

Review

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Multi-antenna Arrays Based Massive-MIMO for B5G/6G: State-of-the-Art, Challenges and Future Research Directions

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Review

Multi-Antenna Arrays based Massive-MIMO for B5G/6G: State-of-the-Art, Challenges and Future Research Directions

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Abstract: This comprehensive article explores Massive MIMO (M-MIMO) design and its associated concepts, focusing on the seamless integration requirements for Beyond 5G (B5G) and 6G networks. Addressing critical aspects such as RF chain reduction, pilot contamination, Cell-Free MIMO, and security considerations, the article delves into the intricacies of M-MIMO in the evolving landscape of B5G. Moreover, the emerging MIMO concepts in this article include AI-enabled M-MIMO three-dimensional beamforming, reconfigurable intelligent surfaces, visible light communication, and THz spectrum utilization. This review highlights challenges and open research issues, including Narrow Aperture Antenna Nodes, Plasmonic Antenna Arrays, Integrated Sensing with M-MIMO, and the application of Federated Learning in M-MIMO systems. By examining these cutting-edge developments, the article aims to contribute to advancing knowledge in the field and inspire future research directions in the exciting realm of B5G and 6G networks.

Keywords: 5G; 6G; M-MIMO; multi-antenna; wireless; federated learning

1. Introduction

The relentless pursuit of innovation in wireless communication technologies has paved the way for the evolution of telecommunication networks from the early days of 2G to the current standards of 5G [1]. As the demand for higher data rates, lower latency, and increased connectivity continues to surge, researchers and industry experts are already setting their sights on the next frontier: Beyond 5G (B5G) and Sixth-Generation (6G) networks [2]. The revolutionary concept of Massive Multiple-Input Multiple-Output (M-MIMO) systems is central to realizing these ambitious objectives.

The innovative M-MIMO is one paramount wireless access technology that can greatly manage ever-increasing global data demand. While small, many smart antennas equipped at Tx and Rx sides can maintain spectrum and energy consumption efficiencies with minimum processing complications. M-MIMO can play a revolutionary role in B5G/6G heterogeneous networks through seamless integration with various technologies such as the Internet of Flying Things (IoFTs), Internet of medical things (IoMTs), smart grid, smart gadgets, smart homes, mobile devices, industry, satellite, Vehicles-to-Every things (V2X) [3,4] as depicted in Figure 1.

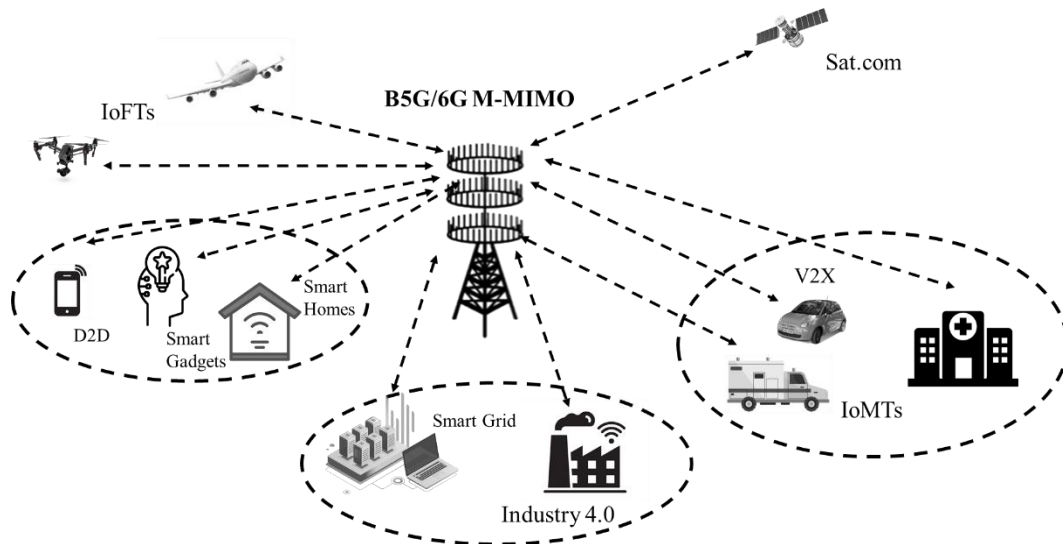


Figure 1. M-MIMO in B5G/6G heterogeneous networks.

In current NR 5G networks, M-MIMO is one of the essential technologies that helps in smooth precoding procedure, energy, and power management. It enables high-frequency communication by exploiting different beamforming (BF) techniques to achieve superior diversity array gain and provide a proficient user experience [5]. While, for B5G/6G cellular networks, various other robust transceiver solutions, and handling strategies have been introduced, such as Reconfigurable Intelligent Surfaces (RIS), Cell-Free (CF) M-MIMO, sourced random access, etc. However, to utilize the full potential of an upper-frequency spectrum with active antenna elements, issues persist in hardware complications, energy consumption, number of RF chains, and algorithm designs, thus demanding further simplification and performance improvement [6]. At its core, M-MIMO represents a paradigm shift in wireless communication, offering unprecedented gains in spectral efficiency, energy efficiency, and reliability [7]. The M-MIMO system, mm-Wave spectrum, and BF mechanisms are already employed in various 5G practical arenas. These technologies mature and prosperously respond to different signal processing, channel propagation, interference, and data transmission responsibilities [8]. However, some persistent challenges in established technologies, ever-growing data requirements, and various upcoming technological integrations are threatening challenges in future mobile communication.

However, realizing the full potential of M-MIMO in the context of B5G and 6G networks necessitates a nuanced understanding of its associated concepts and challenges. Therefore, in this review paper, we broadly discuss the M-MIMO and different valuable features of the upper spectrum and intelligent learning frameworks for the efficient operation of B5G/6G networks. In the context of established technologies, we are only focusing on the M-MIMO, mm-Wave, and BF techniques, and various other accessing established strategies are beyond our review paper scope. This article aspires to deepen understanding of M-MIMO technology and catalyze future research directions in the dynamic realm of B5G and 6G networks. The article aims to contribute to advancing knowledge and fostering innovation in telecommunications by highlighting the challenges and emerging trends in M-MIMO design. This paper will help prospective researchers understand and utilize the contemporaneous adventure of multiple technologies for real-life communication purposes.

1.1. Related literature

Several recent survey papers have addressed the utilization of MIMO configurations in mobile communications. The study conducted by [9] primarily focused on analyzing and presenting detection algorithms for M-MIMO systems, incorporating ML methodologies. Similarly, the study [10] extensively examined M-MIMO detectors employing deep learning (DL) techniques. The study in [11] surveys the challenges and advantages of mm-Wave massive MIMO systems. It addresses enhancements in user throughput, spectral efficiency, and energy efficiency. Various factors

impacting system performance are discussed, including modulation schemes, signal waveforms, multiple access techniques, user scheduling algorithms, fronthaul design, antenna array architectures, and precoding algorithms. In [12], the authors categorized different DL approaches based on their application in 5G domains such as channel coding, M-MIMO, and resource allocation. The study [13] addressed various aspects of radio resource management (RRM) procedures utilizing ML algorithms, presenting a similar categorization as seen in [10]. [14] presents an exhaustive examination of linear precoding techniques for massive MIMO systems in a single-cell scenario. It evaluates the performance of various linear precoding methods regarding sum rate and spectral efficiency. Meanwhile, related literature provides valuable insights into individual components or methodologies within M-MIMO systems. However, existing literature lacks a holistic view of M-MIMO design and does not cover integration aspects of MIMO into future network paradigms in B5G/6G. Similarly, related literature partially covers the emerging B5G/6G paradigm for prevailing challenges and potential research directions in M-MIMO.

Table 1. Summary of related literature.

