

Holographic MIMO Communications: Theoretical Foundations, Enabling Technologies, and Future Directions

Tierui Gong, *Member, IEEE*, Ioanna Vinieratou, *Student Member, IEEE*, Ran Ji, Chongwen Huang, *Member, IEEE*, George C. Alexandropoulos, *Senior Member, IEEE*, Li Wei, Zhaoyang Zhang, *Senior Member, IEEE*, Mérouane Debbah, *Fellow, IEEE*, H. Vincent Poor, *Fellow, IEEE*, and Chau Yuen, *Fellow, IEEE*

Abstract—Future wireless systems are envisioned to create an endogenously holography-capable, intelligent, and programmable radio propagation environment, that will offer unprecedented capabilities for high spectral and energy efficiency, low latency, and massive connectivity. A potential and promising technology for supporting the expected extreme requirements of the sixth-generation (6G) communication systems is the concept of the holographic multiple-input multiple-output (MIMO) surface (HMIMOS), which will actualize holographic radios with reasonable power consumption and fabrication cost. An HMIMOS is an ultra-thin and nearly continuous aperture that incorporates reconfigurable and sub-wavelength-spaced antennas and/or metamaterials. Such surfaces comprising dense electromagnetic (EM) excited elements are capable of recording and manipulating impinging fields with utmost flexibility and precision, as well as with reduced cost and power consumption, thereby shaping arbitrary-intended EM waves with high energy efficiency. The powerful EM processing capability of HMIMOS opens up the possibility of wireless communications of holographic imaging level, paving the way for signal processing techniques realized in the EM domain, possibly in conjunction with their digital-domain counterparts. However, in spite of the significant potential, the studies on HMIMOS-based wireless systems are still at an initial stage, its fundamental limits remain to be unveiled, and critical technical challenges with holographic MIMO communications need to be addressed. In this survey, we present a comprehensive overview of the latest advances in the holographic MIMO communications paradigm, with a special focus on their physical aspects, their theoretical foundations, as well as the enabling technologies for HMIMOS systems. We also compare HMIMOS systems with conventional multi-antenna technologies, especially massive MIMO systems, present various promising synergies of HMIMOS with current and future candidate technologies, and provide an extensive list of research challenges and open directions for future HMIMOS-empowered wireless applications.

Index Terms—Holographic multiple-input multiple-output surfaces (HMIMOS), holography, near-/far-field communications, channel modeling, capacity, electromagnetic information theory, channel estimation, beamforming/beam focusing, reconfigurable intelligent surfaces (RIS).

LIST OF ABBREVIATIONS

1D	One-Dimensional
2D	Two-Dimensional
3D	Three-Dimensional
4D	Four-Dimensional
5G	Fifth-Generation
6G	Sixth-Generation
ADC	Analog-to-Digital Converter
AO	Alternating Optimization
AVF	Antipodal Vivaldi Feed
BS	Base Station
CE	Channel Estimation
CELC	Complementary-Electric-Resonator
CGH	Computer-Generated Holography
CNN	Convolutional Neural Network
CRLB	Cramér-Rao Lower Bound
CS	Compressed Sensing
CSI	Channel State Information
DC	Direct Current
DMA	Dynamic Metasurface
DOF	Degrees of Freedom
EM	ElectroMagnetic
eMBB	Enhanced Mobile Broadband
EOM	Electro-Optic Modulator
GHz	Gigahertz
HDMA	Holographic-pattern Division Multiple Access
HMA	Holographic Metasurface Antenna
HMIMO	Holographic MIMO
HMIMOS	Holographic MIMO Surfaces
IRS	Intelligent Reflecting Surfaces
LC	Liquid Crystal
LEO	Low-Earth-Orbit
LIS	Large Intelligent Surfaces
LOS	Line-of-Sight
LS	Least Square
LWA	Leaky-Wave Antenna
MF	Matched Filter
MHz	Megahertz

T. Gong, L. Wei, and C. Yuen are with the Engineering Product Development (EPD) Pillar, Singapore University of Technology and Design, Singapore 487372. (e-mails: {tierui_gong, yuenchau}@sutd.edu.sg, wei_li@mymail.sutd.edu.sg).

I. Vinieratou and G. C. Alexandropoulos are with the Department of Informatics and Telecommunications, National and Kapodistrian University of Athens, 15784 Athens, Greece. G. C. Alexandropoulos is also with the Technology Innovation Institute, Masdar City 9639, Abu Dhabi, United Arab Emirates (e-mails: {en2180001, alexandg}@di.uoa.gr).

R. Ji, C. Huang and Z. Zhang are with the College of Information Science and Electronic Engineering, Zhejiang University, Hangzhou 310027, China (e-mails: {ranji, chongwenhuang, ning_ming}@zju.edu.cn).

M. Debbah is with the Technology Innovation Institute, Masdar City 9639, Abu Dhabi, United Arab Emirates, and also with the CentraleSupélec, University ParisSaclay, 91192 Gif-sur-Yvette, France (e-mail: merouane.debbah@tii.ae).

H. V. Poor is with the Department of Electrical and Computer Engineering, Princeton University, Princeton, NJ 08544 USA (e-mail: poor@princeton.edu).

MISO	Multiple-Input Single-Output
mMIMO	Massive Multiple-Input Multiple-Output
MMSE	Minimum Mean Squared Error
mMTC	Massive Machine Type Communications
mmWave	Millimeter Wave
MRC	Maximum Ratio Combining
MRT	Maximum Ratio Transmission
NLOS	Non-Line-of-Sight
OAM	Orbital Angular Momentum
OFDM	Orthogonal Frequency-Division Multiplexing
PCB	Printed Circuit Board
PIN	Positive-Intrinsic-Negative
PVF	Planar Vivaldi Feed
QAM	Quadrature Amplitude Modulation
RAN	Radio Access Network
RF	Radio Frequency
RHS	Reconfigurable Holographic Surface
RIS	Reconfigurable Intelligent Surfaces
RL	Reinforcement Learning
RNN	Recurrent Neural Network
SIS	Small Intelligent Surface
SIW	Substrate-Integrated Waveguide
SLM	Spatial Light Modulator
SNR	Signal-to-Noise Ratio
SPP	Surface Plasmon Polariton
SWIPT	Simultaneous Wireless and Information Power Transfer
TCA	Tightly Coupled Antenna
TE	Transverse Electric
TEM	Transverse Electric and Magnetic
TGV	Through-Glass-Via
THz	Terahertz
TM	Transverse Magnetic
UAV	Unmanned Aerial Vehicle
UDN	Ultra-Dense Network
UE	User Equipment
ULA	Uniform Linear Array
umMIMO	Ultra-Massive Multiple-Input Multiple-Output
UPA	Uniform Planar Array
uRLLC	Ultra-Reliable Low Latency Communications
UTC-PD	Uni-Traveling-Carrier PhotoDetector
VR	Virtual Reality
WDM	Wavelength-Division Multiplexing
WEH	Wireless Energy Harvesting
WPCN	Wireless Powered Communication Network
WPT	Wireless Power Transfer
XL-MIMO	Extremely Large-scale MIMO
YUF	Yagi-Uda-Feed
ZF	Zero-Forcing

I. INTRODUCTION

A. Motivation

The fifth-generation (5G) wireless communication is becoming a reality and being deployed world wide [1]–[3]. It enables various functionalities that are shared among three pillar paradigms, including enhanced mobile broadband (eMBB),

ultra-reliable and low-latency communications (uRLLC), and massive machine type communications (mMTC), each of which is oriented to satisfy different aspects of communication requirements. Specifically, eMBB is intended for supporting high data traffic services, such as video streaming applications and mobile augmented reality, with expected peak data rates of 10 and 20 gigabit-per-second, as well as average data rates of 50 and 100 megabit-per-second in the downlink and uplink, respectively. The uRLLC use case involves mission critical applications, such as autonomous driving and remote robotic operation, with a reliability of 99.999% and a low latency of 1 millisecond. Alternatively, mMTC enables massive connectivity applications, e.g., internet of things and internet of vehicles, with a requirement of one million devices per square kilometer, and a demand for low power consumption and low cost devices. The dramatic increases in data, device connections and emerging applications with extreme requirements are pushing the current wireless communications to a new frontier and motivating the emergence of the sixth-generation (6G) wireless networks [4]–[12]. It is estimated and foreseen in the 6G era that (i) the increase in data traffic will exceed 5000 exabytes in 2030; (ii) the services will be expanded to various environments such as space, air, ground and sea, to fulfill a globally ubiquitous connection for realizing the internet of everything; (iii) the emerging applications, such as holographic communications, tactile and haptic internet, fully autonomous driving, as well as high precision manufacturing and automation, etc., will become prevalent and dominant. Under these perspectives, 6G is envisioned to offer extremely immersive experiences, full dimension coverage, extremely low latency, reliability, as well as synthesized functionalities of communication, sensing, control and computing, etc., with native intelligence and integrated security. Compared to 5G, the envisioned 6G will provide a tremendous performance enhancement, offering (i) 100 ~ 1000 times and 10 times higher peak data rates and average data rates reaching over 1 terabit-per-second and 1 gigabit-per-second, respectively; (ii) 10 million devices per square kilometer connection density, which is 10 times larger than that of 5G; (iii) over 99.99999% reliability and less than 0.1 milliseconds air interface latency; (iv) 5 times and 10 ~ 100 times higher spectral efficiency and energy efficiency, respectively; (v) up to 10 Gigahertz (GHz) bandwidth in millimeter-wave (mmWave) frequencies and 100 GHz in Terahertz (THz) and visible light frequencies; and (vi) centimeter level positioning accuracy and supporting high mobility communications of up to 1000 kilometers per hour.

To satisfy the requirements of 5G and promote significant performance enhancement, significant efforts have been made for enhancing the system capacity, reducing the latency and broadening the connectivity, among which three representative technologies, i) massive MIMO (mMIMO) technology by employing a large number of antenna arrays [13]; ii) mmWave communications via utilizing a large amount of unoccupied spectrum resources in mmWave frequencies [14]; iii) and ultra-dense networks (UDNs) with densely deployed small cells [15], stand out as critical enablers. Furthermore, the mMIMO and mmWave communications pair has been verified to be a

good natural combination as on one hand the massive amount of antenna arrays are capable of offering substantial power gains that can combat the severe path loss of high frequency propagation, and on the other hand, mmWave wavelengths allow the integration of a large number of antennas in a limited space. Beyond 5G, mMIMO technology is also envisioned to satisfy the 6G requirements through forming an ultra-massive MIMO (umMIMO) system with a scaled increase in the number of antennas [12], [16]. Likewise, the mmWave frequencies exploited in 5G are expected to move to THz or even visible light frequencies in 6G, forming the THz and visible light communications. Consequently, the small cells in 5G will shrink to a huge amount of tiny cells in 6G, under the UDN framework. Despite the proven feasibility and enhancement in 5G, as well as the promising potentials in 6G, these technologies may encounter severe problems in practical applications. A large number of radio-frequency (RF) chains, essential for supporting mMIMO transmissions, brings in a large amount of power consumption, high hardware cost, and demands a large integration area, especially when operating on high frequencies [17], leading to an unsustainable and energy inefficient communication model. Another challenge with UDNs' tiny cells deployment is inter-cell interference, which is the main system performance restriction aspect. By cooperatively coordinating distributed access points, cell-free mMIMO has been developed with a better interference management capability in theory [18]. However, the potential improvements introduced by such systems are not clear under realistic conditions. Apart from the above problems, one can notice that the mMIMO and umMIMO systems follow a unified paradigm that adapts to the uncontrollable wireless environment. A shift towards an intelligent and software reconfigurable 6G is expected, where the end-to-end communication system, including the wireless environment, can be software programmable. It is also noteworthy that mMIMO and umMIMO systems achieve the critical beamforming functionality by following the beam-space model, depicting the spatial domain with beams in specific angular directions, which is considered as a low dimensional approximation [19]. The approximation optimality is achieved based upon a set of ideal assumptions, i.e., predefined antenna array geometry with perfect calibrations, as well as propagation without mutual coupling and near field scattering, which will be no longer valid as the apertures become larger, shaped in arbitrary geometries and/or covered with dense radiating elements.

To fulfill the requirements of future 6G while compensating the shortcomings of existing technologies, new technologies are emerging. In order to approach the fundamental limits of the wireless environment, a complete electromagnetic (EM) field characterization and a full manipulation of the EM field are expected. Holography, an innovative technology capable of recording and reconstructing the amplitude and phase of wave-fronts, thus greatly enlarging the EM field manipulation freedom, has great potential to enable holographic radios, satisfying the extreme requirements of 6G. On the other hand, with the emergence and development of metamaterials and metasurfaces, as well as their broad applications on wireless communications in the past few years, they impose a great

candidate technology to support 6G with required capabilities and functionalities [20]. Metamaterials and metasurfaces in particular, can be quite feasible solutions for supporting the realization of holography in EM field recording and reconstruction. Metamaterials indicate a class of artificial composite materials capable of interacting with incident EM fields in various expected effective electric and/or magnetic responses not found in nature [21]–[23]. They comprise a collection of sub-wavelength meta-atoms, namely metallic or dielectric micro structures, in a volumetric configuration, whose effective electric and magnetic responses can be represented by permittivity and permeability, respectively. The design structure and employed material define the EM properties of the metamaterial, yielding expected EM responses and enabling desired EM functionalities. In principle, metamaterials are capable of realizing arbitrary values of permittivity and permeability, thus enabling them to manipulate EM fields. However, the main principle followed by metamaterial based devices, namely accumulating propagation phases inside the devices via increasing their thickness for achieving desired field manipulations, inevitably leads to bulky structures which increase the fabrication complexity and limit their applicability. Metasurfaces are developed as a two-dimensional (2D) equivalent of volumetric metamaterials, whose meta-atoms form an ultra-thin planar structure that can be readily fabricated. Without following the propagation phase accumulating principle of metamaterials, metasurfaces utilize the abrupt phase and amplitude discontinuity of EM fields occurring at the interfaces of meta-atoms. As such, spatially varying EM fields with desired amplitude, phase, and/or polarization, can be fully achieved by properly arranging the meta-atoms. Metasurfaces can be further integrated with a programming capability, programmable (reconfigurable or dynamic) metasurfaces can be formulated. The remarkable features (programmable) metasurfaces a broad range of applications, such as metalens [24], metaholograms [25], and metasurface-empowered cloaking [26].

