimization	RIS performance evaluation
AI Framework	TensorFlow	Deep Learning	Scalable neural networks	AI-based optimization
AI Framework	PyTorch	Machine Learning	Dynamic computation graphs	RL and DL models
EM Simulator	HFSS	Electromagnetic Analysis	High-precision FEM solver	Antenna and metasurface design
EM Simulator	CST Studio Suite	EM Simulation	Time-domain and frequency-domain analysis	Unit-cell and system modeling

Table 11 offers a comprehensive tabulation of the variety and significance of resources available publicly that can be used for advancing metasurface research. Researchers will be able to build accurate models using these tools and the datasets, apply sophisticated optimisation techniques and evaluate the system's operation in a realistic environment. In general, open-source platforms and open datasets create a research environment can be described as collaborative and standardised [118]. It can considerably reduce development time, improve the repeatability and help transfer the theory of the innovation to actual products. As the research of 6G moves forward, the provision and expansion of these resources will be crucial in facilitating intelligent, scalable and high-performance metasurface-based wireless communication systems.

Conclusion:

In this paper, a detailed and comprehensive review of a reconfigurable antenna as a disruptive technology for emerging 6G wireless communication systems in the context of metasurfaces is provided. The basic principles of metasurface operation, the mechanisms of electromagnetic control (EMC) of the metasurface, such as phase, amplitude and polarization manipulation, were systematically covered and the enabling technologies of the metasurface were explained in detail. The key technologies such as PIN diodes, varactors, MEMS, liquid crystals and graphene-based materials were thoroughly analyzed for their performance, scalability, and feasibility. Moreover, in the mathematical modeling section, advanced signal processing techniques like phase modulation, reflection coefficient modeling, adaptive beamforming and RIS-assisted channel

modeling were discussed to emphasize the need for intelligent control for the improvement of metasurfaces performance. The paper also emphasized the recent advances of metasurface antenna system, especially in Reconfigurable Intelligent Surfaces (RIS) architecture, THz communication, and holographic MIMO technologies to pursue the goal of intelligent and programmable wireless environments. It included a comprehensive comparative analysis of existing methods, discussing the merits and demerits of various implementations in terms of gain, efficiency, bandwidth, implementation complexity, energy efficiency and deployability of the method used. This analysis revealed that the technology capable of addressing all the 6G related challenges is not one but rather hybrid and integrated technologies are highly likely to offer optimal performance in different 6G use-cases. Besides, various fabrication complexities, switching losses, power consumption, mutual coupling and real-time control constraints were observed as the design problem. It is necessary to solve these problems, to connect the theoretical aspects with the practical use at large scale. Future directions of research are then proposed, highlighting different approaches on autonomous antenna systems with artificial intelligence, the introduction of terahertz, smart electromagnetic environments, the use of digital twin for optimization and totally programmable wireless networks. In short, reconfigurable antennas with metasurface technology will be a key component of the future 6G communication system to enable intelligent, adaptive and high-performance communications. The systems could change the wireless communication paradigm and could offer more accurate and dynamic control of the propagation of electromagnetic waves. Interdisciplinary investigations (involving electromagnetics, materials science and signal and artificial intelligence) are fundamental for fully exploiting metasurface technologies and break new ground for the next generation wireless networks.

References:

[1] W. Yang, J. Li, D. Chen, Y. Cao, Q. Xue, and W. Che, "Advanced Metasurface-Based Antennas: A Review," *IEEE Open J. Antennas Propag.*, vol. 6, no. 1, pp. 6–24, Feb. 2025, doi: 10.1109/OJAP.2024.3465513.

[2] Z. N. Chen, X. Qing, W. Liu, H. Sheng, T. Li, and B. Zhang, "Toward Metantennas: Metasurface Antennas Shaping Wireless Communications," *IEEE Commun. Mag.*, vol. 62, no. 8, pp. 94–99, Aug. 2024, doi: 10.1109/MCOM.001.2400047.

[3] A. C., V. Singh, A. K. Dwivedi, and N. K. Narayanaswamy, "Review: Metamaterial/metasurface applications in antenna domain," *Opto-Electron. Rev.*, pp. 151692–151692, Aug. 2024, doi: 10.24425/opelre.2024.151692.

[4] M. Huang *et al.*, "A comprehensive review of metasurface-assisted direction-of-arrival estimation," *Nanophotonics*, vol. 13, no. 24, pp. 4381–4396, Nov. 2024, doi: 10.1515/nanoph-2024-0423.

[5] H. Kim, S. Oh, S. Bang, H. Yang, B. Kim, and J. Oh, "Independently Polarization Manipulable Liquid- Crystal -Based Reflective Metasurface for 5G Reflectarray and Reconfigurable Intelligent Surface," *IEEE Trans. Antennas Propag.*, vol. 71, no. 8, pp. 6606–6616, Aug. 2023, doi: 10.1109/TAP.2023.3283136.

[6] Z. N. Chen, "Metantennas: From Patch Antennas to Metasurface Mosaic Antennas (Invited Paper)," in *2020 IEEE Asia-Pacific Microwave Conference (APMC)*, Hong Kong, Hong Kong: IEEE, Dec. 2020, pp. 363–365. doi: 10.1109/APMC47863.2020.9331404.