Ref.	Technologies	Contribution	Limitations
[9]	M-MIMO, ML methodologies	Analysis and presentation of detection algorithms for M-MIMO systems	Lacks coverage of integration aspects into future network paradigms in B5G/6G
[10]	M-MIMO detectors, DL techniques	Examination of M-MIMO detectors employing deep learning techniques	Partial coverage of the emerging B5G/6G paradigm and integration aspects of MIMO
[11]	mm-Wave massive MIMO systems	Survey on challenges and advantages of mm-Wave massive MIMO systems	Addresses enhancements in user throughput, spectral efficiency, and energy efficiency, but lacks integration into B5G/6G
[12]	DL approaches in 5G domains	Categorization of different DL approaches based on their application in 5G domains	Provides insights into individual components but lacks a holistic view of M-MIMO design
[13]	RRM procedures utilizing ML algorithms	Presentation of various aspects of radio resource management procedures utilizing ML algorithms	Focuses on RRM procedures and ML algorithms, lacking integration aspects into future network paradigms in B5G/6G
[14]	Linear precoding techniques for massive MIMO	Examination of linear precoding techniques for massive MIMO systems in a single-cell scenario	Evaluates performance of linear precoding methods, but doesn't cover integration aspects into future network paradigms

1.2. Motivation and Contribution

This comprehensive article embarks on the intricacies of M-MIMO design and its pivotal role in shaping the future landscape of telecommunications. With a particular focus on the seamless integration requirements for B5G and 6G networks, the article aims to guide researchers and practitioners to embrace the challenges and opportunities presented by this transformative technology. This article navigates these complexities and critical aspects such as RF chain reduction, pilot contamination, Cell-Free MIMO, and security considerations. Furthermore, the article explores cutting-edge developments and emerging trends that promise to redefine the boundaries of wireless communication. From the integration of Artificial Intelligence (AI) for three-dimensional beamforming to the exploitation of Reconfigurable Intelligent Surfaces (RIS) and the utilization of the Terahertz (THz) spectrum, the article offers invaluable insights into the future trajectory of M-MIMO technology. Noteworthy topics covered in the article include AI-enabled M-MIMO three-dimensional beamforming, and THz spectrum utilization. Moreover, the article delves into key open research issues including; Narrow Aperture Antenna Nodes, Plasmonic Antenna Arrays, Integrated Sensing with M-MIMO, and the application of Federated Learning in M-MIMO systems are dissected with

precision, offering a roadmap for future research endeavors. The overall organization of this review is shown in Figure 2.

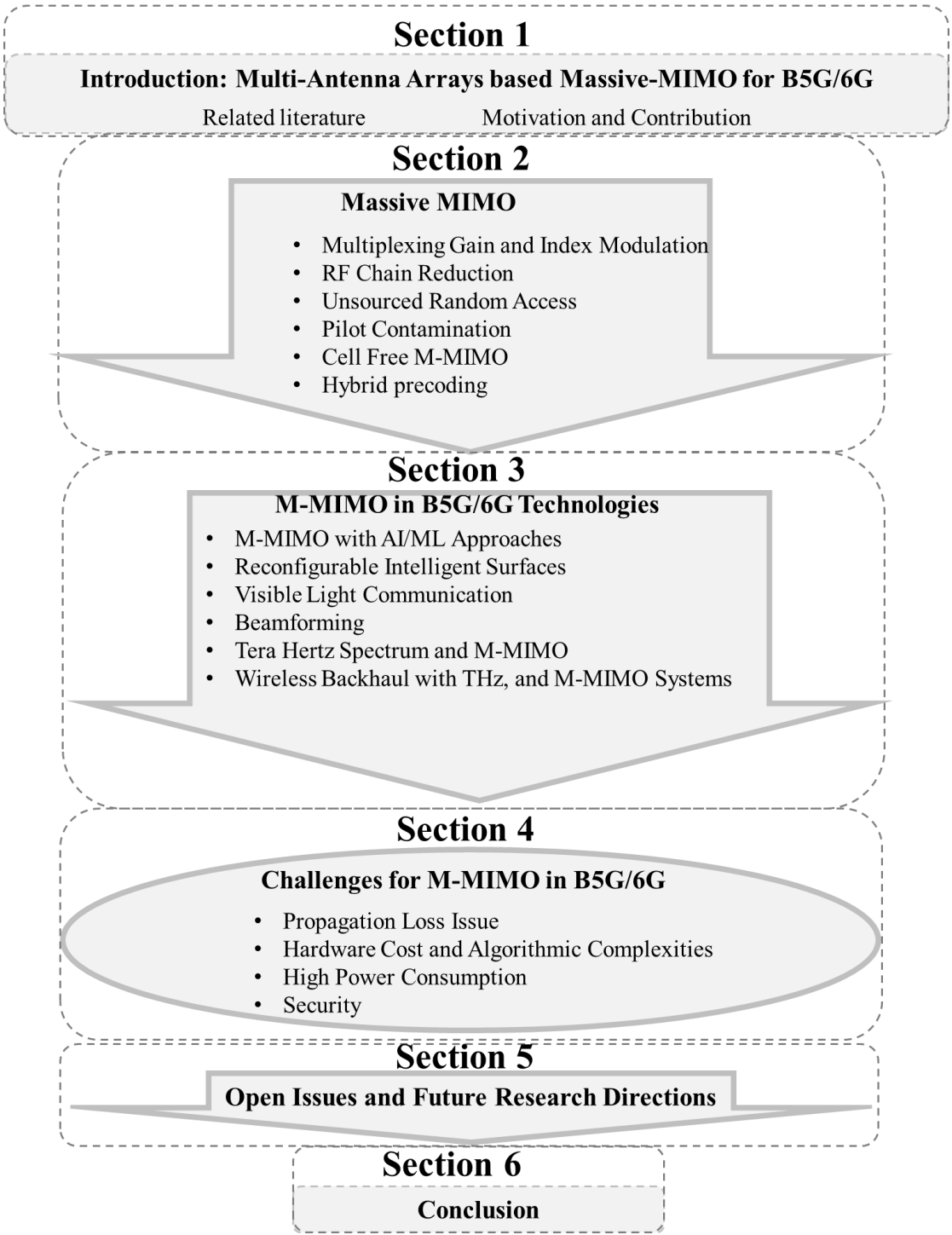


Figure 2. Overall organization of this article.

2. Massive MIMO

The multi-antenna technology i.e., MIMO is the over-the-air accessing technology that can simultaneously transmit (Tx) and receive (Rx) two or more data packets over the same radio frequency band. The traditional MIMO and M-MIMO antenna selection, precoding, decoding, and processing schemes satisfactorily manage 5G applications and workplaces, either indoor or outdoor scenes [15]. Moving forward, focusing on the 6G mobile service platforms, traditional antenna

technologies have been considered incompetent not only because they match the ever-increasing data requisite but also conspicuously demand enhancement in precoding/decoding methods, signal assessment process, and computational time efficiencies to unlatch many unprecedented delay-sensitive cases [16]. Since 6G will be an extension of the 5G network's protocols and architecture, the interplay of the predecessor's technologies and new schemes would enrich the wireless ecosystem. This section is summarized for a consolidated overview in Table 2.

2.1. Multiplexing Gain and Index Modulation

With the swift progress in mobile communication and unconventional paradigm, various novel techniques have recently developed along with the enhancement in antenna's data sensing strategies [17]. For instance, sparse code multiple access (SCMA), non-orthogonal multiple access (NOMA) in the power domain, and orthogonal multiple access are the most promising and scalable solutions for successful mobile connection establishment for B5G/6G networks [18]. This is particularly because the conventional multiplexing technologies were conceptualized and purposefully designed for human-centric mobile network architecture. In contrast, after realizing the intelligent node's growth in each small cell site and current network dynamics where almost everything will support wireless connectivity, baseline multiplexing technologies are not sufficient for machine/user-centric mobile carriers and would incur problems in (i) signal detection algorithmic complexities at the Rx node and (ii) sophisticated constellation matrices design. While in contrast to the standard approaches in developing new and concrete radio communication accessing schemes, many researchers focus on the uncustomary recourse wherein handling of RF propagating characteristics is delved. For instance, many recent studies have focused on controlling the environmental factors of reflection, refraction, meta-surfaces, facades, hoardings, and scattering of propagating RF signals, to enhance the quality-of-service (QoS) and achievable throughput rate. In the context of this, emerging index modulation schemes, [19–21], including media-based modulation, beam index modulation, quadrature index modulation, and spatial scattering modulation, principally use the variants in the signature of received signals by exploiting reconfigurable antennas and Tx additional information bits in rich scattering scenarios, and eventually boost the signal quality at the point of interest [22]. Thus, modern schemes offer careful governance and allocation of spectrum resources and enhance power utilization efficiency by implying a large array of antenna elements with minimal intensity in power transmission [23]. Also, it provides flexibility and, minimizes interference chances, and ensures ubiquitous seamless coverage to the user all the time [24,25]. Though current M-MIMO antennas are performing extraordinarily in a real practical environment for different scenarios, a few persistent issues that are discussed in this section still demand sharp and concrete approaches to optimize the operation of the M-MIMO processing system further [26].