B. Holographic MIMO

Incorporating the powerful capabilities of holography and metasurfaces into future wireless communications, particularly revolutionizing the mMIMO and umMIMO systems, a paradigm shift is expected, from the conventional communication era to the coming 6G. By leveraging the latest advances, holographic MIMO surfaces (HMIMOS) are envisioned as an efficient implementation of mMIMO and umMIMO systems, but go beyond the original scope, revolutionizing the conventional mMIMO and umMIMO communications to the holographic MIMO (HMIMO) communications. To further shed light on the concept, we formally present the following definition: *“holographic wireless communication — it is the physical process of realistically and completely restoring the three dimensional (3D) target scene transmitted by the transceiving ends with the help of new holographic antenna technology and wireless EM signal technology, and at the same time can realize 3D remote dynamic interactions with people, objects and their surrounding environment.”* HMIMO communications follow this definition, which are empowered

by HMIMOS and the corresponding holographic EM domain signal processing. Compared with conventional mMIMO communications, HMIMO communications are expected to revolutionize mMIMO in following aspects.

The first aspect encompassing fundamental changes is in physical perspective. Particularly, on the one hand, mMIMO antenna arrays appear as a spatially discrete aperture whose radiating element locations should be in comply with the half a wavelength condition, which although simplifies transceiver designs without considering mutual coupling of radiating elements, while scarifies a large amount of spatial information. However, HMIMOS are considered as almost spatially continuous apertures whose spacing between radiating elements are much smaller than half a wavelength of incident EM waves. As such, HMIMOS are capable of forming sharp beams with weak sidelobes. More importantly, the nearly continuous aperture can control and record almost continuous phase changes of the wavefront, and manipulate EM fields with an unprecedented flexibility. On the other hand, HMIMOS implement amplitude and phase tuning through a totally different hardware structure, replacing a large amount of costly and power-hungry RF devices by either utilizing the holographic-based leaky-wave antennas (LWAs) [27] or the photonic tightly coupled antenna arrays (TCAs) [28], consequently facilitating communication signal processing in the analog domain based on reconfigurable and simplified hardware with reduced size, weight, cost and power consumption. This also facilitates fabrications of electrically extremely large HMIMOS to combat high path-loss in high frequencies (e.g., THz bands).

The differences in hardware structure as well as the quantitative changes of radiating elements (from sparse to dense) and aperture size (from small to extremely large) brought by HMIMOS, inevitably cause qualitative changes in HMIMO communications, which constitutes the second aspect of revolutions. First of all, the distinct hardware structure of HMIMOS corresponds to a dedicated working mechanism that is different from mMIMO. The unique hardware structure and working mechanism of HMIMOS necessitate new mathematical model for system depiction. The new model should capture the essence of HMIMOS and comply with their physical constraints. This can potentially inspire new design and optimization approaches for future wireless communications. Another qualitative change emerges as radiating elements becoming more and more dense, formulating a spatially continuous aperture. As such, mutual coupling between radiating elements, considered harmful to communication systems and mitigated in mMIMO antenna arrays configured in half a wavelength spacing, cannot be neglected in HMIMO communications. Interestingly, proper exploitation of mutual coupling can possibly realize the super-directivity [29], a phenomenon that describes the significantly large antenna array gains obtained by HMIMOS. This can potentially enhance the receive signal-to-noise ratios (SNRs) and enlarge the coverage area. It is quite necessary to study the mutual coupling effect and present analytically mathematical models for coupling-aware wireless designs. In addition to mutual coupling, spatially continuous apertures allow signal processing to be shifted from conventional digital domain to future EM domain. Consequently,

new analysis and design ideas from electromagnetism will be introduced to revolutionize existing wireless communication frameworks to (hybrid digital-) EM domain ones, paving the way for realizing high flexibility, high spatial resolution, low latency wireless communications. For example, channel models and communication models can be characterized in the EM domain [30], [31]. Furthermore, it is worth mentioning that conventional mMIMO communications, built upon Shannon's information theory, ignore the underlying physical phenomena of EM wave propagation, thereby failing to characterize the ultimate fundamental limits. Blending theories from Shannon and Maxwell, EM information theory is envisioned as the next milestone for guiding wireless analyzes and designs [32]. It is more believed as an interdisciplinary framework to evaluate the fundamental limits of wireless communications at the crossroads of EM wave theory and information theory. Lastly, the remaining qualitative change of HMIMO is induced by the extremely large aperture sizes of HMIMOS. Distinct to mMIMO communications, always considering far-field scenarios, HMIMOS can naturally transform the far-field region to the near-field region (i.e., the Fresnel region) as the aperture size becoming large, which achieves the holographic near-field communications. Compared with mMIMO far-field communications that are angle-aware, HMIMO near-field communications are capable of discriminating not only the angle of an object but also its distance. This leads to a totally distinct near-field channel model and the conventional angle-aware beamforming transforms to the distance-angle-aware holographic beam focusing. This will bring significant benefits in communication performance, such as broadening the degree of freedom (DOF) of communication systems [33].

Taking advantage of the unprecedented flexibility in EM field manipulation as well as the near-field communications, we expect that HMIMOS will enable HMIMO communications to encompass holographic imaging-level radios with ultra-high pixel density and extremely large spatial multiplexing [19], [28], [34]. The extreme spatial multiplexing of HMIMOS is made possible based upon the fact that the nearly infinite number of antennas in HMIMO constitute the asymptotic limit of mMIMO, assuming very large capacity [35]. It is emphasized that previously described HMIMOS are mainly employed as active transceivers. They can be also operated as passive reflectors, coinciding with the reconfigurable intelligent surfaces (RIS) [36] or the intelligent reflecting surfaces (IRS) [37] that are deployed at positions between transceivers, the wireless environment treated conventionally as a random process can thereby be transformed to a smart radio environment that can be intelligently software programmable, promoting communications performance.

C. Vision

It is foreseen that HMIMOS have the potential to drive two possible paradigm shifts from conventional 5G to future 6G, namely, HMIMOS empowered extremely large spatial multiplexing holographic radios and HMIMOS enabled smart radio environment. Based on these insights, we envision a broad range of applications of HMIMOS in future 6G era, as



Fig. 1: HMIMOS-assisted future wireless communications.

illustrated in Fig. 1. It shows a space-air-ground-sea integrated communication network, inside of which we demonstrate several scenarios, such as smart cities, remote mountain areas, forest, desert and sea. HMIMOS can be applied to each case by acting as active transceivers or passive reflectors. For instance, in outdoor communications of smart cities, HMIMOS can be mounted on building surfaces, serving as a base station (BS) for data transmissions to user equipments (UEs) located at offices, homes, schools, factories, etc. and also for communicating with satellites. HMIMOS can be installed on vehicle surfaces or carried by unmanned aerial vehicles (UAVs), acting as passive relays for assisting vehicle and ship communications. The HMIMOS installed on vehicle surfaces can be alternatively be utilized for vehicle sensing, positioning, and/or even tracking. On the other hand, in indoor communications of smart cities, HMIMOS can coat windows and/or walls and transceive outdoor BS signals to indoor UEs and/or reflect existing signals, to meet communication requirements of indoor UEs [38]. We can imagine in the grand space-air-ground-sea integrated communication network shown in Fig. 1 that HMIMOS can be possibly placed on the solar panels of a satellite, bodies/wings of an airplane/airship, or carried by a flying object, providing a relatively high communication performance with reduced cost and power assumption. This is truly beneficial in satisfying communication requirements for emergencies occurring in remote areas, e.g., forest fires, rescues in remote mountain areas, desert and sea. Moreover, the HMIMOS empowered satellites are capable of aiding wireless monitoring in remote areas, such as desertification monitoring. The benefits of HMIMOS also show a great potential in promoting physical layer security of wireless communications that are critical for realizing secure data exchanges in military applications. For example, an early

warning aircraft can utilize HMIMOS to confront enemy interference and wiretaps, offering an accurate and timely early warning detection, as well as assisting a timely situational awareness report and military command feedback. Far beyond the above visions, it is foreseen that the powerful HMIMOS can be applied to a multitude of cases and scenarios in assisting communication paradigm shifts and supporting newly emerged upper layer applications.

D. Prior Work

The appealing benefits brought by HMIMOS attract tremendous research interest. Amongst overview studies, most of them focus on the smart radio environment paradigm shift, where HMIMOS operate as passive reflectors with alternative appellations of RIS/IRS. Following this operating mode, HMIMOS have been extensively investigated from its' theoretical foundations to enabling technologies for various wireless systems in miscellaneous scenarios. We recommend readers to refer to a multitude of overview, survey and tutorial papers seeking the advances of RIS/IRS [43]–[84]. Compared to the extensive studies of HMIMOS as passive reflectors, the investigation on HMIMOS as active transceivers to enable holographic radios is in its infancy. The full potential of HMIMOS remains to be unveiled. To this aim, we mainly focus on this research area, in which emerging overview papers are summarized as follows. In [34], the authors outlined several new research directions beyond mMIMO, in which HMIMOS are listed as one of the most promising enabling technologies. They briefly introduced the basic principles of holography and mentioned the approaches for realizing spatially continuous apertures. They also provided the general HMIMO vision and pointed out open problems of HMIMO communications.

TABLE I: Prior works of HMIMOS and HMIMO communications.

Functionality	Ref.	Date	Main contents	Main contributions
Communication	[34]	2019	Common holographic principles: Recording and reconstruction Approach for realizing approximately continuous apertures Vision and open problems	Envision and analyze HMIMOS as one of the most promising directions.
	[28]	2019	Holographic radio: Uplink/downlink field imaging/synthesizing Photodiode tightly coupled antenna arrays as HMIMOS	Introduce an implementation and system architecture of all-photonic RANs for computational holographic radios.
	[39]	2020	Category by power consumption: Active/passive HMIMOS Category by hardware structure: Continuous/discrete HMIMOS Fabrication methodologies Operation modes: Active transceivers/passive reflectors Functionality, characteristics, communication applications Design challenges and opportunities	Demonstrate HMIMOS from different physical perspectives, list their applications and study their performances in positioning and communications.
	[40]	2021	HMIMOS for wireless communications: Passive/Active HMIMOS for mMIMO communications: Hardware/characteristics Open research challenges	Show advanced analog signal processing capabilities as well as detail operations and equivalent signal models of HMIMOS during transmission and reception.
	[33]	2021	Information-theoretical optimal communications between HMIMOS Communication modes and power scaling law Research directions	Analyze information-theoretical optimal communications of HMIMOS, emphasizing on near-field holographic communications in large HMIMOS regime.
	[27]	2021	LWA structures & EM holographic principle Design considerations/implementations of LWA based HMIMOS Evolution trends and summary	Introduce basic physical working principles of HMIMOS and present various implementations of LWA based HMIMOS.
	[41]	2021	Hardware structure: Feed, waveguide and radiation element Holographic principle: Adjust amplitudes of radiation elements Fabrication methodologies: PIN/varactor diodes & liquid crystals HMIMOS aided communications: System structure/beamforming Key challenges	Detail structure and holographic tuning principle of HMIMOS, show full-wave analysis and propose hybrid holographic and digital beamforming.
Localization	[42]	2021	Localization history and applications Holographic localization enabling technologies Performance limits and enabling algorithms Future directions	Present enabling technologies, performance limits and enabling algorithms for holographic localization, numerically show the error lower bound.

Reference [28], described a promising implementation of all-photonic radio access networks (RANs) for realizing computational holographic radios. This system is enabled by HMIMOS implemented by photonic TCAs. In [39], the authors overviewed HMIMOS with respect to the categorization based on power consumption and hardware structure, fabrication methodologies, as well as operation modes. A certain number of functionalities and characteristics of HMIMOS together with a series of communication applications were highlighted and discussed, respectively. Several challenges of HMIMO communications were finally presented. With a special focus on the advanced analog signal processing capabilities of HMIMOS, reference [40] detailed the operations and equivalent signal path models of HMIMOS during transmission and reception. The authors further analyzed the advantages and capabilities for communications, as well as provided a list of challenges emerged from applications. From a different perspective, the authors of [33] put an emphasis on near-field holographic communications as HMIMOS tend to be large. In this regard, the conventional wireless propagation models are no longer applicable, and new spherical propagation models should be built, which will open up new communication opportunities. From a more physical point of view, reference [27] introduced the LWA based HMIMOS from their basic physical working principles to various physical implementations. More-

over, reference [41] overviewed the basic hardware structure of HMIMOS and the holographic principle for constructing holographic patterns with HMIMOS. Taking advantage of such a holographic principle, the authors suggested a hybrid holographic and digital beamforming scheme for multi-user communications. Beyond the communication capability of HMIMOS, the authors of [42] further facilitated HMIMOS in realizing wireless holographic localization. We list details of these relevant papers, and summarize their main contents and contributions in Table I for ease of reference and comparison.

E. Contribution

Even though the existing papers overview HMIMOS related research areas from different perspectives, spanning from the physical aspects to information-theoretical foundations and critical technologies such as holographic beamforming, they only focus on one of such aspects with limited scopes and details. For example, the holographic principle introduced in [27], [34] and [41] focus only on the basic holographic principle, the EM holographic principle and the HMIMOS holographic configuration, respectively, where they fail to reveal much about the holography applications, technology roadmaps, as well as the differences and connections between these holographic technology roadmaps. Next, references [28],

[33], [34], [39]–[41] present the hardware perspective with limited scopes and details, unable to unveil a more spherical view. What’s more, references [33] and [41] include the theoretical foundation and enabling technology perspective, respectively, while they focus merely on limited contents, such as communication modes, holographic beamforming, unable to cover a comprehensive recent advances of HMIMO communications. Insight of this situation, we present a new survey that covers each possible aspect of HMIMOS and HMIMO communications in detail, which not only provides with a useful reference, but also an origin that inspires more valuable future work to promote this area. To sum up, we list the major contributions of this survey as follows.