[7] A. Ghaneizadeh, P. Gavriilidis, M. Joodaki, and G. C. Alexandropoulos, "Metasurface Energy Harvesters: State-of-the-Art Designs and Their Potential for Energy Sustainable Reconfigurable Intelligent Surfaces," *IEEE Access*, vol. 12, pp. 160464–160494, 2024, doi: 10.1109/ACCESS.2024.3467702.

[8] Z. Liu, Y. Liu, and X. Wang, "Intelligent routing algorithm for wireless sensor networks dynamically guided by distributed neural networks," *Comput. Commun.*, vol. 207, pp. 100–112, Jul. 2023, doi: 10.1016/j.comcom.2023.05.018.

[9] D. Saha, A. E. Olk, L. Wu, and M. R. Bhavani Shankar, "Characterizing RIS-Reflected EM Waves Based on Gaussian Beam Models," in *2024 IEEE Microwaves, Antennas, and Propagation Conference (MAPCON)*, Hyderabad, India: IEEE, Dec. 2024, pp. 1–4. doi: 10.1109/MAPCON61407.2024.10923334.

[10] K. Hersent, P. Mathieu, and J.-C. Wallet, "Gauge theories on quantum spaces," *Phys. Rep.*, vol. 1014, pp. 1–83, May 2023, doi: 10.1016/j.physrep.2023.03.002.

[11] M. Iqbal, T. Ashraf, M. Zubair, S. M. Jameel, M. Jazib, and J.-Y. Pan, "A comprehensive survey on reconfigurable intelligent surfaces (RIS) and STAR-RIS for next-generation wireless networks," *Discov. Appl. Sci.*, vol. 7, no. 11, p. 1253, Oct. 2025, doi: 10.1007/s42452-025-07684-w.

[12] M. Rossanese, P. Mursia, A. Garcia-Saavedra, V. Sciancalepore, A. Asadi, and X. Costa-Perez, "Design and validation of scalable reconfigurable intelligent surfaces," *Comput. Netw.*, vol. 241, p. 110208, Mar. 2024, doi: 10.1016/j.comnet.2024.110208.

[13] Y. J. Lu *et al.*, "A High-Efficiency and Versatile Reconfigurable Intelligent Surface Design Paradigm with Novel Topological Representation," *Engineering*, vol. 48, pp. 163–173, May 2025, doi: 10.1016/j.eng.2024.11.028.

[14] C. Xu *et al.*, "Antenna Selection for Reconfigurable Intelligent Surfaces: A Transceiver-Agnostic Passive Beamforming Configuration," *IEEE Trans. Wirel. Commun.*, vol. 22, no. 11, pp. 7756–7774, Nov. 2023, doi: 10.1109/TWC.2023.3255406.

[15] J. An, Z. Han, D. Niyato, M. Debbah, C. Yuen, and L. Hanzo, "Flexible Intelligent Metasurfaces for Enhancing MIMO Communications," *IEEE Trans. Commun.*, vol. 73, no. 9, pp. 7349–7365, Sep. 2025, doi: 10.1109/TCOMM.2025.3550318.

[16] J. An, C. Yuen, M. D. Renzo, M. Debbah, H. V. Poor, and L. Hanzo, "Flexible Intelligent Metasurfaces for Downlink Multiuser MISO Communications," *IEEE Trans. Wirel. Commun.*, vol. 24, no. 4, pp. 2940–2955, Apr. 2025, doi: 10.1109/TWC.2025.3526843.

[17] K. Shafique and M. Alhassoun, "Going Beyond a Simple RIS: Trends and Techniques Paving the Path of Future RIS," *IEEE Open J. Antennas Propag.*, vol. 5, no. 2, pp. 256–276, Apr. 2024, doi: 10.1109/OJAP.2024.3360900.

[18] V. Sharma, N. Garg, S. Sharma, and V. Bhatia, "A mini-review of signal processing techniques for RIS-assisted near field THz communication," *Front. Signal Process.*, vol. 3, p. 1297945, Jan. 2024, doi: 10.3389/frsip.2023.1297945.

[19] L. G. Da Silva, Z. Chu, P. Xiao, and A. Cerqueira S, "A varactor-based 1024-element RIS design for mm-waves," *Front. Commun. Netw.*, vol. 4, p. 1086011, Mar. 2023, doi: 10.3389/frcmn.2023.1086011.

[20] Y. Ren and V. Friderikos, "Interference aware path planning for mobile robots under joint communication and sensing in mmWave networks," *Comput. Commun.*, vol. 225, pp. 1–9, Sep. 2024, doi: 10.1016/j.comcom.2024.06.012.

[21] D. Satoh, "Analysis for flow termination in the decentralized and centralized pre-congestion notification architecture," *Comput. Netw.*, vol. 233, p. 109876, Sep. 2023, doi: 10.1016/j.comnet.2023.109876.