2.2. RF Chain Reduction

The RF electronic chain circuits are a key element in digital antenna Rx design, it allows the passband communication data signals to be manipulated in the baseband, and achieve greater BF gain, spatial multiplexing gain, and SINR level. The process becomes more beneficial in M-MIMO mode wherein the number of RF chains increases typically from 16 to 64 and successfully enables high bandwidth (BW) applications [27]. The benefits of M-MIMO are directly concerned with the number of RF chains, and unfortunately, larger RF chains lead to greater cost, computational time, complexity, and enormous energy consumption issues, particularly with higher frequency carriers. In contrast to traditional phase shifters using phase gradient over the antenna array aperture to produce RF beams, phase shifting has been employed in the transmitted waves in the near field of the active antenna arrays without the assistance of phase shifters [28]. The authors have fabricated a parasitic layer consisting of metal strips with enhanced geometry, dimension, and position in the near field location of the antenna array, and prototype evaluation conclusively achieved superior beam performance with the low number of RF chains.

2.3. Unsourced Random Access

In sporadic traffic scenarios where the arrival of symbols is unpredictable, generally, a limited number of users/machines are active to transmit small data payloads, commonly carried in the order of 100 bits, in a particular system. It is envisaged that future sporadic traffic cases will proliferate, and extreme throughput requirements will be striven for. In line with this, more efficient multiple-access techniques are needed to handle the network's resources and accommodate the burgeoning count of smart nodes. Previously, grant-based random access techniques have been extensively employed for IoT systems and learned that the end nodes are greatly affected by the antenna's high power dissipation along with latency problems [29,30]. Focusing on the 6G networks and delay-critical applications, a grant-free random access scheme has been proposed wherein the devices/machines arbitrarily select unique training pilots for channel state information (CSI) and activity detection before transmitting data. Also, it does not perform mandatory handshaking protocols with the base station (BS), which is the reason for the high latency in the grant-based system. However, overall performance and channel connectivity support are limited by a certain number of users due to the confined pilot sequence resources. A new grant-free unsourced random access has been introduced as a probable alternative solution to subdue the impact of limited pilot resources [31,32]. Herein, machines/users compulsively exploit the same codebook, and the BS only requires obtaining a list of transmitted data without legally binding them to the particular active users. Deliberating the unsourced random access using existing approaches, such as ALOHA and CDMA, the authors [31] claimed that results were unsatisfactory, hence different revised coding techniques [33], for example, modified coupled coding, covariance-based maximum likelihood estimation, and approximate message passing have been proposed under the assumption of block-fading M-MIMO channel [34,35]. Still, the aforementioned works completely rely on independent and identically distributed (I.I.D) M-MIMO channels, which is indeed impractical in many practical outdoor environments because antennas at the device and the BS locations are subjected to strong correlations.

2.4. Pilot Contamination

To ensure wireless data transmission efficiency and minimize the pilot signaling overhead, pilot training sequences, either orthogonal or non-orthogonal, are reused in the neighboring cells in mobile network architecture. The sole reason is that pilot training sequences are restricted by the channel coherence time interval, and with the increase in the number of smart nodes, more pilot sequences need to be reassigned [36]. Thus, the reuse of pilot sequences in the neighboring cells becomes the reason for frequent interference issues. Though with the large-scale availability of antennas at the BS commendably eliminates the fast fading and additive white Gaussian noise effects, the resulting pilot training issues endure and constitute a major concern in M-MIMO transmission. Since the advent of the M-MIMO system, several studies have been performed on the mitigation of pilot training errors and after much deliberation, the authors in [37] have classified the existing studies into four categories: (i) precoding, (ii) pilot assignment, (iii) pilot design, and (iv) channel estimation. The authors have proposed a joint method of pilot assignment and pilot design-based CSI scheme to minimize the interference effect and showed that pilot assignment has outperformed the random pilot and exhaustive search algorithms at the cost of computing time and complexities.

2.5. Cell-Free M-MIMO

Concentrating on B5G requirements, an intense approach that can support ultra-reliability with multi-connectivity besides low power consumption is much needed. A cell-free (CF) MMIMO is a system that comprises several access points (APs) and coherently provides services to a much smaller group of users on the same time/frequency resources [38]. The new physically distributed antenna model keeps the same QoE for all the users with less signal processing computation [39]. The eminent contribution of CF M-MIMO is its advocacy in channel propagation and channel hardening. The APs are arbitrarily distributed all over the cell coverage area and smart products can connect simultaneously to multiple closely related APs antenna nodes. Hence, to conduct a face-paced packet data transmission process and manage scarce spectrum resources, the network needs to operate in time division duplexing (TDD) mode and exploits uplink (UL) - downlink (DL) channel reciprocity

[40]. By meeting all the essential aspects, it can satisfy high reliability and a very low packet drop rate due to the multi-connectivity feature, and it consumes a very low power amount. A few other promising aspects of CF MMIMO that make it beneficial over centralized antenna design are, (i) a short-range link between AP and users, (ii) covers a maximum area in space and supports ubiquitous connectivity, (iii) increased intelligent devices capacity and provide flexibility in APs deployment, and (iv) capitalizing energy efficiency (EE) and spectral efficiency (SE). These prodigious traits of CF M-MIMO are certainly practical and prudent for cellular, IoT, and D2D services in B5G networks [41]. Moreover, CF M-MIMO shows sustenance for higher frequency spectrums and, maintains timely data symbol delivery, minimizes path losses, and achieves a higher SINR level. The CF multi-antenna process also cultivates the macro-diversity gain by diminishing scattering, shadowing, and fading effects [42]. The potential practical cases of CF M-MIMO and certainly appropriate for current and forthcoming deployments are hot-spot spaces and indoor coverage areas. For example, shopping malls, stadiums, subways, smart train stations, community service centers, etc [43].

2.6. Hybrid precoding

Hybrid precoding is an attractive tool for the extremely high frequencies M-MIMO communication system. As it can significantly reduce the number of RF chains without affecting the total sum rate. In the current literature, most of the hybrid precoding utilizes either high-resolution phase shifters (PSs) or impractical narrow-band mmWave RF channel models. Concentrating on the hybrid precoding attributes, a CEO-based hybrid precoding method has been applied with one-bit PSs for frequency selective wideband mmWave M-MIMO system in [44]. The simulation test validated that the outlined framework achieved an acceptable sum-rate value and relatively higher EE compared to some available techniques. Similarly, while discussing the limitations of conventional hybrid precoding strategies, the authors [45] have proposed an energy-reliable switch and inverter (SI)-based hybrid precoding, and an adaptive cross-entropy (ACE) based hybrid precoding designs have been proposed. Experimental results showed that constructed algorithms can achieve a satisfactory sum-rate value and much better EE than traditional methods on a given model. A new joint beam selection process for analog precoding under a discrete lens array scheme has been presented in [45]. The authors have confirmed the excellence of the devised scheme by improving the system sum-rate, minimizing inter-user interference, and reducing computational complications.

Table 2. M-MIMO systems components.