- We envision possible holographic applications for future wireless communications, where we categorize in terms of several aspects, including entertainment, education, medical healthcare, production and other miscellaneous applications, that potentially cover the main holographic applications of future 6G. We then introduce different technology roadmaps of holography for realizing the envisioned holographic applications. We present from the original optical holography to the computer-generated holography (CGH) and the EM holography, where the transformation from optical holography to CGH and especially to EM holography, as well as the differences among them are demonstrated.
- A comprehensively systematic overview on the physical aspects of HMIMOS, a critical enabler for realizing EM holography, is provided for understanding on the underlying working principle. We demonstrate their physical aspects with respect to hardware structures, holographic design methodologies, tuning mechanisms, aperture shapes, and typical functionalities by almost classifying each content into different categories for providing a panoramic view. We then list representative HMIMOS prototypes and HMIMOS aided communication prototypes that show recent advances of their practical deployments.
- Empowered by HMIMOS, new features of HMIMO communications are emerged, which requires extensive studies urgently to unveil the communication fundamental limits. To this end, we overview the recent advances of HMIMO communications in their theoretical foundations. Particularly, we show the channel modeling of HMIMO communications that is depicted in the EM field level, which provides a first-principle perspective to capture the essence. Afterwards, the performance analysis, such as DOF, system capacity in ideal conditions, and under practical imperfections are demonstrated. We also review the EM field sampling and EM information theory inspired by the first-principle.
- To facilitate HMIMO in practical deployments, enabling technologies are critical for promoting the paradigm shift from conventional communications to HMIMO communications. To this aim, we first discuss several distinctions emerged in HMIMO communication systems, which motivate new developments of physical-layer enabling technologies. We then provide a contemporary survey

on the latest progresses of HMIMO communications in terms of holographic channel estimation and holographic beamforming/beam focusing. We characterize the existing studies with respect to different system models, channel types, and estimation/optimization methods, which shows an explicit presentation of the current advances.

- We provide comparisons between HMIMO and conventional technologies, especially the conventional mMIMO, with respect to hardware, directivity, coverage, capacity and energy efficiency. Afterwards, various extensions of HMIMOS are demonstrated to illustrate their great potentials. In the final, we identify research challenges and future directions of HMIMOS and HMIMO communications for future research.

F. Organization

The rest of the article is established as follows: Section II describes holographic applications and technology roadmaps; Section III characterizes the physical aspects of HMIMOS; We focus on integration of HMIMOS into wireless communications in following sections, where we present theoretical foundations of HMIMO communications in Section IV and provide enabling technologies of HMIMO communications in Section V, respectively; The comparisons with conventional technologies and extensions of HMIMOS to various topics are given in Section VI. Research challenges and future directions of this area are prospected in Section VII; We conclude this article in Section VIII. The main structure of this survey is illustrated in Fig. 2.

II. HOLOGRAPHIC APPLICATIONS AND TECHNOLOGY ROADMAPS

Holography is an innovative technology for high-fidelity 3D imaging by exploiting both wave amplitude (intensity) and phase information. It was first invented to improve the resolution of electron microscopy by Dennis Gabor in 1948 [85]. Compared with the conventional geometrical optics based photography, recording only the wave intensity and presenting a 2D image, holography utilizes coherent light sources for recording the complete wave information and shows a 3D image. It includes two typical stages, namely, recording and reconstruction, following the interference and diffraction principles of waves, respectively. Completely different from the point-to-point mapping of photography, each object point is recorded by the whole recording surface of holography, forming a point-to-surface mapping rule. Each point on the recording surface of the holography captures the information from all the object points. The detailed differences between holography and photography are listed in Table II. With the emergence of holography, many applications and technologies were spurred and developed. It is envisioned that the future 6G will provide an extremely immersive experience in entertainment, education, medical healthcare, production, and so forth by means of holography [8], [10], [12]. Capitalizing on holography, it is feasible to naturally reconstruct a realistic scene, breaking the barriers between the virtual and actual scenes as well as blending the virtual and real worlds seamlessly.

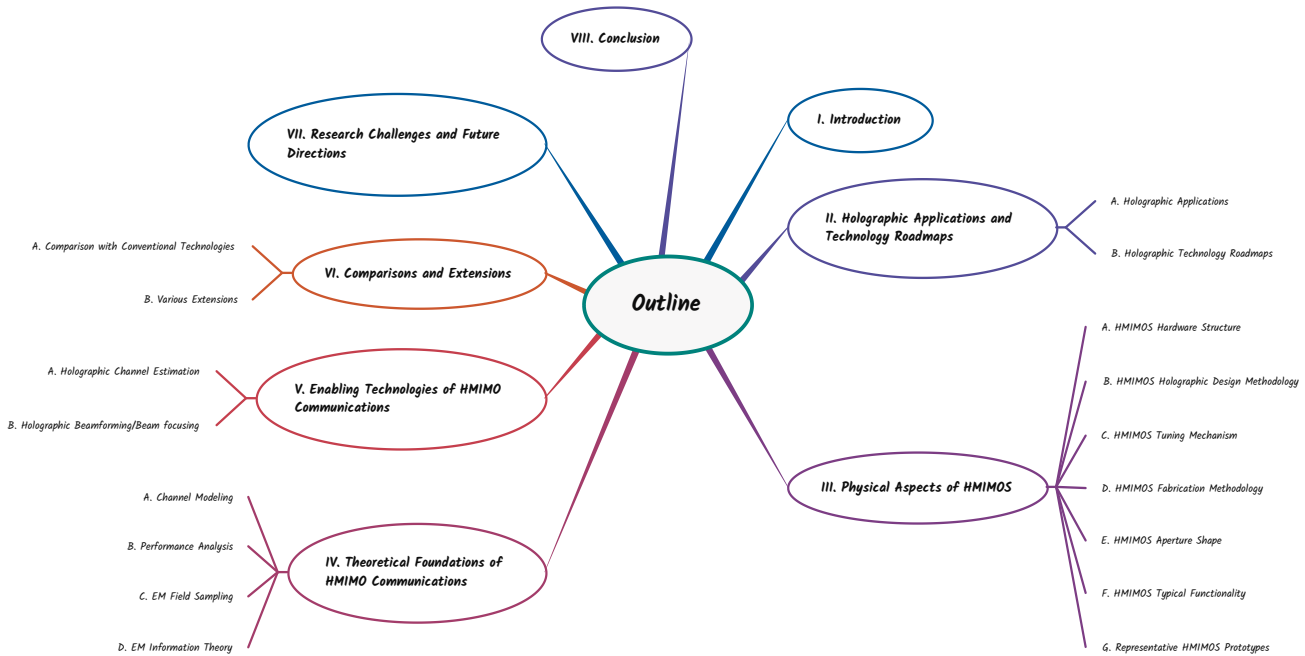


Fig. 2: Organization of the article.

TABLE II: Differences between holography and photography.

Metrics	Holography	Photography
Image dimension	3D	2D
Information recorded	Wave amplitude (intensity) and phase	Wave amplitude (intensity)
Mapping rule	Point-to-surface mapping	Point-to-point mapping
Light source requirement	Coherent light source	Non-coherent light source
Principle followed	Wave interference/diffraction for recording/reconstruction	Geometrical optics

In this section, we describe potential holographic applications of 6G in the first subsection, and later on, present the main holographic technology roadmaps to satisfy the holographic application requirements.

A. Holographic Applications

We present several typical 6G holographic applications encompassing holographic entertainment, holographic education, holographic medical healthcare, holographic production, as well as other miscellaneous applications. In each application category, possible perspectives are proposed. Their details are further depicted in Fig. 3 with corresponding illustrations.

1) *Holographic Entertainment*: Filming, gaming, sports, traveling, dining and cultural cultivation, to name a few, are expected to be empowered and fully revolutionized by holography. People watching a 3D movie will not be limited to traditional 3D video using binocular parallax, but immersed in a realistic viewing experience, provided by holography. For strongly interactive entertainment (e.g., holographic gaming, sporting and traveling), a fusion of holograms with multi-dimensional senses (such as senses of sight, hearing, and feeling) will further construct both deeply interactive and extremely abundant connections between UEs and environments. A multiplicity of interactively immersive experiences can therefore be perfectly achieved. Holographic restaurants

can be built where the senses of smell, taste and sight will be fully integrated and users will be able to experience the whole process of ordering, waiting, and eating based upon their own requirements and preferences. For people who are interested in cooking, the platform will be able to include them in the production process of various dishes seamlessly. People can also entertain themselves with holographic cultural experiences such as understanding etiquette and customs of a country, watching drama and listening to concerts through a holographic virtual stage, visiting museums and taking part in auctions. To date, Microsoft Hololens2 [86] and Hypevrn [87] are two representative products for supporting holographic entertainment.

2) *Holographic Education*: Holography can make learning and teaching more efficient, immersive and consistent through times like the recent pandemic. Students from different locations will be able to attend the same mixed-reality classes. This will provide a realistic learning experience for them but without the need to relocate. Teachers will also benefit from teaching holographic classrooms. They will be able to demonstrate historic events, and also perform complex experiments that would be impossible to, in conventional classrooms. Simultaneously teaching multiple classrooms will be enabled, something very important for underdeveloped countries. For people who conduct scientific research, and



Fig. 3: Holographic applications: (a) holographic entertainment, (b) holographic education, (c) holographic medical healthcare, (d) holographic production, and (e) other miscellaneous applications.

want to share their latest research advances with colleagues via international conferences or workshops, live holographic video conferences will enable fully immersive talks, presentations and collaborations. Holography will be employed to promote the popularization of science and technology, enriching people's scientific understanding and curiosity.

3) *Holographic Medical Healthcare:* Holography will give doctors the ability to visualize the human body with high resolution. It will be used by radiology, planning of surgeries and precise human tissue reconstruction. Surgeons will be able to carry out sophisticated surgeries in distant hospitals and medical professionals will treat their patients remotely. It will also improve the access to specialized consultants for underdeveloped remote areas, where patients are not able to physically visit a doctor. Medical students can get hands-on training on realistic hologram patients and equipment with the help of mixed-reality systems. A recent thrilling advance, a world-first in medical training, was achieved at Addenbrooke's Hospital in Cambridge [88].

4) *Holographic Production:* Introducing holography to industries such as agroforestry, animal husbandry, and fishery

which often operate over large areas will allow them to remotely supervise crops, woods, livestock, fish, etc.. This will simplify the full operation and management processes and reduce operating costs. For industries operating in harsh environments, e.g., mining industry, coal industry and nuclear power industry, holography will assist staff with full perception of the environments, as well as help during emergencies. Holography will be a promising technology for building digital twins in manufacturing. In several aspects, such as improving system designs, testing new products, monitoring and predictive maintenance, as well as lifecycle management.

5) *Other Miscellaneous Applications:* Beyond the potential applications above, holography has a great potential in military applications regarding defense systems. Assisted with internet of battlefield things, full-domain intelligence will be captured and a full-domain holographic battlefield will be reconstructed, enabling holographic situation awareness and holographic combat command [89]. Holography is widely applied to encryption and decryption for information security as well. A 10-bit orbital angular momentum (OAM)-multiplexing hologram for high-security holographic encryption was proposed

in [90]. Image encryption based on interleaved computer-generated holograms was presented in [91]. Optical encryption was realized by reprogrammable meta-hologram in [92]. In addition, holography generalizes its applicability to fault diagnosis, such as microwave holographic diagnosis for antennas [93], and holographic techniques for determining antenna radiation characteristics and imaging aperture fields [94]. Besides, holography has been widely employed in packaging and trademark anti-counterfeiting [95], holographic metrology technology [96], and so forth.

B. Holographic Technology Roadmaps

The major development of holography mainly lies in optical holography with the emergence of lasers and a big breakthrough of obtaining coherent light sources [97]. It was later extended to the more flexible CGH [98] with the assistance of computer technology. The first attempt of introducing holography into the EM region was presented for X-band imaging in [99]. More important in the EM region, a combination of holography with antenna technology promoted a fascinating fashion for achieving holographic wireless communications [100]. In the following subsection, a brief description of the basic principle of holography is presented. Then, three main technology roadmaps for realizing holography are categorized, namely the original optical holography, the CGH, and the EM holography.

1) *Basic Principle of Holography*: The realization of holography mainly includes two steps, recording and reconstruction. In the recording process, the recording media, such as holographic plates, charge coupled device or complementary metal oxide semiconductor cameras etc., are employed to track intensities of the hologram (interference pattern) formed by interfering a known reference wave with a desired object wave. In the reconstruction process, the employed recording medium is illuminated by a replica of the reference wave, thereby reconstructing the object wave perfectly. The main idea of this realization is that the interference between two coherent waves presents their phase differences that can be used for object wave reconstruction subsequently. We illustrate this idea in the following equations (1), (2) and (3). First we denote the object wave \mathcal{O} as:

$$\mathcal{O} = |\mathcal{O}|e^{j\theta}, \quad (1)$$

with $|\mathcal{O}|$ being the wave amplitude and θ being the wave phase. Likewise, we present the reference wave \mathcal{R} :

$$\mathcal{R} = |\mathcal{R}|e^{j\phi}. \quad (2)$$

Assuming an intensity sensitive recording media (alternatively, it only records the phase information), we thus have this intensity of the hologram represented as

$$\mathcal{I} = |\mathcal{O} + \mathcal{R}| = |\mathcal{O}|^2 + |\mathcal{R}|^2 + \mathcal{O}\mathcal{R}^* + \mathcal{O}^*\mathcal{R}, \quad (3)$$

where $*$ indicates the complex conjugate operation. One can directly find that the last two terms in (3) include the phase difference between the reference and object waves, critical for object wave reconstruction. Retaining the intensity of the hologram by recording media, and illuminating the recording

media with a replica of the reference wave, we have the following expression

$$\mathcal{I}\mathcal{R} = |\mathcal{O}|^2\mathcal{R} + |\mathcal{R}|^2\mathcal{R} + \mathcal{O}|\mathcal{R}|^2 + \mathcal{O}^*\mathcal{R}^2. \quad (4)$$

One can see from the last two terms of (4) that it is possible to completely reconstruct the object wave that possesses both the intensity and phase information.