[22] Y.-X. Han, C.-L. Hu, B.-X. Li, and J.-G. Mao, "LnLiSiS4 (Ln = La and Ce): Promising infrared nonlinear optical materials designed by aliovalent substitution from SrCdSiS4," *Mater. Today Phys.*, vol. 31, p. 100987, Feb. 2023, doi: 10.1016/j.mtphys.2023.100987.

[23] C. Qian, L. Tian, and H. Chen, "Progress on intelligent metasurfaces for signal relay, transmitter, and processor," *Light Sci. Appl.*, vol. 14, no. 1, p. 93, Feb. 2025, doi: 10.1038/s41377-024-01729-2.

[24] T. Zhou and Y. Chen, "Thiourea induced the N/S co-doped carbon skeleton suppressing the dissolution of V to boost superior cyclic stability of Na3V2(PO4)3," *Carbon*, vol. 218, p. 118778, Jan. 2024, doi: 10.1016/j.carbon.2023.118778.

[25] A. Casto *et al.*, "Experimental optical retrieval of the Thermal Boundary Resistance of carbon nanotubes in water," *Carbon*, vol. 229, p. 119445, Oct. 2024, doi: 10.1016/j.carbon.2024.119445.

[26] S. Swati, D. Mladenić, and M. Grobelnik, "An Inferential Commonsense-Driven Framework for Predicting Political Bias in News Headlines," *IEEE Access*, vol. 11, pp. 80886–80902, 2023, doi: 10.1109/ACCESS.2023.3298877.

[27] W. Yan, X. Yuan, Z.-Q. He, and X. Kuai, "Passive Beamforming and Information Transfer Design for Reconfigurable Intelligent Surfaces Aided Multiuser MIMO Systems," *IEEE J. Sel. Areas Commun.*, vol. 38, no. 8, pp. 1793–1808, Aug. 2020, doi: 10.1109/JSAC.2020.3000811.

[28] R. Singh, I. Ahmad, F. Alanazi, and D. Alqahtani, "Next-Generation Reconfigurable Antenna Systems for 6G: Challenges, Architectures, and Vision," *IEEE Access*, vol. 13, pp. 196355–196373, 2025, doi: 10.1109/ACCESS.2025.3633193.

[29] W. M. Othman *et al.*, "Key Enabling Technologies for 6G: The Role of UAVs, Terahertz Communication, and Intelligent Reconfigurable Surfaces in Shaping the Future of Wireless Networks," *J. Sens. Actuator Netw.*, vol. 14, no. 2, p. 30, Mar. 2025, doi: 10.3390/jsan14020030.

[30] Y. Zhao *et al.*, "Reconfigurable Antennas for Next-Generation Mobile Communication Networks: A Comprehensive Survey and Tutorial," *IEEE Commun. Surv. Tutor.*, vol. 28, pp. 5267–5306, 2026, doi: 10.1109/COMST.2026.3673688.

[31] M. Zhang, G. Xu, and R. Gao, "Reconfigurable Antennas for Wireless Communication: Design Mechanism, State of the Art, Challenges, and Future Perspectives," *Int. J. Antennas Propag.*, vol. 2024, no. 1, p. 3046393, Jan. 2024, doi: 10.1155/2024/3046393.

[32] W. Chen, L. Chen, Y. Zhao, J. Ren, and X. Shen, "Metasurfaces Empowering 6G Communication and Sensing: Opportunities and Challenges," *IEEE Wirel. Commun.*, vol. 32, no. 1, pp. 158–164, Feb. 2025, doi: 10.1109/MWC.004.2400086.

[33] J. An, M. Debbah, T. J. Cui, Z. N. Chen, and C. Yuen, "Emerging Technologies in Intelligent Metasurfaces: Shaping the Future of Wireless Communications," *IEEE Trans. Antennas Propag.*, pp. 1–1, 2026, doi: 10.1109/TAP.2025.3571069.

[34] V. Karthikeyan, K. Gopalakrishnan, and S. S. Raj, "Advanced antenna technologies in 6G," in *Human-Centric Integration of 6G-Enabled Technologies for Modern Society*, Elsevier, 2025, pp. 71–86. doi: 10.1016/B978-0-443-27434-3.00005-2.

[35] E. Basar *et al.*, "Reconfigurable Intelligent Surfaces for 6G: Emerging Hardware Architectures, Applications, and Open Challenges," *IEEE Veh. Technol. Mag.*, vol. 19, no. 3, pp. 27–47, Sep. 2024, doi: 10.1109/MVT.2024.3415570.

[36] M. V. Katwe *et al.*, "An Overview of Intelligent Meta-Surfaces for 6G and Beyond: Opportunities, Trends, and Challenges," *IEEE Commun. Stand. Mag.*, vol. 8, no. 4, pp. 62–69, Dec. 2024, doi: 10.1109/MCOMSTD.0001.2400032.

[37] H. Jahanbakhsh Basherlou, N. Ojaroudi Parchin, and C. H. See, "Antenna Design and Optimization for 5G, 6G, and IoT," *Sensors*, vol. 25, no. 5, p. 1494, Feb. 2025, doi: 10.3390/s25051494.

[38] C. You *et al.*, "Next Generation Advanced Transceiver Technologies for 6G and Beyond," *IEEE J. Sel. Areas Commun.*, vol. 43, no. 3, pp. 582–627, Mar. 2025, doi: 10.1109/JSAC.2025.3536557.