Area	Ref.	Technologies	Impact	Limitations
Multiplexing Gain and Index Modulation	[19–21]	Emerging index modulation	Variants in received signal signature for improved quality	Requires reconfigurable antennas and Tx additional information bits
	[22]	Media-based modulation	Boosts signal quality at the point of interest	Intensity in the transmission of power needs to be minimal
	[23]	Large array of antenna elements	Enhances power utilization efficiency	Persistent optimization issues in M-MIMO processing system
	[26]	M-MIMO antennas	Performance optimization in various scenarios	Sharp and concrete approaches needed for persistent optimization issues
RF Chain Reduction	[27]	Phase shifting in the near field	Increase in BF gain, spatial multiplexing gain, SINR level;	Cost, computational time, complexity, energy consumption
	[28]	Parasitic layer with enhanced metal strips	Achieved superior beam performance with a low number of RF chains	Integration challenges in B5G due to unknown compatibility and scalability issues

Unsourced Random Access	[29]	Grant-based random access,	Proposes a grant-free random access scheme for delay-critical applications	Limited channel connectivity support due to confined pilot sequence resources
	[31,32]	ALOHA, CDMA	Introduces a new grant-free unsourced random access scheme	Unsatisfactory results with existing approaches such as ALOHA and CDMA
	[33]	Modified coupled coding,	Revised coding techniques for unsourced random access under block-fading M-MIMO channels	It relies on the impractical assumption of I.I.D M-MIMO channels, which is not suitable for many outdoor environments
Pilot Contamination	[36]	Pilot training sequences,	Reuse of pilot sequences in neighboring cells leads to interference issues	Potential interference issues due to frequent reuse of pilot sequences
	[37]	Pilot assignment, Channel estimation	Classification of existing studies into four categories for pilot training error mitigation	Increased computing time and complexities in implementing the joint pilot assignment
Cell Free M-MIMO	[39]	Cell-free MMIMO	Advocacy in channel propagation and channel hardening	It requires significant infrastructure deployment.
	[41]	Cellular, IoT, D2D services in B5G networks	- Provides ubiquitous connectivity and flexibility in APs deployment	Potential scalability issues with an increasing number of devices
	[42]	Higher frequency spectrums	- Sustains higher frequency spectrums.	- May face challenges in compatibility with legacy systems.
Hybrid precoding	[44]	CEO-based hybrid precoding	Achieved acceptable sum-rate value and relatively higher EE	Dependence on one-bit PSs may limit performance in complex environments
	[45]	Energy reliable SI,	Proposed algorithms achieved satisfactory sum-rate value	Energy-efficient designs may require complex hardware implementations

3. M-MIMO in B5G/6G Technologies

As the demand for high-speed and reliable wireless communication continues to soar, the emergence of B5G and 6G technologies promises groundbreaking advancements. Among these, M-MIMO is a pivotal technology reshaping the wireless landscape. Leveraging AI/ML approaches, M-MIMO optimizes network performance by dynamically adapting to changing conditions and user demands and the integration of Reconfigurable Intelligent Surfaces enhances M-MIMO systems by manipulating electromagnetic waves, improving coverage and spectral efficiency as depicted in Figure 3. Furthermore, innovations such as Visible Light Communication, Hybrid Beamforming, and Three-Dimensional Beamforming complement M-MIMO, offering enhanced connectivity and throughput in diverse environments. The exploration of Tera Hertz Spectrum opens up new frontiers for M-MIMO and Wireless Backhaul, enabling ultra-high-speed data transmission and unlocking the potential for futuristic applications. The subsequent subsections thoroughly analyze emerging concepts for M-MIMO integration in B5G/6G technologies.

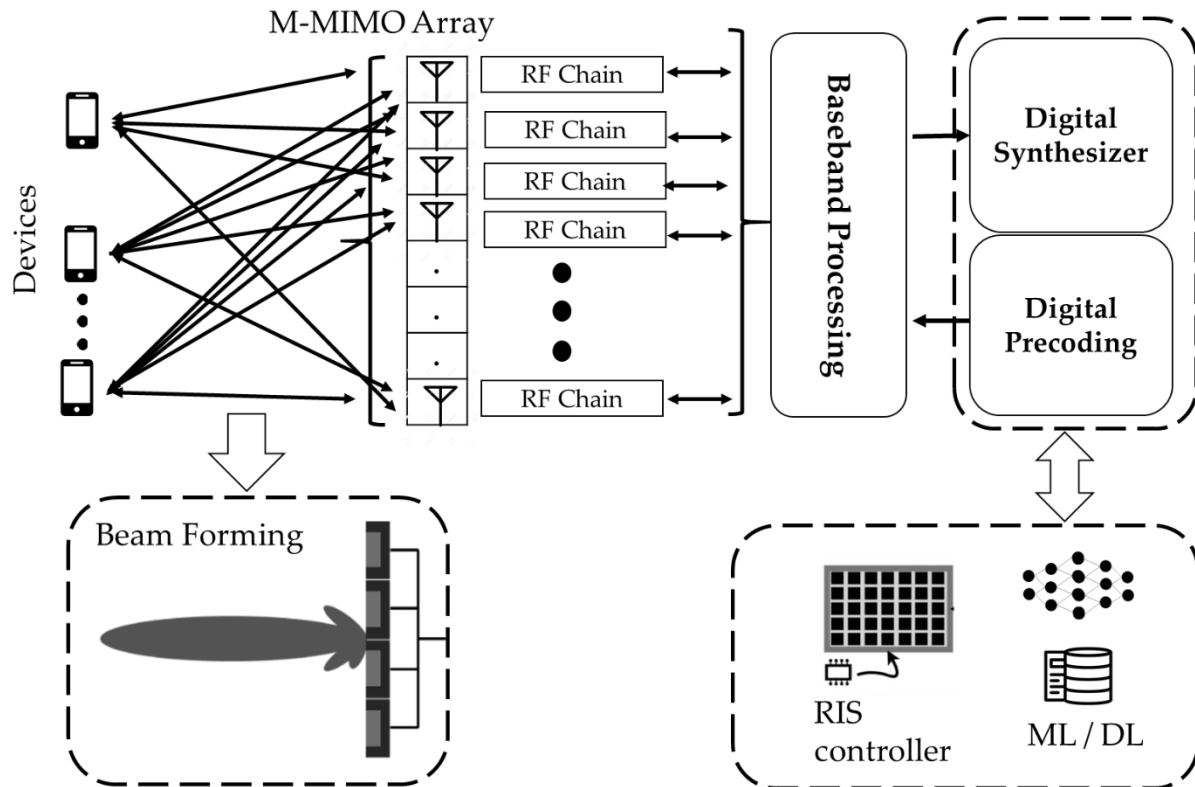


Figure 3. Overall organization of this article.

3.1. M-MIMO with AI/ML Approaches

Current cellular carrier networks pose various intimidating challenges that need immediate attention. For example, it is hard to estimate the channel characteristics of colossal data due to the frequent and large counts of SER. Secondly, a substantial volume of data is generated and sensed by BSs every day to accommodate different users in multi-purpose scenarios. It is a challenging task to examine and characterize useful information accurately [46]. Another important factor is learning the beam combination under the operation of FD, a fast-paced, and enormous data transmission mode [46]. Thus, to manage such constraints in wireless networks, artificial intelligence (AI) and machine learning (ML) algorithms become an effective treatment to mitigate contemporary issues and enhance overall network performance [47]. The idea behind AI/ML with M-MIMO amalgamation is to design a less complicated algorithm and synchronization. Besides, an improvement in the acquisition of users for accessing the link, restrain from regular system faults, and avoid problems in receiving system knowledge of the radio networks [48]. Lately, preliminary evaluations of the exercise of AI/ML algorithms in B5G cellular networks have been investigated by the standardization authorities to validate the idea. Including the International Telecommunication Union (ITU), third-generation partnership project (3GPP), and 5GPPP, as well as other study groups such as FuTURE, and the telecom infra project (TIP). Although the cooperative association of many radio accessing mechanisms with M-MIMO antenna elements is expected to dispense the unprecedented requirement of wireless data services. Yet, the fundamental concern in the concurrent operation of major data propagation technologies is high operational complexities and computation time. It vigorously affects delivering valuable resources to the destination and greatly damages the mobile network's performance and QoE, which is totally unacceptable.