2) *Optical Holography*: Holography is primarily realized via the optical technology, where coherent light sources are produced by a laser. The recording process of optical holography can be found in Fig. 4(a). It can be seen that the laser beam propagates to a beam splitter that divides the single input into two coherent output light beams. On the one hand, the first output beam is controlled to propagate to an object such that the desired object beam is scattered by the object. On the other hand, the second output beam is guided to a mirror for the purpose of reflecting the beam as a reference beam toward the photographic film to superpose with the reflected object beam and thus form a hologram. In this process, the hologram is recorded by the photographic film. With a successful recording process, one can reconstruct the object beam through the experiment setup shown in Fig. 4(b). It is noted from the figure that the object is removed and an extra optical baffle is added for blocking the first output light beam. In this reconstruction process, the laser produces a replica of the beam in the recording process. This beam then propagates along the same path as in the recording process from the beam splitter to the mirror, generating a reconstruction beam identical to the reference beam accordingly. The reconstruction beam illuminates the hologram recorded on photographic film such that the object beam is reconstructed based on light diffraction. From the side of the viewer, a virtual 3D image of the original object is generated. In the optical holography roadmap, different schemes, such as (compressive) optical scanning holography and the phase-shifting holography, each with a unique hardware structure, were presented in [101] and references therein.

3) *CGH*: Conventional optical holography requires a vast of complicated optical components for recording and reconstruction. It also needs a real object for different hologram acquisition, which is inefficient and limits the generalization for imaging of different objects. With the assistance of computer technology and spatial light modulators (SLMs), CGH was invented for mitigating the problems encountered in optical holography. Instead of recording and reconstructing via a hardware-dependent optical manner, CGH performs both recording and reconstruction through numerical calculations. This working mechanism not only reduces the requirement for complicated hardware, but also facilitates imaging for different objects without requiring real objects. The schematic of CGH is depicted in Fig. 5. Basically, the hologram design methods of CGH can be divided into two main groups: wavefront-based and ray-based methods [102]. Through simulating the wave diffraction process, wavefront-based methods numerically calculate the 3D wave fields of a given object/scene, as well as its 2D distribution on the hologram plane. In this group, point cloud model, polygon-based model, and layer-based representation of 3D objects/scenes, all utilizing 3D positional infor-

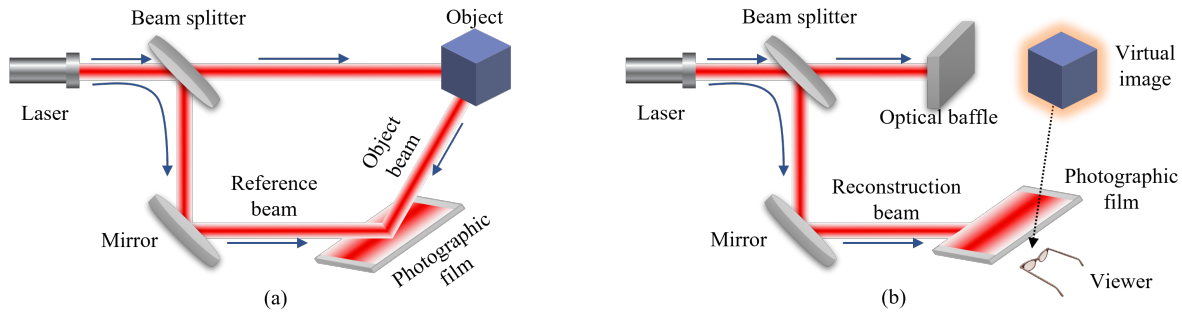


Fig. 4: Schematic of optical holography: (a) recording and (b) reconstruction.

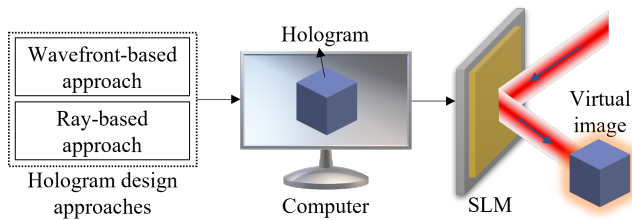


Fig. 5: Schematic of CGH.

mation, are the most widely adopted approaches. Differently, capturing incoherent 2D images of a given 3D object/scene based on the transformation from ray-based representations to wavefront-based holographic information, ray-based methods generate the hologram accordingly. This group consists of two typical categories: the holographic stereogram and the multiple viewpoint projection holography. With arbitrarily computer-generated holograms illuminated by the reconstruction beam, high-fidelity virtual 3D images can be reconstructed. The recent advances of CGH can be further referred to [102] and [103].

4) *EM Holography*: We know that holography is capable of realizing 3D imaging as mentioned in optical holography and CGH. This kind of imaging can be interpreted as wave field reconstruction of a given object, which can be generalized to the EM region. Combining holography with antenna technologies, novel holographic wireless communications can be achieved based on the EM holography. In this regards, we embrace two typical schemes for realizing the EM holography, namely, holographic LWA based EM holography [27] and photonic TCA based EM holography [28], [104]. Each scheme will be explained in more detail subsequently as follows.

Holographic LWA based EM holography: In such type of communication systems, an EM wave source used for reference wave generation replaces the role of the laser in optical holography, an EM antenna aperture, referred to as HMIMOS, plays the role of photographic film, and one or more communication nodes take the place of the object, correspondingly. It is note-worthy that the EM wave source can be located externally or integrated internally into the HMIMOS, which is one of the main differences compared to optical holography structures. Take the typical integration case for example, we present the schematic of EM holography

with recording and reconstruction processes in Fig. 6, complying with those shown in optical holography. The HMIMOS commonly consists of a substrate with one or more feeds integrated inside and radiating elements printed on its surface (see Section III for hardware details). The substrate serves as a waveguide, allowing reference waves to propagate along it. The feeds are used for launching reference waves coming from RF chains. The radiating elements are designed to construct various holograms with corresponding explicit textures or to approach holograms via different tuning mechanisms without presenting a specific texture. With configured holograms, specific radiations, with radiating signals leaked from the reference waves, can be realized.

During the recording process, the hologram should be designed and constructed by HMIMOS. By back-propagating the object wave from a given direction to HMIMOS, a certain hologram is obtained as a superposition of object and reference waves, as depicted in Fig. 6(a). To explicitly show this process, we describe the reference wave excited by a point source within a lossless substrate as

$$E_{rw} = A_r e^{-j\beta_r d_r(x,y)}, \quad (5)$$

where A_r denotes the amplitude of reference wave, a constant in the lossless substrate; β_r represents the wavenumber of reference wave; $d_r(x,y)$ indicates the distance between the (x,y) -coordinate of HMIMOS and the point source (assumed as the original coordinate), expressed as $d_r(x,y) = \sqrt{x^2 + y^2}$. Additionally, denote by $d_o(x,y)$ the distance between object and (x,y) -coordinate on HMIMOS, by β_0 the free-space wavenumber, as well as by ϕ and θ the azimuth and elevation angles of the object, respectively. The phase variation caused by $d_o(x,y)$ can be described through a projection of the free space wavenumber on x and y axis, respectively. We express this process as $[\beta_0 \sin \theta \cos \phi, \beta_0 \sin \theta \sin \phi][x, y]^T = \beta_0(x \sin \theta \cos \phi + y \sin \theta \sin \phi)$. Based on the result, the field distribution of object wave on the (x,y) -coordinate of HMIMOS is given by

$$E_{obj} = A_o e^{j\beta_0 d_o(x,y)} = A_o e^{j\beta_0(x \sin \theta \cos \phi + y \sin \theta \sin \phi)}, \quad (6)$$

where A_o indicates the wave amplitude. At any given (x,y) -coordinate of HMIMOS, the hologram can be formulated based on (5) and (6) as $E_{int} = E_{obj} E_{rw}^*$ that is detailed as

$$E_{int} = A_o A_r e^{j(\beta_0(x \sin \theta \cos \phi + y \sin \theta \sin \phi) + \beta_r \sqrt{x^2 + y^2})}. \quad (7)$$

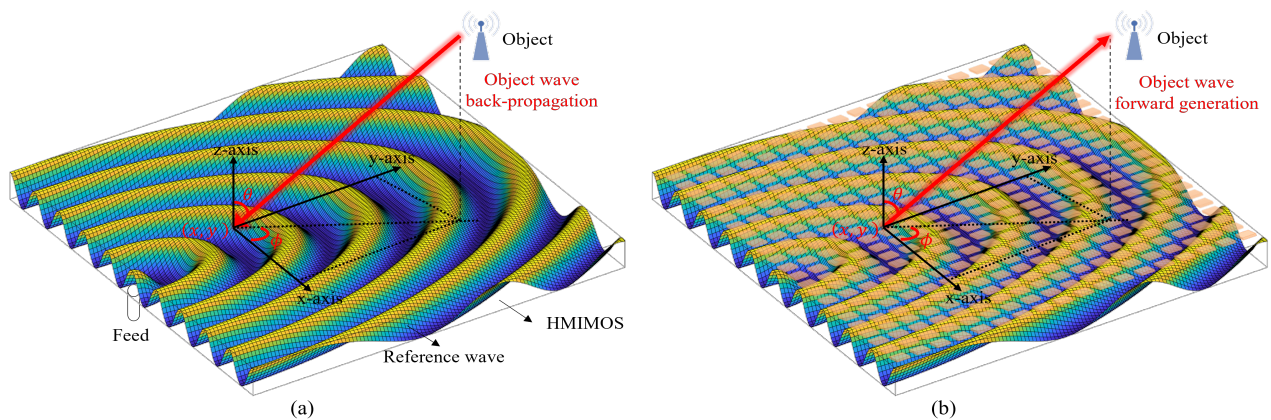


Fig. 6: Schematic of holographic LWA based EM holography: (a) Recording and (b) reconstruction.

By properly designing the HMIMOS for capturing the hologram, one can realize the recording process of EM holography. It is note worthy that HMIMOS can be implemented through various hardware forms in fixed or tunable mechanisms, which will be detailed in the next section.

In reconstruction process, with the hologram implemented by HMIMOS based on (7), an object wave toward the (ϕ, θ) -direction can be forward generated once the reference wave is excited and travels along the surface, as demonstrated in Fig. 6(b). The mapping rule of an HMIMOS from reference wave to object wave obeys the LWA theory [105]–[107] that follows the wave diffraction principle.

Photonic TCA based EM holography: In this kind of communication systems, the EM holography is realized through an optical domain processing with the assistance of photonic TCA based HMIMOS that realize a holographic RF-optical mapping capable of achieving a domain transformation from RF signals to optical beams and vice versa, as demonstrated in Fig. 7. The mapping is enabled by electro-optic modulators (EOMs) and uni-traveling-carrier photodetectors (UTC-PDs), responsible for transformations from electrical to optical signals in reception stage and oppositely from optical to electrical signals in transmission stage, respectively. Each EOM, connected to one radiating element, upconverts the received RF signal to optical regime to be propagated by an optical-fiber bundle. Additionally, each UTC-PD is bonded to adjacent radiating elements of HMIMOS enabled by flipchip technology. UTC-PDs are capable of converting optical beams to electrical signals with high power, large bandwidth and high converting efficiency, making them feasible to directly drive the radiating elements with a very large bandwidth, i.e., ≥ 40 GHz.

The optical domain processing is facilitated by an optical-feed that drives the photonic TCA based HMIMOS for signal transmissions, and by an SLM that performs massive spatial processing, i.e., the optical Fourier transform, to the optical-fiber beams in signal reception. It is noted that the optical processing proceeds in parallel with the speed of light, capable of reducing latency and achieving a real-time processing. In detail, the optical-feed is designed based on two phase-locked lasers whose frequencies are offset with a specific value that serves as the RF carrier to be transmitted. The combined

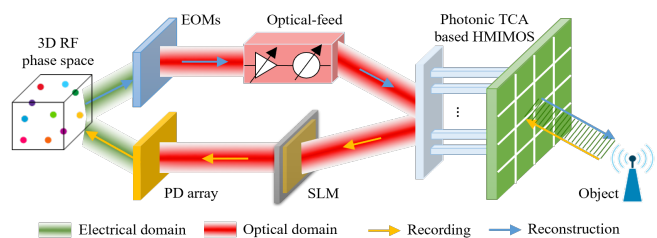


Fig. 7: Schematic of the photonic TCA based EM holography: Recording and reconstruction.

output of lasers is divided into a certain amount of fibers that connect to UTC-PDs in a point-to-point mapping. This designed optical-feed is capable of realizing tunable RF waves in amplitudes and phases. Likewise, the SLM serves as a ‘lens’ that images the optical beams originating from RF signals through EOMs onto a PD array with each PD corresponding to a unique spatial information of the RF signal.

To present a clear demonstration of the working principle, we describe the recording and reconstruction as follows. In recording process, as shown by the recording flow in Fig. 7, the object wave is received by photonic TCA based HMIMOS whose output RF signals are transformed to optical beams via upconverted EOMs. The resulting optical beams are carried by an optical-fiber bundle, and propagated to the SLM for spatial processing and imaging. Afterwards, the images are presented onto a PD array with accurate separations for finally constructing a 3D constellation of objects in an RF phase space. Such a space provide an accurate feedback for synthesizing spatial RF wave fields for transmissions. Next, in reconstruction process, as shown by the reconstruction flow in Fig. 7, the electrical signals guided by the 3D RF phase space are first transformed to optical beams via EOMs that are followed by an optical-feed for the purpose of achieving amplitude and phase control. The outputs of optical-feed are routed to photonic TCA based HMIMOS by driving UTC-PDs for directly exciting the radiating elements. As such, an intended synthesis of spatial RF wave field is achieved to the object.