[39] L.-Z. Song, Y. Wen, R. Sauleau, P.-Y. Qin, S. Maci, and Y. J. Guo, "Empowering Future 6G Wireless Networks With Transmitarray Antennas: A Review," *IEEE Trans. Antennas Propag.*, vol. 74, no. 1, pp. 125–140, Jan. 2026, doi: 10.1109/TAP.2025.3618756.

[40] F. Qamar, S. H. A. Kazmi, K. A. Z. Ariffin, M. Tayyab, and Q. N. Nguyen, "Multi-Antenna Array-Based Massive MIMO for B5G/6G: State of the Art, Challenges, and Future Research Directions," *Information*, vol. 15, no. 8, p. 442, Jul. 2024, doi: 10.3390/info15080442.

[41] S. Prasad Tera, R. Chinthaginjala, G. Pau, and T. Hoon Kim, "Toward 6G: An Overview of the Next Generation of Intelligent Network Connectivity," *IEEE Access*, vol. 13, pp. 925–961, 2025, doi: 10.1109/ACCESS.2024.3523327.

[42] W. K. New *et al.*, "Fluid Antenna Systems: Redefining Reconfigurable Wireless Communications," *IEEE J. Sel. Areas Commun.*, vol. 44, pp. 1013–1044, 2026, doi: 10.1109/JSAC.2025.3632097.

[43] Z. Hamzavi-Zarghani, L. Matekovits, and W. Bösch, "Reconfigurable Antennas Enabled by Tunable Metasurfaces for Next-Generation Wireless Communications: A Review," *Electronics*, vol. 15, no. 8, p. 1610, Apr. 2026, doi: 10.3390/electronics15081610.

[44] S. Sowmiya, P. Senthilkumar, T. Kuppuraj, A. Mishra, P. Muralidharan, and S. Rosaline, "The Creation of Intelligent Surfaces for the Purpose of Next-Gen Wireless Networks," in *2024 4th International Conference on Advance Computing and Innovative Technologies in Engineering (ICACITE)*, Greater Noida, India: IEEE, May 2024, pp. 229–234. doi: 10.1109/ICACITE60783.2024.10616689.

[45] A. Alomainy *et al.*, "The 2026 roadmap on wireless and microwave metasurfaces," *J. Phys. Appl. Phys.*, vol. 59, no. 13, p. 133001, Apr. 2026, doi: 10.1088/1361-6463/ae2b7c.

[46] F. Mehmood and A. Mehmood, "Recent Advancements in Millimeter-Wave Antennas and Arrays: From Compact Wearable Designs to Beam-Steering Technologies," *Electronics*, vol. 14, no. 13, p. 2705, Jul. 2025, doi: 10.3390/electronics14132705.

[47] I. F. Akyildiz, A. Kak, and S. Nie, "6G and Beyond: The Future of Wireless Communications Systems," *IEEE Access*, vol. 8, pp. 133995–134030, 2020, doi: 10.1109/ACCESS.2020.3010896.

[48] A. Umer, I. Müürsepp, M. M. Alam, and H. Wymeersch, "Reconfigurable Intelligent Surfaces in 6G Radio Localization: A Survey of Recent Developments, Opportunities, and Challenges," *IEEE Commun. Surv. Tutor.*, vol. 27, no. 6, pp. 3526–3560, Dec. 2025, doi: 10.1109/COMST.2025.3536517.

[49] A. Jabbar, M. A. Jamshed, Q. Abbasi, M. A. Imran, and M. Ur-Rehman, "Leveraging the Role of Dynamic Reconfigurable Antennas in Viewpoint of Industry 4.0 and Beyond," *Research*, vol. 6, p. 0110, Jan. 2023, doi: 10.34133/research.0110.

[50] W. Ma *et al.*, "A Survey on Reconfigurable and Movable Antennas for Wireless Communications and Sensing," *IEEE Commun. Surv. Tutor.*, vol. 28, pp. 4842–4882, 2026, doi: 10.1109/COMST.2026.3663021.

[51] Y. Yang, M. Mao, J. Xu, H. Liu, J. Wang, and K. Song, "Millimeter-Wave Antennas for 5G Wireless Communications: Technologies, Challenges, and Future Trends," *Sensors*, vol. 25, no. 17, p. 5424, Sep. 2025, doi: 10.3390/s25175424.

[52] V. K. Quy, A. Chehri, N. M. Quy, N. D. Han, and N. T. Ban, "Innovative Trends in the 6G Era: A Comprehensive Survey of Architecture, Applications, Technologies, and Challenges," *IEEE Access*, vol. 11, pp. 39824–39844, 2023, doi: 10.1109/ACCESS.2023.3269297.

[53] C. Pan *et al.*, "Reconfigurable Intelligent Surfaces for 6G Systems: Principles, Applications, and Research Directions," *IEEE Commun. Mag.*, vol. 59, no. 6, pp. 14–20, Jun. 2021, doi: 10.1109/MCOM.001.2001076.