Recent works on the successful operation of wireless communication with AI/ML M-MIMO and other facilitating technologies have been presented in the section. Advanced ML and situational awareness tools have been integral to wireless systems in addressing various issues in the physical layer. Following the theme, the application of ML for mmWave beam alignment has been exhaustively examined to solve complicated non-linear problems and gain potential advantages. In an article [49], a beam alignment process with partial beams using the ML (AMPBML) scheme has

been investigated for the MU-mmWave M-MIMO network. The proposed method minimized training slots and aligned beams for multiple users concurrently and successfully conducted MU mmWave M-MIMO communication. The authors in [50] have discussed the mmWave beam prediction issue in a highly mobile vehicular environment. A novel ML tool and situational awareness availability have been proposed to learn the beam information. Consequently, situational awareness helped improve prediction accuracy, and the model managed to achieve good throughput at the cost of little loss of performance. Many studies have confirmed that ML and deep learning approaches are prolific in estimating information's angle of arrival (AoA). In an article [51], the authors have recently gathered AoA information via appropriate mmWave beam selection in the UL direction using learning-based methods. It proposed two learning processes: k-nearest neighbors, support vector classifiers; and one deep learning method: the multilayer perception. A unique beamformer set with a bigger and configurable beamwidth has also been established. To validate the plausibility of the scheme a computer simulation revealed that in terms of classification accuracy and sum-rate performance, the proposed solution is relatively close to exhaustive search results.

Another article [52] evaluated the deep learning compressed sensing (DLCS) technique in MU-mmWave M-MIMO systems for robust channel estimation. The results proved that the channel estimation performance of the implemented scheme via simulation test was better than that of contemporary processes. Power consumption and massive hardware costs are the most challenging phenomena in the full exploitation of mmWave RF signals in M-MIMO antenna systems. It is defined as the total number of RF chains needed for BF and the increased power utilization with the antenna ratio. Therefore, many authors have focused on the applicability of lens antenna arrays and proposed dictionary-trained beam selection matrices [53]. Experimental values verified the essence of the proposed technique by enhancing channel estimation performance. Few authors have tried to extract the benefits of the deep learning method and attempted a low-rank channel recovery scheme for a hybrid BF array-based M-MIMO system to acquire full CSI [54]. Analytical studies revealed that novel design has the potential to attain the full-rank LS solution. The authors have furnished a neural hybrid BF/combining strategy to tackle hybrid precoding constraints and overcome the traditional issues in the mmWave multi-antenna streams [55]. The authors experienced results showing that the proposed scheme established higher BER than other linear matrix decomposition methods. This sub-section is summarized in Table 3.

Table 3. M-MIMO systems and AI/ML approaches.

Tech.	Ref.	Area	Impact	Limitations
M-MIMO with AI/ML Approaches	[49]	ML (AMPBML)	Minimized training slots, concurrent beam alignment for multiple users	Potential loss of performance
	[50]	ML	Improved mmWave beam prediction in highly mobile vehicular environments	Minor loss of performance
	[51]	ML (k-NN, SVM, multilayer perception)	Improved angle of arrival (AoA) estimation	Computational inefficiency
	[52]	Deep learning (DLCS)	Better channel estimation performance in MU-mmWave M-MIMO systems	Potential power consumption and hardware cost challenges
	[53]	Dictionary-trained beam selection matrices	Enhanced channel estimation performance	Experimental validation required
	[55]	Neural hybrid BF/combining strategy	Higher BER compared to other linear matrix decomposition methods	Potential limitations in practical implementation

3.2. Reconfigurable Intelligent Surfaces

In order to overcome the intrinsic deficiencies of antenna technologies, conventional relaying approaches, path loss problems, algorithmic difficulties, and computing time, a prospective RIS concept has been prompted, especially for high precision delay-sensitive arenas [56]. By definition, it is a programmable metasurface comprised of passive electronic components with very low power

consumption, and each element can positively regulate the incident signal to a specific degree of phase shift via a central controller connected by RIS (as shown in Fig. 4), and approximately achieve an equal threshold of passive BF gains [57]. Each passive component on the metasurface has the potential to fine-tune the signals independently and reflected signals from RIS can positively converge to the desired location, hence achieving very high data success reliability [58]. However, the larger the size and geographical distribution of the RIS array in a particular environment, the greater the data success probability ratio, but would intimidatingly escalate the algorithmic complications and add a significant latency in delivering the packet, even in the short symbol transmission [59]. Therefore, the array's size is paramount because many future mobile services and robotic assignments will demand stringent delay management with ultra-high reliability, and a diligent evaluation of RIS array size in line with the surrounding environment is crucial [60,94]. Recently, a comparative study has been conducted to demonstrate the elegance of the RIS-aided M-MIMO systems over conventional M-MIMO systems by adopting a genetic framework that completely depends on statistical CSI [61]. Similarly, portraying the essence of RIS in a complex dynamic environment under statistical CSI in M-MIMO systems, the authors analyzed that the interplay of M-MIMO and RIS metasurfaces would certainly enrich the communication environment besides decrease the implementation complications and signaling overhead cost [62]. In another study, [63] researchers investigated the performance of RIS-aided M-MIMO under imperfect CSI with ZF detectors and identified that greater system capacity can be achieved with minimal RIS complexity. Still, latency evaluation and energy management have remained open issues that demand further exploration. This sub-section is summarized in Table 4.

Table 4. Reconfigurable Intelligent Surfaces for M-MIMO systems in B5G/6G.

Tech.	Ref.	Area	Impact	Limitations
Reconfigurable Intelligent Surfaces	[56]	Algorithmic difficulties, computing time	High-precision delay-sensitive arenas with programmable metasurface capabilities and low power consumption.	Increasing the size and geographical distribution of the RIS array escalates algorithmic complications
	[57]	RIS, passive BF	Each element of RIS can independently fine-tune signals, leading to high data success and reliability.	Complicated algorithms, adding latency in packet delivery.
	[58]	RIS, passive components	RIS can positively converge reflected signals to desired locations	Requiring stringent delay management and ultra-high reliability.
	[59]	RIS, algorithmic complications, latency	The size of the RIS array significantly impacts the data success probability ratio and latency	Increasing the size of the RIS array adds to algorithmic complications
	[60]	RIS, delay management, ultra-high reliability	Achieves stringent delay management and ultra-high reliability	It is difficult to ensure ultra-high reliability and manage delays in communication systems.
	[63]	RIS-aided M-MIMO, imperfect CSI, ZF detectors	Investigation of RIS-aided M-MIMO performance under imperfect CSI with ZF detectors	Latency evaluation and energy management require further exploration.

3.3. Visible Light Communication

More than 70% of the data volume is predicted to be generated from indoor environmental locales [64]. To release the congestion of the current RF spectrum and enable low-cost as well as extremely reliable data access solutions, visible light communication (VLC), which is also referred to as LiFi in the current radio access network (RAN) architecture evolved as a viable supplement owing to many desirable aspects, for instance: (1) low hardware and processing cost because VLC uses standard lighting framework to reap illumination and communication benefits, (2) very large BW resources (of the order of THz), (3) green communication because of low energy consumption, (4) high SINR (due to the illumination size of lux), (5) security and interference avoidance which makes VLC compatible for hospitals, aircraft, healthcare centers, schools, and those localities where RF

transmission are not befitted. Moreover, to meet the future extreme data rate demand, the throughput rate of VLC systems also heavily relies on the number of transmitting light emitting diodes (LEDs) arrays and receiving photodiodes (PDs) and coined the term M-MIMO VLC system [65]. In spite of that, the performance of the M-MIMO VLC system is severely affected by two factors that need further investigation: (1) amplification noise at the receiver using ZF or MMSE, (2) non-linear transfer characteristics of LED, results in non-linear distortion and poor symbol rate performance [66]. A novel approach was introduced in the study [67] to address spatial multiplexing challenges in VLC MIMO systems and enhance spectral efficiency (SE). The approach uses joint IQ independent component analysis (ICA), and leverages ML techniques specifically tailored for a 2x2 MIMO system in the VLC domain. The proposed ML methodology allows two optical signals to be effectively split into parallel streams, mitigating spatial cross-talk and inter-symbol interference. Similarly, the study [68] proposed an artificial neural network (ANN)-based joint spatial and temporal equalization scheme for the MIMO-VLC system. This ANN-based solution surpasses traditional decision feedback equalization (DFE) by effectively addressing nonlinear transfer functions and cross-talk within a real optical MIMO communication channel, whether imaging or non-imaging. The data structure feeding the ANN incorporates both predicted signal vectors with feedback delay lines and received signal vectors with feedforward delay lines, thereby optimizing signal processing for improved system performance. This sub-section is summarized in Table 5.