We summarize holographic technology roadmaps in terms

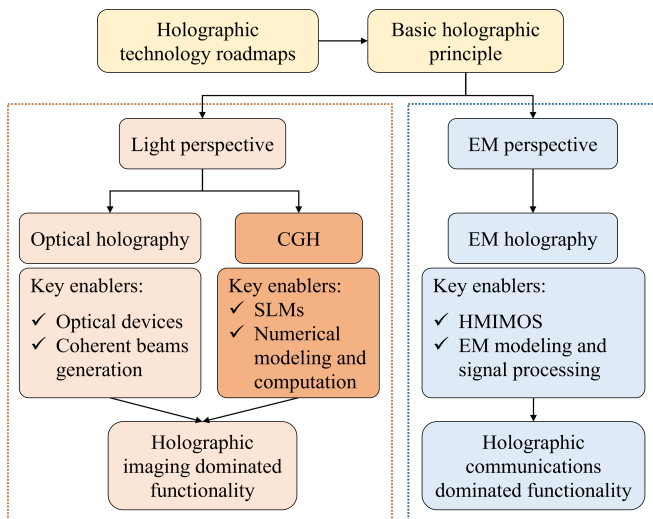


Fig. 8: Block diagrams of previously listed holographic technology roadmaps in terms of their distinctions.

of their distinctions as shown in Fig. 8 after the presentation of each technology previously. It can be found that both optical holography and CGH follow the light perspective since they manipulate light beams in achieving holograms. Differently, EM holography is in comply with the EM perspective because it mainly interacts with EM fields during the working process. Moreover, optical holography and CGH are commonly applied for realizing holographic imaging, while EM holography is mainly used for achieving holographic communications. More important, the three technologies rely on different key enablers due to distinct working mechanisms. More specific, optical holography depends on optical devices and generation of coherent light beams; CGH relies on SLMs carrying computer-generated holograms which require efficient numerical modeling and computations; and EM holography demands HMIMOS as a physical entity support and the corresponding EM modeling and signal processing in reaching the functionality. In the subsequence of the article, we mainly focus on the EM holography and its application in wireless communications.

III. PHYSICAL ASPECTS OF HMIMOS

EM holography can be understood macroscopically as the interference superposition of two EM waves. Under a certain reference wave, the formed hologram establishes a point-to-point mapping to the object wave, as demonstrated in holographic LWA based EM holography. It is however different in photonic TCA based EM holography that can mostly be considered as persisting the principle of conventional phased array antennas while shifting the feed processing from the RF domain to the optical domain via UTC-PDs. If only focusing on the antenna aperture, we see that the photonic TCA based HMIMOS comply with the conventional phased array antennas, where each radiating element is independently tunable. Based on this insight, in this section, we mainly focus on the LWA based HMIMOS for inherent differences.

In order to realize the reconstruction process of EM holography, it is necessary to employ one or more feeds to generate

the reference waves, and to carry the hologram on a specifically designed HMIMOS, such that desired radiations can be achieved when the reference waves illuminate the HMIMOS. It is worth noting that the feed can be placed in different positions: (P1) integrated into the HMIMOS, and (P2) located externally of the HMIMOS. In the (P1) setting, the feed position can be divided into three cases: Surface-fed, bottom-fed, and edge-fed. In addition, there are different hardware structures of the feed that excite various propagation modes of a reference wave, which will be detailed next. Otherwise in the (P2) setting, the feed can be placed behind the HMIMOS to form a lens-like radiation through signal refraction. It can also be located in front of the HMIMOS to form a desired specular-like radiation by signal reflection. In such a case, the feed can be implemented by a horn antenna, producing the required near/far-field reference wave for illuminating HMIMOS to generate the object wave. Moreover, the HMIMOS can implement a specific hologram via designing the radiating elements in different shapes, by distinct materials, through fixed or tunable mechanisms, as well as following different design methodologies. We embrace each of the details of HMIMOS structures as follows.

A. HMIMOS Hardware Structure

The building blocks of an HMIMOS mainly include three components that can be macroscopically summarized as feed, substrate, and radiating element. The structure schematics of an HMIMOS with four possible structures are shown in Fig. 9. It is emphasized that this figure only exhibits representative schematics, while the feed, substrate, and radiating element can be in different types that will be detailed as follows.

1) *Feed*: The feed is utilized to generate a reference wave to propagate along the HMIMOS, thus exciting a desired object wave accordingly. It has different forms in accordance with its locations ((P1) and (P2)) and propagation mode of a reference wave that it supports, as well as depends on the material of substrate sometimes. Its realizations can be implemented by various hardware. We discuss each content as follows.

Location and Propagation Mode: As seen from Fig. 9, the feed position can be located on the surface displayed by schematic (a), and can be located at the bottom or the edge of substrate illustrated by schematic (b) and (c), respectively. The surface-fed form is used for supporting a transverse electric (TE) propagation mode of reference wave, where the electric field is transverse to the propagation direction while the magnetic field is perpendicular to the propagation direction. Oppositely, the bottom-fed form facilitates a transverse magnetic (TM) propagation mode of reference wave, where the magnetic field is transverse to the propagation direction while the electric field is perpendicular to the propagation direction. Furthermore, the edge-fed form matches the quasi transverse electric and magnetic (TEM) propagation mode of reference wave. It is first worthy noting that in the TEM mode, both electric and magnetic fields are perpendicular to each other and also perpendicular to the propagation direction. The microstrip line structure, depicted in Fig. 9(c), leads to the quasi TEM mode that makes the propagation resemble the TEM mode.

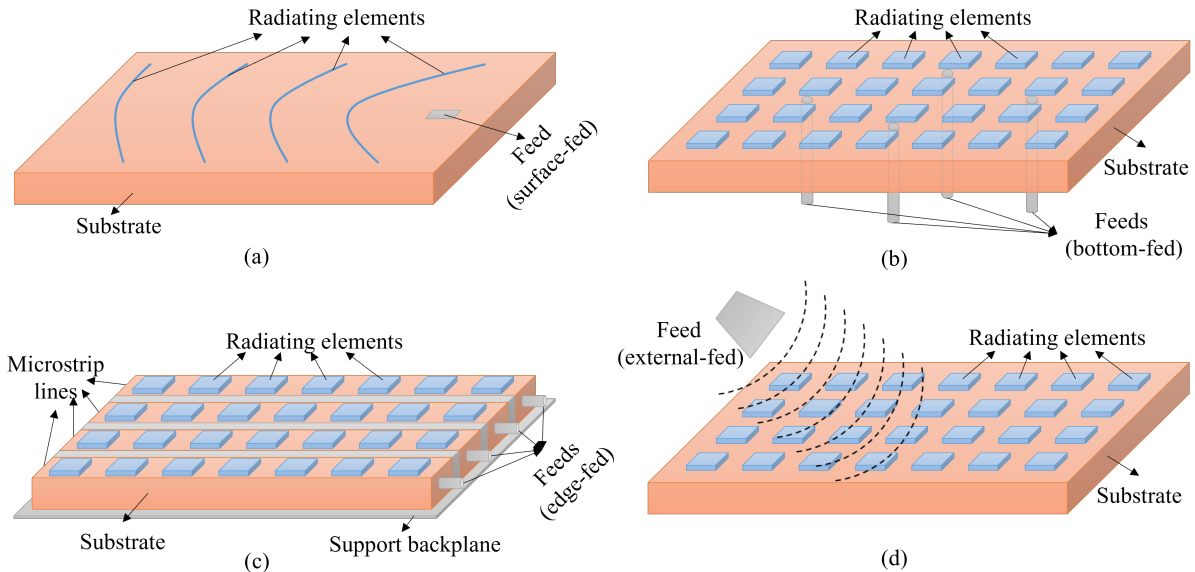


Fig. 9: Structure schematics of an HMIMOS: (a) curve-shaped strip grating radiating elements excited by a surface-fed feed; (b) square-shaped radiating elements excited by bottom-fed feeds; (c) square-shaped radiating elements excited by edge-fed feeds; (d) square-shaped radiating elements excited by external-fed feed.

The schematics in Fig. 9(a)(b)(c) belong to (P1), in which the reference wave propagates along the aperture surface that can be interpreted as surface wave, and the feed can be called as surface wave launcher accordingly. In a different way, the reference wave can be external-fed as depicted by Fig. 9(d) that belongs to (P2). In this case, the reference wave propagates in free space, which is termed as space wave. If the space wave further forms a plane wave, it follows a TEM propagation mode.

Hardware: Apart from the location configuration previously described, the hardware of the feed can be different as well. For the TE propagation mode, dipoles [108], planar Vivaldi feed (PVF), antipodal Vivaldi feed (AVF), and dipole based Yagi-Uda-feed (YUF) [109], [110], are capable of exciting such a propagation. Furthermore, an array of dipole sources was employed as the hardware structure for exciting the TE mode reference wave in [111]. The array enables a planar wavefront of the reference wave instead of a circular one generated by a single source. As such, the curve-shaped strip grating pattern driven by one feed as seen from Fig. 9(a) will become a line-shaped strip grating pattern (e.g., one-dimensional (1D) periodic metallic strip pads employed in [111]). Alternatively, the TE propagation mode can be excited by multiple substrate-integrated waveguide (SIW) horns within a substrate layer [112], [113]. For the TM mode propagation, single or multiple bottom-fed vertical monopoles are widely adopted in designing artificial impedance surfaces [114]–[117], enabling a single or multiple beam radiations. The feed can be alternatively replaced by a bottom-fed coaxial probe, as in [118], [119]. Depending on the employed glass-based substrate, the feed is realized by a through-glass-via (TGV) [120]. Furthermore, the coaxial probe is not only adopted for exciting the TM propagation mode, but also utilized for generating the quasi TEM propagation mode [121]. In

TABLE III: Configurations of a feed.

Equivalent name	Propagation mode	Hardware	Location
Surface wave	TE	Dipole (array) PVF AVF YUF SIW	Surface-fed
	TM	Monopole Coaxial probe TGV	Bottom-fed
	Quasi TEM	Coaxial probe	Edge-fed
Space wave	TEM (if plane wave)	Horn antenna	External-fed

such a setup, the reference wave is excited by an edge-fed coaxial probe, and then propagates along the microstrip line to terminated by a matched load eventually. For the generation of external-fed reference wave, the feed can be implemented by a horn antenna [122], [123].

To provide a complete reference of feed configurations, we summarize and list the equivalent names of reference wave, and their propagation modes, as well as the feed hardware and corresponding locations in Table III.

2) **Substrate:** The substrate is basically utilized as a waveguide that enables the reference wave injected by the feed to propagate along it. When integrating periodic partially reflecting surface on the top of a substrate, the reference wave can be leaked out to the free space. The main criterion for substrate selection is to satisfy the LWA principle with its physical properties, particularly the permittivity and permeability, being appropriately chosen [107]. Moreover, the selection criterion also depends on the fabrication availability and the cost constraint.

From a geometrical perspective, the substrate can be in a plate shape as shown in Fig. 9(a)(b), or in a microstrip line shape as depicted in Fig. 9(c). The two different geometric shapes are respectively responsible for supporting the reference wave propagation in either the surface wave mode or the waveguide mode. In addition, the substrate of an HMIMOS can be composed of different materials, based on which we can category into individual groups mainly including the dielectric substrate and the semiconductor substrate. Details of each group will be described as follows.

Dielectric Substrate: Dielectric materials are the most widely used for constituting the substrate of an HMIMOS. We enumerate three categories: printed circuit board (PCB) laminates substrate, silicon dioxide (glass) substrate, and anisotropic artificial dielectric substrate. In the first category, the commonly used PCB laminates as HMIMOS substrate are commercially available, including Duroid 5880, Rogers 3010, FR4, Rogers RO4003, Rogers 3003, Rogers RT6010, Taconic TLA-5/TLA-6, etc. The PCB laminates are competitively priced products with exceptional mechanical and electrical stability, as well as show a low dielectric loss which is well suited for high frequency/broadband applications. References [114]–[116], [118], [119], [121], [124]–[128] presented the utilization of grounded PCB that laminates to form a single/multiple layers for supporting various shaped subwavelength radiating elements, e.g., square metal/graphene patches, metallic strip gratings, and slot-shaped metamaterial elements etc. In the second category, the silicon dioxide (glass) substrate possesses a low dielectric loss as well. In [111] and [117], a grounded and graphene sheet/patches transferred silicon dioxide substrate was employed for realizing electrically tunable THz HMIMOS, respectively. In [120], a glass substrate was adopted for designing a high-gain mmWave HMIMOS. Such an efficient approach enables large physical antenna apertures with low fabrication tolerances and low cost material simultaneously. In the third category, an anisotropic artificial dielectric substrate is manufactured, where a composite layer of 0.015-in thick alumina 99% and 0.015-in thick TMM-4 materials is synthesized with acceptable requirements [129]. Comparing the three different substrates based HMIMOS from existing studies, we directly find that the PCB laminates substrate is more applied to frequencies below mmWave while the latter two are designed for mmWave or even THz frequencies.

Semiconductor Substrate: Semiconductor materials are another important branch for being substrate of an HMIMOS. Among various semiconductors, silicon is highly advocated because the large size and easy availability of low-cost high-quality silicon wafers, excellent mechanical strength and high thermal conductivity, as well as the high carrier lifetime in high-resistivity silicon devices [130]. The authors presented a novel direct current (DC) controlled silicon PIN diode design on a silicon substrate, employing the lithographic technology in [130], [131]. Such silicon PIN diodes are capable of realizing a similarly switchable functionality compared with conventional switches, thus paying the way for implementing a reconfigurable HMIMOS. The authors of [112] provided a Si/GaAs laminated substrate design for an HMIMOS with multibeam switchable capability. The substrate consists of

a dual semiconductor layer (Si and GaAs) connected via a specified coupling slot hosted on a middle conductive layer. The choice of Si mostly exploits the appropriate wafer thickness for fabrication, while the selection of GaAs provides a possibility for reconfigurability design by further growing Schottky diodes on this layer.

3) **Radiating Element:** The radiating elements mounted on the substrate surface form either uniform or non-uniform patterns, allowing a (reconfigurable) transformation from the reference wave in various modes to the radiated EM object waves. The radiating elements can be made of different materials and created in various shapes in discrete or (approximately) continuous forms, which will be described below. Before that, it is note worthy that the size of radiating elements and the distance between two adjacent ones are generally in subwavelength (e.g., $\lambda/10 \sim \lambda/5$ for meta-atoms with λ being the free space wavelength [43]), allowing a full manipulating and sampling on EM waves.