[54] T. Zhang *et al.*, "Digital Twin Enabled 6G Cell-Free Multi-Function Reconfigurable Metasurfaces Communications: Concepts, Challenges, and Future Directions," *IEEE Netw.*, vol. 39, no. 5, pp. 145–154, Sep. 2025, doi: 10.1109/MNET.2024.3520242.

[55] H. Ojukwu, B.-C. Seet, and S. U. Rehman, "Metasurface-Aided Wireless Power Transfer and Energy Harvesting for Future Wireless Networks," *IEEE Access*, vol. 10, pp. 52431–52450, 2022, doi: 10.1109/ACCESS.2022.3170106.

[56] X. Zhao, M. Jian, Y. Chen, Y. Zhao, and L. Mu, "Reconfigurable Intelligent Surfaces for 6G: Engineering Challenges and the Road Ahead," *Intell. Converg. Netw.*, vol. 6, no. 1, pp. 53–81, Mar. 2025, doi: 10.23919/ICN.2025.0004.

[57] S. Shivshankar, P. Kar, and N. Acharya, "Reimagining Wireless: A Literature Review of the 6G Cyber-Physical Continuum," *Telecom*, vol. 6, no. 4, p. 91, Nov. 2025, doi: 10.3390/telecom6040091.

[58] C. Nwufo, O. Simpson, and Y. Sun, "Reconfigurable Intelligent Surfaces (RIS) and Their Role in Next-Generation Wireless Networks: An Overview," *Trans. Emerg. Telecommun. Technol.*, vol. 36, no. 6, p. e70164, Jun. 2025, doi: 10.1002/ett.70164.

[59] Y. Jay Guo, C. A. Guo, M. Li, and M. Latva-aho, "Antenna Technologies for 6G – Advances and Challenges," *IEEE Trans. Antennas Propag.*, pp. 1–1, 2026, doi: 10.1109/TAP.2025.3550434.

[60] M. N. A. Siddiky, M. E. Rahman, M. S. Uzzal, and H. M. D. Kabir, "A Comprehensive Exploration of 6G Wireless Communication Technologies," *Computers*, vol. 14, no. 1, p. 15, Jan. 2025, doi: 10.3390/computers14010015.

[61] J. A. Hodge, K. V. Mishra, and A. I. Zaghloul, "Deep Inverse Design of Reconfigurable Metasurfaces for Future Communications," 2021, *arXiv*. doi: 10.48550/ARXIV.2101.09131.

[62] C. Pichot *et al.*, "New and Emerging Directions in the Fields of Antennas and Propagation," *IEEE Trans. Antennas Propag.*, vol. 73, no. 1, pp. 566–581, Jan. 2025, doi: 10.1109/TAP.2024.3514092.

[63] W. Long, R. Chen, M. Moretti, W. Zhang, and J. Li, "A Promising Technology for 6G Wireless Networks: Intelligent Reflecting Surface," *J. Commun. Inf. Netw.*, vol. 6, no. 1, pp. 1–16, Mar. 2021, doi: 10.23919/JCIN.2021.9387701.

[64] D. Uzer and A. Özge Çınar Ak, "Metasurface-Based Reconfigurable Antennas and Intelligent Reflecting Surfaces for B5G and 6G Applications," in *Materials Science*, vol. 24, M. Alibakhshikenari, Ed., IntechOpen, 2026. doi: 10.5772/intechopen.1014035.

[65] A. Jabbar *et al.*, "60 GHz Programmable Dynamic Metasurface Antenna (DMA) for Next-Generation Communication, Sensing, and Imaging Applications: From Concept to Prototype," *IEEE Open J. Antennas Propag.*, vol. 5, no. 3, pp. 705–726, Jun. 2024, doi: 10.1109/OJAP.2024.3386452.

[66] L. Bariah *et al.*, "A Prospective Look: Key Enabling Technologies, Applications and Open Research Topics in 6G Networks," *IEEE Access*, vol. 8, pp. 174792–174820, 2020, doi: 10.1109/ACCESS.2020.3019590.

[67] M. A. Saeed and A. O. Nwajana, "A review of beamforming microstrip patch antenna array for future 5G/6G networks," *Front. Mech. Eng.*, vol. 9, p. 1288171, Feb. 2024, doi: 10.3389/fmech.2023.1288171.

[68] A. M. Montaser and K. R. Mahmoud, "Design of Intelligence Reflector Metasurface Using Deep Learning Neural Network for 6G Adaptive Beamforming," *IEEE Access*, vol. 10, pp. 117900–117913, 2022, doi: 10.1109/ACCESS.2022.3220701.

[69] A. Ghaneizadeh, P. Gavriilidis, M. Joodaki, and G. C. Alexandropoulos, "Metasurface Energy Harvesters: State-of-the-Art Designs and Their Potential for Energy Sustainable Reconfigurable Intelligent Surfaces," *IEEE Access*, vol. 12, pp. 160464–160494, 2024, doi: 10.1109/ACCESS.2024.3467702.

[70] K. Rasilainen, T. D. Phan, M. Berg, A. Pärssinen, and P. J. Soh, "Hardware Aspects of Sub-THz Antennas and Reconfigurable Intelligent Surfaces for 6G Communications," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 8, pp. 2530–2546, Aug. 2023, doi: 10.1109/JSAC.2023.3288250.