Table 5. Visible Light Communication for M-MIMO systems in B5G/6G.

Tech.	Ref.	Area	Impact	Limitations
Visible Light Communication	[64]	LiFi, RF Spectrum Congestion, Indoor Environments	Release congestion of RF spectrum - Enable low-cost, reliable data access	Performance affected by amplification noise at the receiver ZF or MMSE -
	[65]	M-MIMO VLC System,	Future data rate demand can be met through M-MIMO VLC systems	Affected by amplification noise at the receiver and non-linear LED
	[67]	VLC MIMO systems, Joint IQ independent component analysis (ICA), ML techniques	Addressing spatial multiplexing challenges, Enhancing spectral efficiency (SE)	ML processing and computational requirements in resource constraint devices
	[68]	MIMO-VLC system, (ANN, Joint spatial and temporal equalization	Surpassing traditional decision feedback equalization (DFE), Addressing nonlinear transfer functions and cross-talk	Increased complexity and interoperability issues Vulnerable to data privacy issues

3.4. Hybrid Beamforming

BF was first proposed and designed by Zhang, and Molisch [69], exploiting the combinatorial work of digital precoding and analog BF schemes. The interplay of analog and digital beamformers was initiated to balance both schemes' cost and overall performance. Hybrid BF, in general, is considered a spatial filter that has the potential to strengthen the desired signal elements and circumvent the impact of unwanted signal components in proximity. The major advantage that leads to Hybrid BF selection is the number of RF chains, which is lower and limited by the number of transmitted packet data symbol streams. Whilst the BF and diversity gains are subject to the number count of antenna elements (as shown in Fig. 5). In a practical scenario, firstly at the Tx side, digital BF is executed at the baseband level (i.e., the phase of transmitted signal and amplitude is calculated at the baseband frequency level). Next, analog BF helps control the antenna's transmitted RF energy phase with sophisticated phase shifters [70]. The technique manages to reduce energy in the sidelobe and simultaneously receives data packets in a specific direction.

Similarly, the wide-scale M-MIMO antenna arrays offer many DoFs that help to improve the network performance by minimizing fading effects. Implementing Hybrid BF is considered an optimum choice for M-MIMO antenna systems compared to the case of digital BF for B5G networks. The legacy digital BF request for at least one RF chain for each antenna element thus resulted in huge

algorithmic complexities and costs, especially in mmWave M-MIMO communication [71]. Conversely, hybrid BF utilizes analog phase shifters with fewer RF chains, ultimately supporting fewer complexities and cost efficiency with almost the same network service. Overall, Hybrid BF is a method that adjusts a sharp tradeoff between the SE, EE, and sophisticated hardware difficulties to reap the benefits of analog and digital BF techniques.

The BF techniques have shown prolific behavior in a real NR 5G communication environment and mitigated several conventional constraints. Previously, two-dimensional (2D) BF was employed to achieve spatial diversity gains and avoid in-air transmission losses [72]. This theme has justified the 5G radio communication demands, yet 2D beam features are severely restricted to design issues. It is primarily because its beam patterns only propagate in two planes, either vertical or horizontal. Thus, it can solely differentiate users from two angles, i.e., horizontal or vertical.

Following the continuous progression of various intelligent wireless access technologies and deficiencies in conventional mode, 2D BF has also steadily evolved to three-dimensional (3D) BF methods [73]. The advanced 3D BF technique is regarded as the major modification in beam management and antenna lobes patterns, as it can regulate the strength of the RF beam patterns spatially in different directions. Realizing the small aperture of a large-scale MIMO antenna packed closely at the BS, the 3D BF technique is manifested as a suitable candidate due to its agility in identifying users in space [74]. It also helps in achieving spatial domain usage efficiency by forming the random cubic angle dimensions of beam patterns. Nonetheless, the performance of the 3D BF in cellular communication extensively relies on the properties of antenna RF beam patterns. It is a prime technology for B5G that can significantly improve network performance and SE. Thus, in-depth analysis and applications of 3D BF in the presence of M-MIMO communication are indispensable. This sub-section is summarized in Table 6.

Table 6. Hybrid Beamforming for M-MIMO systems in B5G/6G.

Tech.	Ref.	Area	Impact	Limitations
Hybrid Beamforming	[64]	LiFi, RF Spectrum Congestion, Indoor Environments	Release congestion of RF spectrum - Enable low-cost, reliable data access	Performance affected by amplification noise at the receiver ZF or MMSE -
	[65]	M-MIMO VLC System,	True data rate demand can be met through M-MIMO VLC systems	Affected by amplification noise at the receiver and non-linear LED
	[69]	Beamforming (BF), Hybrid BF	Explored the combination of digital precoding and analog BF schemes. Balancing cost and performance	Legacy digital BF requires one RF chain per antenna element.
	[70]	Digital BF, Analog BF, Phase Shifters	Reducing sidelobe energy, directing RF energy, improving network performance, minimizing fading effects	Complex algorithmic requirements, high costs in legacy digital BF, especially in mmWave M-MIMO communication
	[71]	Hybrid BF	Combining analog and digital BF, utilizing fewer RF chains, reducing complexity and cost	Difficulty in balancing the tradeoff between spectral efficiency (SE), energy efficiency (EE), and hardware difficulties
	[72]	2D Beamforming	Achieving spatial diversity gains, avoiding in-air transmission losses	Severe restriction to design issues due to propagation limited to two planes (vertical or horizontal)
	[73]	3D Beamforming	Major modification in beam management and antenna lobe patterns	Performance extensively relies on properties of antenna RF beam patterns

3.5. Tera Hertz Spectrum

The THz frequency bands are already on the horizon and many wireless accessing public and private research sectors are testing different ranges of THz spectrum [75]. The wireless standardization authorities firmly said that THz bands in the range between 0.1 THz to 10 THz are the potential candidates for the upcoming mobile 6G communications networks and will assist in managing the speedy data demand of the future Internet of Everything (IoE) [76]. Tremendously

high-frequency radio bands are competent to raise the different parameters of wireless carriers. Specifically, secrecy and privacy, large access to green line spectrum, reputable energy plus power consumption, flexible and stringent wireless backhaul connection, support of ultra M-MIMO antennas, sophisticated and portable hardware components inclusive of focused beam patterns, and an interference-friendly propagation environment [77,78]. The initial concept started circulating after the successful completion of 3GPP release-17 standards and protocols, after that, a lot of attention has been dedicated to enabling a tremendous high-frequency radio spectrum in indoor and outdoor B5G use cases. Likewise, further analysis and bench tests, particularly for extreme URLLC cases, are utterly needed and worthwhile for radio communication furtherance [79].