Radiating Element Material: The materials for implementing radiating elements of an HMIMOS can be metal, dielectric materials, or graphene etc., depending on their characteristics and design considerations. Metals are mostly adopted for realizing conductive radiating elements, inside of which electric currents oscillate at certain frequencies based on external EM fields. Metals are suitable for low frequencies as they behave as perfect electric conductors with neglectable losses when working at low frequencies. However, when the frequency goes higher, the ohmic losses inevitably exist in metallic radiating elements, which greatly degrades the radiating efficiency. Low loss and high refractive index dielectric materials are capable of addressing the loss issues faced by metals. In addition, the dielectric materials can potentially promote a smaller form factor and a wide range of bandwidth compared with the metallic counterparts [132]. Notably, for its unique but excellent mechanical, electronic and optical characteristics, the newly discovered graphene [133] has attracted enormous attentions, and has found a wide range of applications for implementing radiating elements [111], [117]. Graphene composes of carbon atoms in the hexagonal structure, and possesses excellent properties such as low loss, electronic tunability, and strong light matter interactions. The advantages enable graphene an excellent candidate for designing transceivers operating on THz or even optical frequencies.

Radiating Element Shape and Surface Pattern: In regard to the radiating element shape of an HMIMOS, metallic strip gratings, shown in Fig. 9(a), emerge as the earliest realizations [100], [134], and it is still employed in recent years [126]. The strip gratings are periodically located on specific positions, namely, the local maximum phase lines of hologram. They can be curve-shaped or line-shaped depending on a single or an array of feeds employed. To enhance the flexibility, reference [129] utilized non-contacting metallic dipoles as discrete samples of one continuous strip grating. The surface pattern is formed by a series of strip gratings. As the location of one strip grating (i.e., radiating element) is only placed in a given position, which reveals that the EM fields of the given position can be sampled whereas the information of remaining positions are lost. As such, this kind of HMIMOS cannot

TABLE IV: Radiating element configurations.

Design methodology	Radiating element shape	Radiating element type	Surface pattern
Locally maximum phase lines of hologram	Curve/line-shaped strip grating	Discrete	A series of strip gratings
Macroscopic surface impedance based approach	(Slitted) square/ellipse-shaped patches Circle-shaped patches with (cross) slot Coffee bean Grain of rice Double π Double anchor Square/hexagon-shaped loop-wire unit Cross-shaped patches C-shaped radiating elements	Approximately continuous	<ul style="list-style-type: none"> ○ Textured surface pattern: Concentric ellipses, spiral, and concentric circles ○ A superposition of multiple textured surface patterns ○ A division of multiple textured surface patterns
Geometric polarizable particle based approach	Slot-shaped radiating elements CELC	Approximately continuous	Present implicit textured pattern

construct the hologram as far as possible, leading to a limited control over the radiating properties.

To mitigate the problem, it is expected to cover more small size radiating elements over the surface for realizing a dense EM field sampling. To this aim, a multitude of subwavelength conductive patches were designed as radiating elements of artificial impedance surfaces [114], [115]. The conductive patches are relatively small compared with the wavelength of interest, allowing the scatter properties to be described using a macroscopic effective surface impedance. Moreover, the conductive patches can be customized in flexible sizes, shapes, and gaps between two adjacent ones, demonstrating a specific surface pattern, as well as allowing a realization of required macroscopic surface impedance and thereby the desired radiation. The surface impedance is basically guided by the holographic principle, providing a point-to-point connection between the hologram and the intended radiation as well as a point-to-point connection between the hologram and the surface pattern. One can design the radiating elements based on the holographic principle, showing a corresponding surface pattern and generating a desired EM field radiation. In [114], [115], The authors adopted square-shaped patches and vary their gaps for obtaining required surface impedance, generating a textured surface pattern in an appearance of concentric ellipses. Employing slitted-square patches, the authors further implement tensor impedance surfaces that are capable of controlling over EM wave polarization. In [120], the authors utilized slitted circle-shaped patches to form a spiral surface pattern for realizing a high-gain holographic antenna. Alternatively, the authors of [135] designed HMIMOS with spiral surface pattern, implemented by an array of subwavelength metallic blocks drilled with dielectric holes. Beyond the square-shaped patches, the radiating element shape can be more various as circle-shaped patch with (cross) slot, coffee bean, grain of rice, double π , double anchor [136], square/hexagon-shaped loop-wire unit [137], cross-shaped patch [122], and C-shaped radiating element [123]. If multibeam is further supported, the conductive patches are designed to form a superposition of multiple textured surface patterns, or a division of multiple textured surface patterns in one single shared HMIMOS [138]. The previous studies follow a common point-to-point mapping between surface pattern and

beam direction. Without obeying such a mapping, the authors of [127] provided a novel HMIMOS based on spoof surface plasmon polaritons (SPPs), which can control the propagation wavenumber of reference wave in different directions while retain the surface pattern fixed as concentric circles.

Following a distinct design methodology, namely, the geometric polarizable particle based approach (find in the next subsection), the authors used slot-shaped radiating elements, located on holographic principle guided positions [118], and located on designed positions that repeat periodically [112], respectively, for designing the multibeam holographic antennas. Such radiating elements were later extended to PIN-controlled slot-shaped units for achieving reconfigurability [119], [121]. Adopting more advanced complementary-electric-resonator (CELC) units as radiating elements, reference [139] further increased the phase accuracy and the hologram range. It should be emphasized that the slot-shaped radiating elements [112], [119], [121] and the CELC based radiating elements [139] are repeated periodically over the surface without presenting an explicit textured surface pattern.

To sum up, we present a list of main configurations for radiating elements, including the design methodologies (presented in the following subsection), radiating element shapes and types, as well as the generated surface patterns, in Table IV for ease of reference.

B. HMIMOS Holographic Design Methodology

The previously described surface pattern of an HMIMOS can be in various forms that correspond to different design methodologies. We itemize three main holographic design methodologies, from the original locally maximum phase lines of hologram to the recent macroscopic surface impedance based approach and the recent geometric polarizable particle based approach. Each will be detailed as follows.

Locally Maximum Phase Lines of Hologram: The primary holographic design is achieved via the locally maximum phase lines of hologram for its straightforward and easy interpretation. It should be first noted that the hologram generated by reference wave and object wave is indeed an interference wave with a certain period. This hologram includes a certain number of locally maximum phase lines within a dedicated

distance, each of which exists within one period. The design methodology enables radiating elements located at the locally maximum phase lines of hologram, forming a surface pattern consisted of a series of curve/line-shaped strip gratings. The resulting surface pattern allows the generation of object wave with a specific direction.

To explicitly show this methodology, we assume a y -direction propagating reference wave $E_{rw} = A_r e^{-j\beta_r y}$, and an object wave steering toward a given direction, $\theta = \theta_s$ and $\phi = \pi/2$. Based on (7), the hologram is reduced to

$$\hat{E}_{int} = A_r A_o e^{j(\beta_r + \beta_0 \sin \theta_s)y}, \quad (8)$$

whose wavenumber is given by $\beta_r + \beta_0 \sin \theta_s$, equivalent to wavelength $\frac{2\pi}{\beta_r + \beta_0 \sin \theta_s}$. Within each wavelength of the hologram, the radiating element is placed on the locally maximum phase line (namely the peak value achieved coordinates). All locally maximum phase lines of hologram within the effective HMIMOS aperture form the surface pattern constructed by a series of curve/line-shaped strip gratings.

From such a design methodology, one can see that the phase information between strip gratings are inevitably lost, lowering the performance of holographic mapping between reference wave and object wave. We can alternatively interpret this from sampling perspective that the radiating elements take a small amount of specific samples of the reference wave, incurring the result of under-sampling. Another noticeable question is that an HMIMOS based on this design methodology is not reconfigurable. Each surface pattern only corresponds to a specific wave radiation, such that one should change the surface pattern for obtaining another expected wave radiation.

Macroscopic Surface Impedance Based Approach: Deploying a large amount of subwavelength conductive patches over the surface, the reference wave can be densely sampled. The relatively small sizes of radiating elements and adjacent distances compared with wavelengths of both reference wave and object wave, enable the scatter properties to be described using macroscopic effective surface impedance. The macroscopic effective surface impedance is defined as the ratio of electric field E_x to magnetic field H_y near the surface averaged over the unit cell, which can be expressed as $Z = \int_{cell} \frac{E_x}{H_y} ds$ [115]. It is related to substrate permittivity and thickness, as well as the period and gap between adjacent radiating elements. For instance, high impedance values are achieved with high substrate permittivities, thick substrate, large period and small gap. Under a desired surface impedance, the radiating elements can be engineered in various shapes as shown in Table IV.

Holographic design realized by the macroscopic surface impedance based approach is to collect a large amount of specifically designed radiating elements for obtaining the expected surface impedance that is determined by the hologram created via the interference between reference wave and object wave. To be more specific, the surface impedance of (x, y) -coordinate is given by [115]

$$Z(x, y) = j [X + M \Re (E_{obj} E_{rw}^*)], \quad (9)$$

where X is the real-valued average impedance value, and M denotes the real-valued modulation depth that spans the entire available range of impedance values. (9) builds a mapping

between the surface impedance and the hologram. Combining this mapping with the relation between surface impedance and geometry parameters of substrate and radiating elements, one can readily correspond the hologram to geometry parameters. With a selected substrate (permittivity and thickness are fixed), the hologram is implemented as a surface pattern that is constructed by a large amount of patches with specific periods and gaps, displaying as concentric ellipses, spiral or concentric circles. These textured surface patterns corresponds to different radiation properties, determining the radiation directions. Holographic design via macroscopic surface impedance can be dated back to the sinusoidally-modulated reactance surfaces whose modal surface impedance is modulated sinusoidally for realizing an expected radiation [140], [141].

It should be emphasized that the above surface impedance is designed for radiating single object wave. When multiple object waves are required to be radiated simultaneously, the surface impedance is designed as a division or a superposition of multiple textured surface patterns on one shared aperture. For the division case, the surface impedance design of each division follows from (9), indicating a corresponding object wave. While for the superposition case, the surface impedance design is guided by the following expression

$$Z(x, y) = j \left[X + \frac{M}{K} \sum_{k=1}^K \Re (E_{obj_k} E_{rw_k}^*) \right], \quad (10)$$

where K is the number of object waves. In this case, HMIMOS allow multi-beam radiations simultaneously, where each object wave is excited by one reference wave.

Taking the surface impedance approach for holographic design can be finalized to the designs of geometry parameters of substrate and radiating elements, which imposes a limitation on the realization of reconfigurable HMIMOS, namely once the geometry parameters are designed, the radiating properties are determined accordingly. Tunability can be achieved by introducing special materials, such as graphene. Bridging the connection between conductivity of graphene and surface impedance, the radiation properties are tunable with an external DC control on graphene conductivity [111], [117].

Geometric Polarizable Particle Based Approach: An alternative holographic design is achieved from a geometric perspective via using the polarizable particles (dipoles) based approach [139], [142]. It is feasible as a radiating element is small enough compared with the free space wavelength, thus its radiation field can be well described by that of a dipole [139]. This approach describes the generated radiations as a weighted sum of far-field patterns of all dipoles. Each radiating element corresponds to a weight that follows a specific constraint and is configured by the holographic principle.

Assume a far-field radiation and adopt a 1D microstrip line HMIMOS for example (shown as one microstrip line of the aperture in Fig. 9(c)). Under these settings, the radiation wave

of HMIMOS at distance $d_o(x, y)$ can be expressed as [139]

$$E_{rad} = \frac{A_r \omega^2}{4\pi d_o(x, y)} e^{-j\beta_0 d_o(x, y)} \underbrace{\times \cos \theta \sum_{n=1}^N \alpha_n(\omega, x, y) e^{-j\beta_r d_r(x, y)} e^{-j\beta_0 d_r(x, y) \sin \phi}}_{AF(\theta, \phi)}, \quad (11)$$

where ω denotes the operating frequency, $\alpha_n(\omega, x, y)$ represents the weight of the n -th radiating element (located at the (x, y) -coordinate) at frequency ω , and $AF(\theta, \phi)$ is defined as the array factor. It is emphasized that β_r and $d_r(x, y)$ are the same as in (5). Comparing the object wave in (6) with the radiation wave in (11), we should have the array factor $AF(\theta, \phi)$ be some constant to ensure $E_{obj} = E_{rad}$, which means that the HMIMOS radiates an expected wave to the object. As such, the weights of all radiating elements satisfying the requirement can be obtained as [139]

$$\alpha_n(\omega, x, y) = e^{j\beta_r d_r(x, y)} e^{j\beta_0 d_r(x, y) \sin \phi}. \quad (12)$$

One can see from (12) that the weights require full control over the phase of each radiating element, which cannot be satisfied due to the inherent constraints faced by each radiating element. Each radiating element can be considered as a resonant electrical circuit scattering as a dipole, and each weight (ignore the index n and its coordinate (x, y)) has the Lorentzian form expressed as [139]

$$\alpha(\omega) = \frac{F\omega^2}{\omega_0^2 - \omega^2 + j\omega\gamma}, \quad (13)$$

where F is the real-valued oscillator strength, ω_0 denotes the resonance frequency, and $\gamma = \frac{\omega_0}{2Q_m}$ describes the damping factor with Q_m being the quality factor of the resonator. The amplitude and phase of the weight are coupled through the connection $|\alpha(\omega)| = \frac{F\omega|\cos \psi|}{\gamma}$ with $\psi = \tan^{-1} \left(-\frac{\gamma\omega}{\omega_0^2 - \omega^2} \right)$, which limits the weight range to a restricted subset compared with the independent control over amplitude and phase. The radiating element can be tuned in two possible cases, namely by either shifting the resonance frequency or changing the damping factor. Depending on the selected tuning case, the weights can be configured in three forms: Amplitude-only, binary amplitude, and Lorentzian-constrained phase.