[71] M. M. Amri, L. Y. Sabila, and D. Sulisworo, "Reconfigurable intelligent surfaces: A promising frontier for future generations of wireless technology," *IEEE Potentials*, vol. 43, no. 2, pp. 37–47, Mar. 2024, doi: 10.1109/MPOT.2024.3472295.

[72] G. Li and M. Lu, "Research Progress on 6G Communication Antenna Technology," *Electronics*, vol. 15, no. 6, p. 1173, Mar. 2026, doi: 10.3390/electronics15061173.

[73] S. Chen *et al.*, "Trends, Challenges, and Key Technologies of Beam-Space Multiplexing Based on Metasurfaces," *IEEE Wirel. Commun.*, vol. 32, no. 3, pp. 130–138, Jun. 2025, doi: 10.1109/MWC.005.2400107.

[74] M. Ahmed *et al.*, "Active Reconfigurable Intelligent Surfaces: Expanding the Frontiers of Wireless Communication-A Survey," *IEEE Commun. Surv. Tutor.*, vol. 27, no. 2, pp. 839–869, Apr. 2025, doi: 10.1109/COMST.2024.3423460.

[75] T. Sharma, A. Chehri, and P. Fortier, "Reconfigurable Intelligent Surfaces for 5G and beyond Wireless Communications: A Comprehensive Survey," *Energies*, vol. 14, no. 24, p. 8219, Dec. 2021, doi: 10.3390/en14248219.

[76] S. Basharat, M. Khan, M. Iqbal, U. S. Hashmi, S. A. R. Zaidi, and I. Robertson, "Exploring reconfigurable intelligent surfaces for 6G: State-of-the-art and the road ahead," *IET Commun.*, vol. 16, no. 13, pp. 1458–1474, Aug. 2022, doi: 10.1049/cmu2.12364.

[77] A. Jabbar *et al.*, "Next-Generation Programmable Holographic Metasurface Antenna," in *2025 Photonics & Electromagnetics Research Symposium - Spring (PIERS-Spring)*, Abu Dhabi, United Arab Emirates: IEEE, May 2025, pp. 1–8. doi: 10.1109/PIERS-Spring66516.2025.11276430.

[78] S. Singh, A. Verma, and N. Kaushik, "Metasurfaces and Their Applications in Antenna Technology," *Macromol. Symp.*, vol. 415, no. 2, p. e70321, Apr. 2026, doi: 10.1002/masy.70321.

[79] F. Naeem, G. Kaddoum, S. Khan, K. S. Khan, and N. Adam, "IRS-Empowered 6G Networks: Deployment Strategies, Performance Optimization, and Future Research Directions," *IEEE Access*, vol. 10, pp. 118676–118696, 2022, doi: 10.1109/ACCESS.2022.3220682.

[80] W. Khalid, Z. Kaleem, R. Ullah, T. Van Chien, S. Noh, and H. Yu, "Simultaneous Transmitting and Reflecting-Reconfigurable Intelligent Surface in 6G: Design Guidelines and Future Perspectives," *IEEE Netw.*, vol. 37, no. 5, pp. 173–181, Sep. 2023, doi: 10.1109/MNET.129.2200389.

[81] S. Shrivastava and A. Taneja, "Reconfigurable Intelligent Surfaces: A Road Towards Smart Wireless Communication," *Int. J. Commun. Syst.*, vol. 38, no. 16, p. e70233, Nov. 2025, doi: 10.1002/dac.70233.

[82] C. Huang *et al.*, "Holographic MIMO Surfaces for 6G Wireless Networks: Opportunities, Challenges, and Trends," *IEEE Wirel. Commun.*, vol. 27, no. 5, pp. 118–125, Oct. 2020, doi: 10.1109/MWC.001.1900534.

[83] Y. Xiao *et al.*, "Space-Air-Ground Integrated Wireless Networks for 6G: Basics, Key Technologies, and Future Trends," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 12, pp. 3327–3354, Dec. 2024, doi: 10.1109/JSAC.2024.3492720.

[84] F. Yang, P. Pitchappa, and N. Wang, "Terahertz Reconfigurable Intelligent Surfaces (RISs) for 6G Communication Links," *Micromachines*, vol. 13, no. 2, p. 285, Feb. 2022, doi: 10.3390/mi13020285.

[85] D. Sarkar, Yogita, S. S. Yadav, V. Pal, N. Kumar, and S. K. Patra, "A Comprehensive Survey on IRS-Assisted NOMA-Based 6G Wireless Network: Design Perspectives, Challenges and Future Directions," *IEEE Trans. Netw. Serv. Manag.*, vol. 21, no. 2, pp. 2539–2562, Apr. 2024, doi: 10.1109/TNSM.2023.3348138.

[86] M. Ashif Islam Oni, Y. Yang, and S. Dey, "Advances in Metantennas: Classification and Future Prospects," *IEEE Access*, vol. 13, pp. 183933–183963, 2025, doi: 10.1109/ACCESS.2025.3624655.