In the THz spectrum, especially radio waves above 300 GHz would be highly advantageous in spectroscopy, holographic, industry 4.0, remote surgery, and ultra-massive scale operational amenities [80]. The mmWave and THz untapped spectrum and availability of bundle of different channel BW, besides their attractive propagation qualities and applicability in real environment scenarios are also the major motives behind the inclusion of M-MIMO in ongoing 5G and future networks [81]. Generally, single antenna propagation has very bad directivity and random radiation patterns of RF waves. It is critical in the current wireless communication and for B5G to implement very high directive antennas. The researchers suggested that this could be conceivable by deploying massive antenna elements in the given electronic and geometrical composition, without compromising the size of arrays [82]. However, antenna construction and design for 1000 GHz and above frequency bands, deployment scenarios, channel categorization, and impact of environmental effects, etc., need extensive further exploration [83,84]. Fig.6 portrays the RF spectrum in mmWave and THz electromagnetic radiations. Another impactful propagation property of the THz spectrum is its efficiency in diminishing many traditional antenna transmission issues while link budgeting can display a high sense of reliability and adaptability in radio signal propagation. Nonetheless, new techniques overcome many challenges but always introduce various other unprecedented obstacles [85]. For example, spatial multiplexing and dedicated user-centric beam transmitting mechanisms are highly susceptible to various types of blockages, such as inter-cluster interference, control channel interference, etc [86]. Whereas, issues related to SER performance, receiver model and structure, channel modeling, and spectrum sensing need to be addressed to achieve the potential of THz M-MIMO transmission systems. Table 6 compares different bands’ channel parameters and characteristics [87]. Some of the recent technical works that have been derived by different researchers across the world for energetic and ultra-reliable seamless transmission of data symbols using THz in the M-MIMO system are discussed in the section. This sub-section in summarized in Table 7.

Table 7. Tera Hertz Spectrum for M-MIMO systems in B5G/6G.

Tech.	Ref.	Area	Impact	Limitations
Tera Hertz Spectrum and M-MIMO	[64]	THz frequency bands (0.1 THz to 10 THz)	Potential candidates for 6G networks	Need for further analysis and bench tests, particularly for extreme URLLC cases
	[76]	THz spectrum	Enhance wireless carriers' parameters (secrecy, privacy, energy efficiency, etc.)	Deployment challenges, environmental impacts
	[77]	mmWave, untapped spectrum	Attractive propagation qualities	Challenges in achieving very high directive antennas
	[79]	THz spectrum (above 300 GHz)	Advantages in spectroscopy, holographic, industry 4.0, remote surgery design	Need for extensive exploration of antenna
	[80]	M-MIMO in 5G and future networks	Utilization of mmWave and THz spectrum, attractive propagation qualities	Susceptibility to various types of blockages
	[81]	Very high directive antennas	Achieving high directive antennas for B5G	Challenges in deployment, environmental impacts
	[82]	RF spectrum in mmWave and THz	Impactful propagation properties of THz spectrum	Deployment challenges, susceptibility to blockages

[83,84]	THz M-MIMO transmission systems	Energetic and ultra-reliable seamless transmission of data symbols	Issues related to SER performance, receiver model and structure, channel modeling, spectrum sensing
[86]	Spatial multiplexing	Achieving the potential of THz M-MIMO transmission systems	Susceptibility to inter-cluster interference, control channel interference
[87]	Different bands' channel parameters and characteristics	Comparison between bands' characteristics	Need for addressing issues related to SER performance, receiver model and structure, channel modeling, spectrum sensing

3.6. Wireless Backhaul with THz

To institute an ultra-dense network (UDN) with high consistency, well-grounded infrastructure, and cost-effective network operation management, higher spectrum (i.e., GHz and THz) backhaul connection between high power BS and low power nodes is vital [88–90]. The large-scale spatial streams MMIMO armed with BF mechanism, and distributed over a large geographical area using high-frequency bands would be beneficial to avoid fiber optic and copper cables, and other pertinent hardware deployment costs [91,92]. It has been decidedly validated by scientific societies, engineers, and academia that extreme frequency channel BW is acceptable and reliable to securely govern the wireless backhaul in UDN multi-tier HetNet systems [93]. The prominent attributes of mmWave and THz spectrums over backhaul transmission are: (i) most of the spectrum is untapped in mmWave and THz bands, and the underutilized frequency bands leverage to ignite the GHz and higher transmission BW. (ii) M-MIMO or ultra M-MIMO with narrow beams using BF and RIS would empower the ultra-high frequency resources to support signal directivity and link quality by resisting path losses [94]. This sub-section is summarized in Table 8.

Table 8. Wireless Backhaul with THz for M-MIMO systems in B5G/6G.

Tech.	Ref.	Area	Impact	Limitations
Wireless Backhaul with THz	[88,89]	Higher spectrum backhaul	Enables ultra-dense network (UDN) with high consistency and cost-effectiveness	Potential challenges in hardware deployment and maintenance
	[91,92]	Large-scale spatial streams MMIMO	Reduces reliance on fiber optic and copper cables, lowers hardware deployment costs	Interference and coordination issues due to densely packed nodes
	[93]	Extreme frequency channel BW	Enhances wireless backhaul reliability and efficiency	Compatibility issues with existing infrastructure and devices
	[94]	RIS for backhaul transmission	Improves signal directivity and link quality	Challenges in beamforming and susceptibility to atmospheric conditions

4. Challenges for M-MIMO in B5G/6G

4.1. Propagation Loss Issue

The data rates requisite in the mobile communication system are increasing rapidly because of the simultaneous interaction of enormous intelligent devices. Concerning this, the THz band will also play a key role in future high BW applications' performance, as severe signal distortion and poor diffraction characteristics remain the limiting elements of the radio coverage area. The authors in the paper [95] have proposed a combined method of RIS and low-complexity beam training and hybrid BF design for the THz multi-user M-MIMO system to reduce THz band propagation loss. Also, a ternary tree has been proposed for the BS and users to reduce search complexities. After performing a numerical analysis, the results showed that with adequate quantization resolution with M-MIMO, the designed scheme would apply to future THz communication. In another article [96], the researchers discuss the issues of inter-symbol and inter-user interferences, in addition to propagation loss at THz frequency bands. A single carrier minimum mean square error (MMSE) precoding and detection framework has been presented for frequency-selective THz channels to eliminate the

inevitable obstacles. The authors have suggested via simulation test that the proposed scheme is capable of holding satisfactory performance in terms of bit error rate. Few researchers have fabricated joint BF based on fractional programming in plasmonic ultra M-MIMO antenna elements to overcome the THz frequency band attenuation problem in [97] [150]. The proposed methodology achieved reputable channel performance and has shown high reliability in a realistic communication environment. In article [98], the authors attempt to resolve the propagation constraints and enhance the THz communication range as well as achievable capacity. It presented the ultra M-MIMO concept by using plasmonic nano-antenna arrays to overcome the limitation of channel propagation. And eventually, to enable wireless tera-bits/sec links between compact smart products over several tens of meters. Preliminary results of the proposed scheme have shown that frequencies in the 0.06 – 1 THz range metamaterial nanoantenna system can be considered to design plasmonic nano-antenna elements with hundreds of elements in a few cm² for both transmission and reception.

4.2. Hardware Cost and Algorithmic Complexities

Although the hybrid precoding process has exhibited excellent results in the reduction of hardware costs and algorithmic complications in mmWave M-MIMO networks, However in THz, communication blockages and path loss have a significant impact on the link performance and a modified hybrid precoding technique is demandable. Therefore, in a recently published paper, [99] the authors have employed a two-way amplify and forward (AF) relay in OFDM-based THz M-MIMO system and achieved higher performance than other existing schemes regarding sum-rate and EE. Meanwhile, a low-complexity beam squint mitigation method along with orthogonal matching pursuit (OMP) mechanism with low training overhead has been utilized for the interference and propagation constraints of the THz spectrum [100]. The simulation results validated that the designed scheme enabled accurate CSI acquisition in low SNR and advised that wideband M-MIMO will play a key role in optimizing THz mobile networks. In article[101] researchers have attempted to combat the fundamental challenge of millidegree-level 3D direction-of-arrival (DoA) prediction and millisecond-level beam tracking with reduced pilot overhead in THz dynamic array-of-subarrays (DAoSA) systems. A DAoSA-MUSIC and DL-based DCNN scheme have been exploited to mitigate the super-resolution DoA estimation issue. The proposed methods accomplished super-resolution DoA estimation, eliminated 50% pilot training overhead, and exploited much better performance over contemporary methods.