First, in the amplitude-only case, the radiating element is near resonance such that $\alpha(\omega) = -j\frac{F\omega}{\gamma}$. By adjusting the oscillator strength F or the damping factor γ , one can tune the weight by its amplitude without changing its phase. The amplitude-only weight is deduced from (12) by taking its real part in the following formulation [139]

$$\alpha_n(\omega, x, y) = X_n + M_n \cos(\beta_r d_r(x, y) + \beta_0 d_r(x, y) \sin \phi), \quad (14)$$

where X_n and M_n are real-valued positive variables. Additionally, the binary amplitude case is applicable to radiating elements tuned between ‘‘ON’’ and ‘‘OFF’’ states, which can be realized by toggling the resonance frequency between a valid value within the operating frequency and an invalid value

outside the operating frequency. In this case, each radiating element achieves only two amplitudes, given by [139]

$$\alpha_n(\omega, x, y) = X_n + M_n \Theta \cos(\beta_r d_r(x, y) + \beta_0 d_r(x, y) \sin \phi), \quad (15)$$

where $\Theta \in \{0, 1\}$ enables $\alpha_n(\omega, x, y)$ to be an offset square wave. Finally, the Lorentzian-constrained phase case depicts the inherent coupling between amplitude and phase faced by the weight. The Lorentzian resonator limits the range of phase within $[0, \pi]$, losing the untouchable set $(\pi, 2\pi]$. Building the following weight function expressed as [139]

$$\alpha_n(\omega, x, y) = \frac{j + e^{j(\beta_r d_r(x, y) + \beta_0 d_r(x, y) \sin \phi)}}{2}, \quad (16)$$

the phase of $\alpha_n(\omega, x, y)$ is ensured to have a range of $[0, \pi]$, and the amplitude satisfies the constraint of $|\alpha_n(\omega, x, y)| = \left| \cos \left(\frac{\beta_r d_r(x, y) + \beta_0 d_r(x, y) \sin \phi}{2} \right) \right|$.

C. HMIMOS Tuning Mechanism

As the continuous developments of HMIMOS, conventional non-tunable designs, basically being fixed when the design and fabrication completed, are shifting to the paradigm with dynamically reconfigurable capabilities. The tunability enables an HMIMOS capable of achieving any required hologram by dynamically adjusting the radiating elements for exciting intended object waves. In doing so, the up-to-date tuning mechanisms for realizing reconfigurable HMIMOS are mainly based on lumped elements (positive-intrinsic-negative (PIN) and varactor diodes), liquid crystals (LCs), graphene, and photosensitive devices, detailed as follows.

Lumped Element Tuning: PIN diodes belong to a class of tunable lumped electronic elements that can be controlled by forcing external DC bias voltages, thereby allowing a feasible solution for implementing reconfigurable HMIMOS. A PIN diode is capable of presenting two states, referred to as ‘‘ON’’ and ‘‘OFF’’, by forward biasing and reverse biasing via DC bias voltage, respectively. The ‘‘ON’’ state can be modeled as a resistor-inductor concatenation circuit with a negligible forward resistance (effectively short-circuit), otherwise, the ‘‘OFF’’ state is equivalent to a capacitor-inductor concatenation circuit presenting a high reverse resistance (effectively open-circuit) [119]. By incorporating each PIN diode in the center of a slot-shaped radiating element, the resonance frequency can be controlled, as well as the coupling between radiating elements and the reference wave can thus be determined [119], [121]. It is worth noting that the state control of each PIN diode is guided by the holographic principle. Another type of tunable lumped element can be used for achieving reconfigurability is the varactor diode. Compared with the PIN diode, it is capable of continuous phase tuning instead of the discrete ‘‘ON’’ and ‘‘OFF’’ states. In [113], the authors presented a metasurface architecture that allows electronic beamsteering from a specifically designed layout with each radiating element controlled by two varactor diodes. The main advantages of lumped elements enabled reconfigurability depend on their low-cost and easy implementation, opening up a wide range of applications in realizing the tunability.

TABLE V: Tuning mechanisms of HMIMOS.

Tuning mechanism	Working frequency	Pros and cons
Lumped element	(Sub-) mmWave	Pros: Low cost/power consumption, fast tunable response, easy implementation Cons: Limited to a relatively low working frequency
Liquid crystal	(Sub-) mmWave	Pros: Flexible integration into various structures and low power consumption Cons: Slow tunable response and relatively low working frequency
Graphene	THz	Pros: Superior electronic properties and ultra-fast tunable response Cons: Difficulty in manufacturing for large area graphene
Optical (Photodiode)	GHz - optical	Pros: Superior electronic properties and ultra-fast tunable response Cons: Difficulty in strictly guaranteeing the phase stability requirement
Electro-mechanical (Piezoelectric actuator)	mmWave	Pros: Efficiently modify the EM properties with low loss Cons: Slow tuning speed and limited device size
Thermal (Vanadium dioxide)	mmWave	Pros: Sufficient tuning range and integration compatibility Cons: Slow tuning speed due to time consuming of heating and cooling

According to the intrinsic properties, lumped elements are mostly applied to (sub-) mmWave frequencies.

Liquid Crystal Tuning: As a special class of soft condensed matter, LCs exhibit properties between a state of liquids and solid crystals. They are capable of flowing as liquids and simultaneously exhibiting the anisotropy with molecules oriented in a solid crystal-like way. The LCs also demonstrate an excellent tunable capability under external stimuli, such as electric or magnetic bias field, which controls the permittivity tensor of LCs. The tunability was utilized for achieving reconfigurable HMIMOS in [128], [143], [144]. These studies design a similar LC-controlled HMIMOS, where LCs are filled in cavity boxes between slots and radiating patches to implement the reconfigurability by exciting radiating patches using external DC bias voltages. The time LCs are forced by external voltage, and their molecules are aligned in a specific direction, presenting a corresponding permittivity. Otherwise, the molecules are parallel to the surface resulting in a different permittivity. The varying permittivity changes the capacitance of radiating elements, consequently allowing a tunability of the resonance frequency. The LC-controlled HMIMOS has several advantages, including flexible integration into various structures thanks to the fluidity, and low power consumption owing to the mostly capacitive operations of LCs with negligible currents. However, the main disadvantage is the relatively slow response of LCs, leading to limited applications to extremely fast tunability requirements.

Graphene Tuning: Graphene was discovered and isolated by Nobel laureates, Andre Geim and Konstantin Novoselov, in 2004 [145]. It is an atomic-scale 2D material composed of carbon atoms in hexagonal structure. It possesses superior mechanical, electronic and optical properties, namely ultra-high breaking strength, ultra-high charge carrier mobility and ultra-low resistivity for desired conductivity, as well as high transparency due to the ultra-thin thickness. The excellent properties, especially from an electronic perspective, allow a realization of dynamically controllable conductivity via electric or magnetic manners, enabling a feasible way for implementing reconfigurable devices, particularly for HMIMOS [111], [117]. These studies design HMIMOS by stacking the ultra-thin graphene sheet onto a grounded silicon dioxide substrate, and then control the conductivity of graphene via DC bias voltages for achieving an arbitrarily desired surface

impedance guided by the holographic principle. The main difference between these studies is the adopted conductivity tuning manner, namely pixel-by-pixel electrical control enabled by a relatively huge biasing network in [117], and a more succinct electrical control network coordinated by two groups of 1D biasing pads in [111]. The graphene based HMIMOS generally work on THz frequencies and exhibit a nanosecond-scale or even faster control response, providing a potential satisfaction for ultra-fast tunability. However, a large area free-standing graphene is difficult to manufacture, which will restrict its application to HMIMOS with a large aperture area.

Optical Tuning: In optical tuning, the reconfigurability can be implemented via either utilizing photosensitive semiconductors, e.g., silicon, or driving dedicated devices, such as photodiodes. By properly illuminating/driving via optics, the corresponding photosensitive semiconductors/dedicated devices are optically controlled for achieving on/off inter-connections between radiating elements, thereby realizing the reconfigurability. In [146], the authors showed a Si based checkerboard metasurface that is controlled optically by a laser source. The illuminating focal point of laser controls the electrical connection between two conductive metal patches exploiting the photoconductive properties of silicon. Different in [147]–[149], the authors proposed to use the dedicated photodiodes for realizing an optically controlled TCA. The photodiode is capable of achieving an optical-to-electrical transformation that can directly drive radiating elements with high power and high linearity. This scheme is mainly deployed in photonic TCA based EM holography. Optical tuning is becoming a disruptive alternative because of its inherent advantages. It is capable of obtaining an ultrafast tunable speed and protecting signals from EM interference. Specially, the photodiodes based scheme for TCA based HMIMOS is proved to facilitate a full-optical processing in implementing wireless communication systems. To be specific, photodiodes assist in building optical domain processing with very large bandwidth and reducing power consumption and hardware cost compared to the conventional electrical domain processing. Combined with optical fiber, long distance HMIMOS deployments, where HMIMOS and signal processing units are in different locations, can be practical. It may encounter one main problem of such optical

tuning systems that the high phase stability of parallel optical signals should be strictly guaranteed which is generally difficult as optical fibers are sensitive to surrounding environments (temperature, vibration, airflow, and sound) that will greatly influence the signal phases.

Others: Besides the mentioned tuning mechanisms, some others utilizing different principles are proposed. In [150], the authors presented electro-mechanically tunable metasurfaces with high gain and beam steerable capabilities at mmWave frequencies. The required tuning is obtained by controlling a piezoelectric actuator for varying the mechanical separation between radiating elements and a ground layer. It provides an extremely low loss scheme that can efficiently modify the EM properties as it directly controls the interspacing distances. However, this type of tuning approaches usually suffer from their slow tuning speed and limited device size. Another vanadium dioxide integrated reconfigurable metasurface was demonstrated in [151] for mmWave beam scanning. The vanadium dioxide belongs to the phase changing material, which exhibits a phase transition from metal to insulator under thermal variations. Based on this useful property, [151] implemented the tunability via applying voltage to heating electrodes that control the dielectric properties of vanadium dioxide. Such a thermal tuning scheme can generally achieve a sufficient tuning range and a required compatibility for integration, while it however suffers from a slow tuning speed due to the time consuming heating and cooling.

To summarize, we provide a summary of various tuning mechanisms with respect to their working frequency as well as their pros and cons, which can be found in Table V.

D. HMIMOS Fabrication Methodology

Various fabrication methodologies for implementing HMIMOS are invented based on surface lithography technologies, mainly including photolithography, electron-beam lithography, focused-ion-beam lithography, interference lithography, self-assembly lithography and nanoimprint lithography [152]. Among these lithography technologies, photolithography is broadly applied to semiconductor integrated circuits with high throughput at microscale and nanoscale. The ultimate nanostructures are shaped on substrates after experiencing several steps, such as exposure, developing, etching, depositing and lift-off processes. Besides, electron-beam lithography is capable of drawing arbitrary patterns with several nanoscale resolution. It performs a direct-write fashion without using a photomask, creating a maskless lithography. Alternatively, the focused-ion-beam lithography is another direct-write technology for creating fine nanostructures on a surface. Differently, utilizing the interference of more than one coherent laser beams, interference lithography achieves the nanostructure patterning. It can be considered as a new modality of photolithography. Furthermore, self-assembly lithography is enabled for creating various large-area nanostructures by utilizing the principle of intermolecular balance of attractive and repulsive forces for spontaneously assembling. Lastly, nanoimprint lithography is mostly applicable to create large-area periodic subwavelength structures in a single step with

low-cost and high throughput. Additionally, the commercially employed PCB laminates for implementing HMIMOS make it feasible to apply the off-the-shelf PCB fabrication technology directly. This makes the fabrication price competitive and guarantee expected mechanical and electrical stability.

E. HMIMOS Aperture Shape

HMIMOS can be in various shapes based on the installation requirement and the design availability. One of the simplest aperture shapes is the 1D microstrip line [121], [128]. With radiating elements lined up in a row, HMIMOS are capable of radiating EM fields. It is further emphasized that the dominated aperture shape employed by most HMIMOS is 2D planar, where square/rectangle-shaped apertures [112], [116] and circular/hexagon-shaped apertures [110], [123], [144] are currently typical forms employed. The aforementioned 1D microstrip line can be packed onto a common panel to form a 2D planar HMIMOS. Beyond these aperture shapes, reference [127] presented a special 2D circular HMIMOS with 16 splitted strip branches. Even through the 2D planar aperture is prevalent in shape design, it is necessary to design conformal HMIMOS to meet special installation requirements. The authors of [153] demonstrated a cylinder-shaped conformal lens fed by one/more sources, capable of realizing a wide-angle beam steering by collimating the incident spherical wave front into a plane wave front. Alternatively, The authors of [154] designed a cylindrical conformal HMIMOS constructed by multiple waveguide-fed 1D microstrip lines. Subsequently, the authors of [155] presented a cylinder-shaped conformal omnium-HMIMOS that is capable of achieving a linear-to-circular polarization conversion. Breaking the barrier that traditional surface impedance based HMIMOS are restricted to 2D plane or 3D cylinder, the work [156] utilized the Voronoi partition for designing an HMIMOS, which can be adapted to form arbitrary conformal aperture. The various aperture shapes enable a great potential of HMIMOS to be deployed in a multitude of positions both in normal or special shapes.

F. HMIMOS Typical Functionality

HMIMOS are capable of achieving a wide variety of functionalities for EM manipulations. Although they can be utilized as RIS/IRS that have being widely investigated recently, we notice that RIS/IRS mainly work as passive reflectors and their working mechanisms do not directly follow a holographic operating rule. Therefore, we mainly focus on HMIMOS working as transceivers that are guided by the holographic principle. Based on existing studies, we list two typical functionalities of HMIMOS, namely EM wave polarization and EM wave steering. Each of the functionality will be described as follows. It should be emphasized that HMIMOS possessing either one or more functionalities mainly depend on the design purpose and scheme feasibility.

EM Wave Polarization: It is known to us that the EM wave polarization indicates the oscillation orientation of a transverse wave. The polarization functionality of HMIMOS is capable of achieving a transformation of the oscillation orientation via different designs or tuning mechanisms. Most studies mainly

focus on generating a desired wave without polarization control, such as [111], [114], [117], [121] to name a few, which indicates that these HMIMOS present a single polarization mode with a predefined oscillation orientation. In study [115], the authors presented a design method for polarization control through creating a tensor surface with anisotropic radiations. The control over polarization is achieved by varying the shape of radiating elements (make a specific slit on each patch) with a careful design on geometric parameters of the slits. The authors of [157] later implemented a circularly polarized HMIMOS by patterning a spiral like surface impedance. Furthermore, the authors of [125] proposed to control over polarization using a scalar surface, which greatly reduces the design complexity comparing with that of tensor surfaces. The polarization control is achieved by dividing the HMIMOS aperture into different regions and changing the phase of surface impedance modulation of one region relative to others, capable of realizing arbitrary linear polarization and circular polarization. Alternatively, the study [158] proposed to design an orthogonally discrete unit-cell with four working states for realizing linearly and circularly polarized waves via matching surface impedance along two orthogonal directions. It should be emphasized that the polarization mentioned above becomes fixed once the HMIMOS are fabricated. To encompass more polarization states, the authors of [118] demonstrated a dual-polarization HMIMOS using linearly polarized, slot-shaped radiating elements located in horizontal and vertical directions. Additionally, a dual circularly polarized HMIMOS was designed and experimented in [159] and [160], respectively. Differently, the study [116] introduced a class of polarization-diverse HMIMOS that enable horizontal, vertical or circular polarization via multiple excitation sources that act as switches. Subsequently, the study [161] presented a polarization reconfigurable HMIMOS capable of achieving linear, and right/left-hand circularly polarization via integrating a feed structure switched by PIN diodes into a polarization-insensitive surface [137].