[87] S. A. Khaleel, E. K. I. Hamad, N. O. Parchin, and M. B. Saleh, "Programmable Beam-Steering Capabilities Based on Graphene Plasmonic THz MIMO Antenna via Reconfigurable Intelligent Surfaces (RIS) for IoT Applications," *Electronics*, vol. 12, no. 1, p. 164, Dec. 2022, doi: 10.3390/electronics12010164.

[88] A. Magbool, V. Kumar, Q. Wu, M. Di Renzo, and M. F. Flanagan, "A Survey on Integrated Sensing and Communication With Intelligent Metasurfaces: Trends, Challenges, and Opportunities," *IEEE Open J. Commun. Soc.*, vol. 6, pp. 7270–7318, 2025, doi: 10.1109/OJCOMS.2025.3594049.

[89] M. Shafi, R. K. Jha, and S. Jain, "6G: Technology Evolution in Future Wireless Networks," *IEEE Access*, vol. 12, pp. 57548–57573, 2024, doi: 10.1109/ACCESS.2024.3385230.

[90] F. Naeem, M. Ali, G. Kaddoum, C. Huang, and C. Yuen, "Security and Privacy for Reconfigurable Intelligent Surface in 6G: A Review of Prospective Applications and Challenges," *IEEE Open J. Commun. Soc.*, vol. 4, pp. 1196–1217, 2023, doi: 10.1109/OJCOMS.2023.3273507.

[91] S. Han, G. Luo, F. Qu, M. Lestas, and F.-Y. Wang, "Empowering Vehicle Connectivity—The SOTA and Future Prospects of Reconfigurable Intelligent Surfaces in Mobile Communications: A Review," *IEEE Sens. J.*, vol. 25, no. 17, pp. 32021–32037, Sep. 2025, doi: 10.1109/JSEN.2025.3586678.

[92] S. Thomas, J. Singh Virdi, A. Babakhani, and I. P. Roberts, "A Survey on Advancements in THz Technology for 6G: Systems, Circuits, Antennas, and Experiments," *IEEE Open J. Commun. Soc.*, vol. 6, pp. 1998–2016, 2025, doi: 10.1109/OJCOMS.2025.3549710.

[93] F. Antunes, A. Ramos, T. Varum, and J. N. Matos, "An Overview of Polarization, Frequency and Beam Reconfigurable Antennas," *IEEE Access*, vol. 14, pp. 53910–53933, 2026, doi: 10.1109/ACCESS.2026.3680566.

[94] S. K. Das, B. Champagne, I. Psaromiligkos, and Y. Cai, "A Survey on Federated Learning for Reconfigurable Intelligent Metasurfaces-Aided Wireless Networks," *IEEE Open J. Commun. Soc.*, vol. 5, pp. 1846–1879, 2024, doi: 10.1109/OJCOMS.2024.3378266.

[95] R. Liu, Q. Wu, M. Di Renzo, and Y. Yuan, "A Path to Smart Radio Environments: An Industrial Viewpoint on Reconfigurable Intelligent Surfaces," *IEEE Wirel. Commun.*, vol. 29, no. 1, pp. 202–208, Feb. 2022, doi: 10.1109/MWC.111.2100258.

[96] S. Latreche and H. Bellahsene, "A comprehensive survey on 6G: Enabling technologies, key applications, and future challenges," *Frankl. Open*, vol. 15, p. 100559, Jun. 2026, doi: 10.1016/j.fraope.2026.100559.

[97] J. Saini, "Metamaterials in Communication Devices: A Review of Advances and Application," in *Materials Science*, vol. 11, A. Kumar Goyal, Ed., IntechOpen, 2025. doi: 10.5772/intechopen.1010641.

[98] A. T. Anilkumar, Z. Hassan, S. Shila, R. E. Zannat, and P. Sekhar, "Flexible Antennas for 6G Communication and Harsh Environments: Design, Materials, Fabrication, Testing, and AI/ML Integration," *IEEE Access*, vol. 14, pp. 36126–36157, 2026, doi: 10.1109/ACCESS.2026.3667649.

[99] M. Deng *et al.*, "Reconfigurable Intelligent Surfaces Enabled Vehicular Communications: A Comprehensive Survey of Recent Advances and Future Challenges," *IEEE Trans. Intell. Veh.*, vol. 10, no. 8, pp. 4191–4216, Aug. 2025, doi: 10.1109/TIV.2024.3476934.

[100] F. Bilotti *et al.*, "Reconfigurable intelligent surfaces as the key-enabling technology for smart electromagnetic environments," *Adv. Phys. X*, vol. 9, no. 1, p. 2299543, Dec. 2024, doi: 10.1080/23746149.2023.2299543.

[101] M. R. Castellanos, S. Yang, C.-B. Chae, and R. W. Heath, "Embracing Reconfigurable Antennas in the Tri-Hybrid MIMO Architecture for 6G and Beyond," *IEEE Trans. Commun.*, vol. 74, pp. 381–401, 2026, doi: 10.1109/TCOMM.2025.3621272.

[102] Z. Xiao *et al.*, "Antenna Array Enabled Space/Air/Ground Communications and Networking for 6G," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 10, pp. 2773–2804, Oct. 2022, doi: 10.1109/JSAC.2022.3196320.