4.3. High Power Consumption

Several recent studies have shown the great potential of CF M-MIMO in wireless communication. The authors [102] compared the EE and SE between CF and cellular M-MIMO systems along with practical deployment metrics for rural, urban, and suburban environments. While a high power consumption issue in CF networks is considered [103] and to tackle the constraint a novel low-complexity power control technique with zero-forcing (ZF) precoding design has been formulated. Likewise, the authors [104] have investigated the performance of CF M-MIMO systems by examining the DL coverage probability and achievable rate. The results showed that CF M-MIMO outperformed the small cell design under coverage and rate. Since low-quality antennas are required to guarantee energy and economic efficiencies in realizing the CF M-MIMO realistically, hardware impairments become a challenging problem. The authors [105] have proposed a steady hardware distortion model to analyze the performance of UL and DL CF M-MIMO systems with transceiver hardware design impairment. In consequence, the numerical results of the proposed scheme validated the performance of CF M-MIMO without compromising the quality of service (QoS). The authors [106] have investigated the impact of hardware impairments on the physical layer security of a CF M-MIMO system with a pilot spoofing problem. An LMMSE channel estimator for the proposed design has been derived, and a closed-form ergodic secrecy rate has been attained. In consequence, phase noise drastically degraded the antenna performance and LOS components may be exposed to fading variations for particular cases.

4.4. Security

The prevalence of wireless access devices and hefty data volume usage for assorted mobile applications, such as mobile payment, banking, social media activities, etc [107]., provide agility and readiness in human's routine activities. Unfortunately, privacy and information security are two prime concerns that remain vulnerable issues, owing to the dynamic broadcast nature of wireless communication. Concerning this, the authors [108] have developed a spoofing attack detection method, i.e., channel virtual/beam-space representation for static and online detection algorithms for dynamic mmWave M-MIMO 5G networks. The results showed 25% and 99% improvements in detection rate with channel virtual and learning-based schemes, respectively. Authentication plays a pivotal role in providing robust security service by confirming the identity of a requesting node and refrain adversarial impersonation to access the channel. The authentication method has become a prominent requirement in M-MIMO antenna systems due to the inability of conventional cryptography-based authentication protocols. Numerous studies have been conducted on the physical layer protocol authentication methods [109–111], and authors in [112] have classified them into three broad types: watermarking, channel-based, and fingerprinting authentications. Nonetheless, all of the proposed strategies are precisely based on the non-M-MIMO systems and considered ideal transceiver hardware design which is not a practical approach. Though few recent studies have utilized intelligent learning techniques [113,114], particularly for upcoming aerial platform scenarios [27,115], more advanced approaches are much needed.

5. Open Issues and Future Research Directions

Various methods and experimental tests have been developed for the efficient and smart usage of M-MIMO systems in 5G cellular networks. Moreover, new wireless technologies such as ultra-massive MIMO, THz, sub-mmWave, and VLC require immense research effort and practical analysis before the appropriate deployment in the current radio communication environment. A few of the prospective research activities in M-MIMO and other discussed technologies for B5G networks are discussed below.

5.1. Narrow Aperture Antenna Nodes

The massive-scale deployment of advanced intelligent antenna systems can minimize the effects of fading, noise, and interference. This wide-ranging implementation increases the load on the system performance and raises computational and algorithmic complexities. Future M-MIMO antenna arrays should be configured with minimum cost and sophisticated small-area components [116]. Fairness among the smart objects is another important aspect in M-MIMO deployment due to its prevalence throughout the cell. In a conventional approach, M-MIMO system throughput can be enhanced by only scheduling users with high SINR values and ignoring the rest of the access requests, especially those who reside at cell edges and have poor channel conditions. This would certainly demean the user reputation and can escalate overall unsatisfactory network performance, thus high-level fairness among all the smart nodes must be ensured [117].

5.2. Plasmonic Antenna Arrays

To increase antenna elements, at the BS, beyond the scope of M-MIMO and remove the barrier of $\lambda \setminus 2$ sampling of space dimension, the graphene-based plasmonic structure can be a probable solution to develop nanoscale transceiver designs with maximum space dimension $\lambda \setminus 20$, eventually densely integrate large elements in small footprints (1024 elements under the 1mm² dimension). Regrettably, graphene does not conduct appropriate signal processing at high-frequency bands, further study on the incorporation of metasurfaces into the plasmonic transceiver arrays has been suggested [118]. The plasmonic reflectarray antenna is another promising approach to enable ultra M-MIMO in a 3D environment with sizes ranging from 1 mm² to 100 mm² depending on mmWave or THz operating frequency bands. Undeniably, the sub-wavelength size of reflectarray elements permits controlled reflections in non-specular directions and reflections with polarization conversion [119].

5.3. Integrated Communication and Sensing with M-MIMO

The upcoming 6G wireless services will be exclusively based on the simultaneous exposure of radio communication and sensing paradigm. In mobile networks, sensing precisely concerns the location of objects, design, detection, and estimation of moving object speed via RF signals. Implementation of sensing using WiFi focusing on indoor scenarios has been comprehensively discussed in [120]. While sensing for outdoor use cases using cellular networks, application scenarios could be traffic operation and monitoring, the discovery of free parking slots in dense proximity, humidity detection in agriculture cases, and vehicles plus pedestrians detection, etc.; therefore, further research in this direction would enrich the future 6G wireless systems [121]. Furthermore, the authors [122] have presented the vision of distributed joint communication and sensing systems exploiting distributed M-MIMO antenna systems for purposes such as ultra-reliable communication, precise localization, and distributed radar capabilities in passive mode. In the future, factories will not only stipulate very high data success probability but also strive for extremely accurate localization, and stringent integrated communication and sensing approaches with distributed M-MIMO have been characterized as an attractive theme for 6G networks.

5.4. Federated Learning in M-MIMO

D2D communication can be the key element for improving the efficiency of distributed federated learning computations [123]. In this regard, the channel transmission characteristics need to be perfectly modeled to maintain the SER boundary up to 10⁻⁸ percentile and evade convergence rate performance issues. Unfortunately, the reconstruction of local gradient vectors at the central server node, which is assessed and computed and then transmitted from the smart devices, is a paramount challenge in system design. To subdue, a compressive sensing scheme to trigger the server to iteratively locate the linear MMSE of the transmitted signal by using its sparsity aspect was presented [124]. The results showed perfect reconstruction and reduced the performance gap between centralized and federated learnings, the same approach could be further analyzed for the device scheduling method, or design a transmission strategy for broadcasting the parameter vector to the radio devices and investigate the performance of federated learning over an M-MIMO system. Since accurate channel estimation and pilot training overhead are critical parameters in low latency and high-reliability data symbol transmission for time-sensitive critical cases. Recently researchers have analyzed FL approaches to resolve the everlasting estimation and signaling overhead problems [125,126]. For this topic, academic explorers can design federated and distributed learning-based channel estimation schemes that can be exploited in multiple scenarios without extra training [127].

6. Conclusions

To overcome the conventional obstacles of wireless networks, various new designs and advancements in technologies such as large-scale multi-antenna arrays, hybrid BF, higher spectrum, and IAB links have been introduced. This article discusses the M-MIMO system's feasibility, applicability, and key aspects in B5G networks. Additionally, the paper provides insight into the effectiveness of M-MIMO with other enabling technologies precisely BF, higher frequency bands (i.e., mmWave, and THz), IAB communication, and AI/ML algorithms. Although wide-scale MMIMO system possesses enormous benefits for current 5G and upcoming 6G wireless networks. Still, many implementations and signal optimization issues need to be diminished to touch the full potential of smart active antenna elements processing. Similarly, other cornerstone technologies, such as BF and mmWave, demand upgradation in antenna designs and propagation strategies. Besides the essence of the THz spectrum is also a key element to support the abundance of wireless equipment and meet future necessities. This paper highlights the recent trends and state-of-the-art research schemes presented in the literature.

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