[103] H. Tataria, M. Shafi, A. F. Molisch, M. Dohler, H. Sjöland, and F. Tufvesson, "6G Wireless Systems: Vision, Requirements, Challenges, Insights, and Opportunities," *Proc. IEEE*, vol. 109, no. 7, pp. 1166–1199, Jul. 2021, doi: 10.1109/JPROC.2021.3061701.

[104] M. U. F. Qaisar *et al.*, "The Role of ISAC in 6G Networks: Enabling Next-Generation Wireless Systems," *IEEE Trans. Netw. Sci. Eng.*, vol. 13, pp. 7825–7861, 2026, doi: 10.1109/TNSE.2026.3666665.

[105] H. Abu Bakar, R. Abd Rahim, P. J. Soh, and P. Akkaraekthalin, "Liquid-Based Reconfigurable Antenna Technology: Recent Developments, Challenges and Future," *Sensors*, vol. 21, no. 3, p. 827, Jan. 2021, doi: 10.3390/s21030827.

[106] N. Sharma and S. Sharma, "A Review on Unlocking Performance Insights for Next Generation Connectivity With AI in 6G Communication," *Radio Sci.*, vol. 60, no. 7, p. e2025RS008222, Jul. 2025, doi: 10.1029/2025RS008222.

[107] Z. Ning *et al.*, "6G Communication New Paradigm: The Integration of Autonomous Aerial Vehicles and Intelligent Reflecting Surfaces," *IEEE Commun. Surv. Tutor.*, vol. 27, no. 6, pp. 3382–3416, Dec. 2025, doi: 10.1109/COMST.2025.3526251.

[108] R. Alghamdi *et al.*, "Intelligent Surfaces for 6G Wireless Networks: A Survey of Optimization and Performance Analysis Techniques," *IEEE Access*, vol. 8, pp. 202795–202818, 2020, doi: 10.1109/ACCESS.2020.3031959.

[109] K. Shafique and M. Alhassoun, "Going Beyond a Simple RIS: Trends and Techniques Paving the Path of Future RIS," *IEEE Open J. Antennas Propag.*, vol. 5, no. 2, pp. 256–276, Apr. 2024, doi: 10.1109/OJAP.2024.3360900.

[110] M. Z. Chowdhury, Md. Shahjalal, S. Ahmed, and Y. M. Jang, "6G Wireless Communication Systems: Applications, Requirements, Technologies, Challenges, and Research Directions," *IEEE Open J. Commun. Soc.*, vol. 1, pp. 957–975, 2020, doi: 10.1109/OJCOMS.2020.3010270.

[111] M. J. Khan, S. Ahmad, I. Singh, and Z. Fatima, "Metamaterials in 5G and the Path towards 6G: Enabling Advanced Wireless Communication," in *Compact and Flexible Microwave Devices*, 1st ed., D. K. Choudhary, I. Singh, M. K. Singh, and A. K. Jain, Eds., Wiley, 2025, pp. 25–47. doi: 10.1002/9781394275588.ch2.

[112] M. Ali Jamshed *et al.*, "Reconfigurable Holographic Surfaces and Near Field Communication for Non-Terrestrial Networks: Potential and Challenges," *IEEE Wirel. Commun.*, pp. 1–8, 2026, doi: 10.1109/MWC.2026.3654486.

[113] S. Sharma, R. K. Jha, and A. Kumar, "Emerging Technologies and Challenges to Move Towards 6G Wireless Network," *Int. J. Commun. Syst.*, vol. 38, no. 12, p. e70146, Aug. 2025, doi: 10.1002/dac.70146.

[114] J. Chen *et al.*, "A Survey on Directional Modulation: Opportunities, Challenges, Recent Advances, Implementations, and Future Trends," *IEEE Internet Things J.*, vol. 12, no. 16, pp. 32581–32615, Aug. 2025, doi: 10.1109/JIOT.2025.3574824.

[115] N. Sharma and A. Kaur, "A Systematic Review of Meta-Surface Based Antennas for Thz Applications," *Radio Sci.*, vol. 59, no. 9, p. e2024RS007980, Sep. 2024, doi: 10.1029/2024RS007980.

[116] Y. Zhang, S. Ogurtsov, V. Vasilev, A. A. Kishk, and D. Caratelli, "Advanced Dielectric Resonator Antenna Technology for 5G and 6G Applications," *Sensors*, vol. 24, no. 5, p. 1413, Feb. 2024, doi: 10.3390/s24051413.

[117] J. Liu and J. Kong, "Stacked Intelligent Metasurfaces: Key Technologies, Scenario Adaptation, and Future Directions," *Electronics*, vol. 15, no. 2, p. 274, Jan. 2026, doi: 10.3390/electronics15020274.

[118] A. Judice, S. Malhotra, and M. Sharma, "Recent Developments in MIMO Antenna Architectures and their Future Directions," in *2024 7th International Conference on Circuit Power and Computing Technologies (ICCPCT)*, Kollam, India: IEEE, Aug. 2024, pp. 1798–1803. doi: 10.1109/ICCPCT61902.2024.10673128.