EM Wave Steering: The steering capability of HMIMOS enables EM waves to be constructively and destructively controlled to generate a single or multiple concurrent beams for different directions. As such, we encompass the EM wave focusing and scattering in the scope of steering capability. The initial steering capability of HMIMOS is mainly enabled for supporting a single-beam radiation from the primary fixed configuration to the tunable capability afterwards. In this branch, the studies [100], [126], [129], [134] presented HMIMOS with a single-beam radiation based on the “locally maximum phase lines of hologram” design methodology. The single beam is generated based on strip grating (discrete dipole) radiations that are constructively superposed in-phase in the desired direction and destructively canceled in remaining directions. The design methodology leads to an inevitable lost of phase information that restricts the performance of beam radiation. Later, the authors of [114], [115], [125] designed single-beam radiated HMIMOS following from the macroscopic surface impedance based approach, allowing a more accurate manipulation on EM waves. The pioneer studies inspire a multitude of research activities on single-beam

radiated HMIMOS [120], [137], [158], [162], and were later promoted one step forward with reconfigurable capabilities via utilizing DC controlled graphene conductivity [111], [117] for realizing a global surface impedance control. The global surface impedance control then evolved to a local surface impedance control via using mixed-signal integrated circuits, as conceptually shown in [163]. Alternatively, based on the geometric polarizable particle based approach, the article [139] demonstrated different single-beam HMIMOS with a discuss on various radiation weights. The reconfigurability was further achieved in [119], [121] facilitated by PIN diodes and in [128], [143], [144] enabled by LCs. Beyond realizations of single-beam radiation, the steering capability for supporting multibeam radiations attracts great interests for the great application potential in supporting future communication systems. Several multibeam HMIMOS with fixed beam radiations were respectively presented based on the geometric polarizable particle based approach [118], as well as by designing specific impedance patterns for being a transmit array [110], [138], [158] and a reflect array [164], [165]. Furthermore, extending the static configuration of multibeam radiations, references [112], [166] achieved a dynamically switchable multibeam radiations, implemented by switching different feed ports. Going one step further, a multibeam radiated HMIMOS capable of achieving the dynamic reconfigurability was designed in [167].

Beyond above mentioned efforts, the steering capability of HMIMOS also facilitates the multibeam scanning with the changes of frequencies [124] and promotes the multiwavelength multiplexing [168]. Moreover, specifically designed HMIMOS are capable of respectively radiating multiple high-order Bessel beams and vortex beams that carry different OAM modes [123], [169], [170]. A little bit further, it is appealing to integrate multiple functionalities using one single HMIMOS. The authors of [171] investigated diverse EM responses of a large-scale programmable metasurface, where they realized reconfigurable polarization conversions and dynamic steering capabilities on the same surface via using PIN diodes. We show typical functionalities of HMIMOS in Fig. 10.

G. Representative HMIMOS Prototypes

In the progressive evolution of HMIMOS, a variety of prototypes are designed and fabricated, based on which numerous functionalities and capabilities of HMIMOS are experimented. The validations powered by prototypes will enormously promote the commercial uses and wide deployments for supporting future communications. In this section, we first select representative HMIMOS prototypes for demonstrating the main advances in this area. Beyond HMIMOS prototypes, we then list recent advances of HMIMOS aided communication prototypes that validate communication capability from an end-to-end perspective. We believe that the existing and emergence of prototypes will push the validations/applications of HMIMOS to a new level, and will also play a critical role in validating future wireless communications.

HMIMOS Prototypes: We present prototypes of HMIMOS by characterizing their physical parameters and functional capabilities, with which we carry out in three categories based

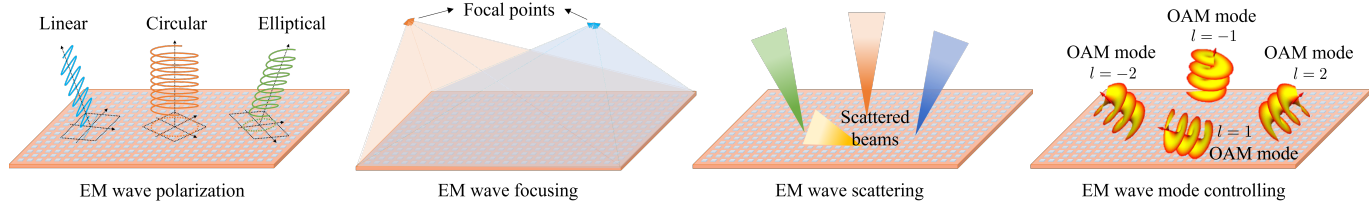


Fig. 10: Typical functionalities of HMIMOS.

on the design methodologies. Based on the locally maximum phase lines of hologram, the authors in [126] designed two $55.5\text{mm}/49.0\text{mm} \times 30\text{mm}$ HMIMOS with 20 and 12 strip gratings (radiating elements), respectively, for achieving a fixed direction radiation at 60 GHz with more than 20dBi maximum gain achieved. Utilizing the more advanced macroscopic surface impedance and geometric polarizable particle based approaches, a multitude of HMIMOS prototypes are presented. In [116], the authors designed a $9.6\lambda \times 8\lambda$ (λ free space wavelength) HMIMOS with 3000 metallic patches operating at 12 GHz for demonstrating a polarization-diverse capability. This aperture achieved a 16dBi radiation gain with 1.06 circular-polarized axial ratio and 3.57% aperture efficiency. The work [120] employed the glass package technology to enable a $35\text{mm} \times 35\text{mm}$ aperture that consists of 28900 circular pixels and operates at 150 GHz. This structure achieved a maximum 24.7dBi antenna gain and a 4.7° 3dB beamwidth. Capable of supporting multibeam radiations, the authors of [166] fabricated a $255.5\text{mm} \times 255.5\text{mm} \times 1.5\text{mm}$ aperture covered by 73×73 units. They measured a higher than 17.2dBi peak gain at 18 GHz. In addition, employing a reflecting working mode, the authors of [164], [165] designed a $18\text{mm} \times 18\text{mm}$ aperture containing 2025 units for achieving multibeam radiations with linear polarization and circular polarization. In the linearly polarized multibeam case, they measured a 23.5dBi peak gain of each beam, 47.2% aperture efficiency, lower than -10dB cross-polarization and -26dB sidelobe at 15 GHz. In the circularly-polarized multibeam case, 19.43dBi peak gain of each beam, 45.8% aperture efficiency, higher than 25dB cross-polarization discrimination, below -17dB sidelobe, and 3dB axial ratio bandwidths of 19.23% and 18.26% were achieved at 13 GHz. Adopting a semiconductor substrate (Si/GaAs) for HMIMOS design, the authors of [112] presented a $56\lambda_g \times 56\lambda_g$ aperture with λ_g being the wavelength of reference wave in GaAs at 94 GHz. The prototype is capable of radiating multiple beams via switching different feed ports, with a directivity gain of 31.9dBi and a reflection coefficient lower than -15dB . Enabled by tunable devices and materials, reconfigurable HMIMOS are spurred. The authors used PIN diodes to dynamically control the radiation of each unit in [121]. They designed a 1D microstrip line aperture that includes 79 slot-shaped units with an unit periodicity of $\lambda_g/3.3$ and each unit $\lambda_g/2.5$ long and $\lambda_g/17.5$ wide. The antenna gain was measured as 14.6dBi with 35% aperture efficiency, 4.1° half-power (3dB) beamwidth, and higher than 20dB polarization purity. Alternatively, the authors of [128] utilized LCs to enable the tunability. An aperture with 43 radiating elements

was fabricated with a beam scanning capability of $-60^\circ \sim 60^\circ$ at 10 GHz. With a specifically designed decoupling structure, improvements on antenna gain and sidelobe can be maximally achieved by 3.93dB and 7.7dB, respectively, compared with antennas without the decoupling structure.

Beyond the representative prototypes mentioned above, several initial commercial products (39 GHz CPE beamformer, 28 GHz RAN beamformer, 28 GHz repeater beamformer, and 14 GHz A2G beamformer) were released by Pivotalcommware company for different business users (from original equipment manufacturers to network operators) with distinct requirements, such as radio access, signal relay, and air-to-ground broadband communications. Take the 28 GHz RAN beamformer for instance, the product is capable of achieving a wide angle beam steering of $-60^\circ \sim 60^\circ$ in both azimuth and elevation directions, as well as a fast beam switching of 100ns execution rate and $4\mu\text{s}$ update rate. It also supports horizontal polarization and vertical polarization, as well as achieves a high holographic beamforming gain of 25dBi with 6° half-power beamwidth in both azimuth and elevation directions [172]. The products demonstrate a great potential of HMIMOS in promoting communication systems with a tremendous reduction in cost, size, weight and power consumption.

HMIMOS Aided Communication Prototypes: By integrating HMIMOS into communication systems, one can evaluate communication performance and verify new capabilities through HMIMOS aided communication prototypes, which is critical for future communication validations. The authors of [53] first integrated a 256-element HMIMOS as RF chain-free transmitter and space-down-conversion receiver into a communication system to form an end-to-end MIMO prototype working at 4.35 GHz. Using a 16 quadrature amplitude modulation (QAM), an experimental 2×2 MIMO-16QAM transmission with 20 megabit-per-second data rate is achieved, validating the great potential of HMIMOS to enable cost-effective and energy-efficient systems. Beyond such an early work, the same team built various communication system prototypes by fully exploiting the HMIMOS functionalities. They demonstrated various end-to-end communication prototypes, including binary frequency-shift keying/phase-shift keying/QAM transmitters, pattern modulation system, multichannel direct transmission system, and space-/frequency-division multiplexing system [173]. Besides, the authors in [174] built an HMIMOS aided wireless communication prototype using a 256-element reflecting platform. The prototype was constructed by modular hardware (hosts, USRPs and an RIS) and flexible software (source and channel coding,

TABLE VI: Physical aspects of HMIMOS.

Design methodology	Ref.	Beam mode	Polarization mode	Tunability	Tuning mechanism	Aperture shape	Substrate type	Reference wave type	Feed & position	Radiating element	Operating frequency		
Locally maximum phase lines of hologram	[134]	Single	Single	✗	✗	2D planar (square)	Dielectric	Surface wave	A pyramidal horn Edge-fed	Curve-shaped metal strips	11.7 — 12.3 GHz		
	[129]			WR28 waveguide Edge-fed	Curve-shaped metallic dipoles				35 GHz				
	[126]			AUF, Planar YUF Surface-fed	Curve-shaped metal strip gratings				60 GHz				
Macroscopic surface impedance based approach	[114]	Single	Single	✗	✗	2D square, 3D cylinder	Dielectric	Surface wave	A monopole Bottom-fed	Square-shaped metal patches	17 GHz		
	[115]			Slitted square-shaped metal patches	10 GHz								
	[125]			Square-shaped metal patches	12 GHz								
	[162]			✗									
	[120]			✗									
	[116]			Polarization-diverse	✗					✗			
	[111]	Single	✓	Graphene	2D square, 3D cylinder	Dielectric	Surface wave	A Dipole array Edge-fed	Graphene strips	2 THz			
	[117]		✓	Graphene					A monopole Bottom-fed	Square-shaped graphene patches	1 THz		
	[158]	Multiple	Single	Single	✗	✗	2D planar (square)	Dielectric	Surface wave	A monopole Bottom-fed	Square-shaped cells (four metal patches)	11 GHz	
	[124]				✗	✗					Square-shaped metal patches	16 — 19GHz	
	[138]				✗	✗	2D planar (circular)			Four monopoles Bottom-fed	Ellipse-shaped metal patches	✗	
	[110]				✗	✗					An AUF Surface-fed	Square-shaped metal patches	12 — 18 GHz
	[158]				✗	✗	2D planar (square)			A monopoles Bottom-fed	Square-shaped metal patches	11 GHz	
	[164]				✗	✗						A horn feed External-fed	Square-shaped metal patches
	[165]				✗	✗					Slitted square-shaped metal patches		13 GHz
	[166]				✗	✗					Surface wave	Four monopoles Bottom-fed	Square-shaped metal patches
[168]	✗				✗	Two monopoles Bottom-fed	Square-shaped metal patches			17 GHz, 20 GHz			
[169]	✗				✗	Two dipoles Bottom-fed	Slitted square-shaped metal patches			30 GHz, 30.5 GHz			
Geometric polarizable particle based approach	[128]	Single	Single	✓	LC	1D micro-strip line	Dielectric	Waveguide	A coaxial feed Edge-fed	Square-shaped metal patches	10 GHz		
	[143]			✓	LC	2D planar (square)				Square-shaped meta-atom	30 GHz		
	[144]			✓	LC	2D planar (hexagon)				Slot-shaped radiating elements	20 GHz		
	[119]			✓	PIN diode	2D planar (square)							
	[121]	✓	PIN diode	1D micro-strip line	A coaxial feed Edge-fed	20 GHz							
	[118]	Multiple	Dual	✗	✗	2D planar (square)	Dielectric	Waveguide	A coaxial feed Bottom-fed	Slot-shaped radiating elements	25 GHz		
	[112]		Single	✗	✗		Semi-conductor		Multiple SIWs Edge-fed	94 GHz			
[113]	✓			Varactor	Dielectric		Surface wave		Multiple SIWs Edge-fed	CELC	10 GHz		
Others (Spoof SPPs) (OAM)	[127]	Single	Single	✗	✗	2D planar (circular)	Dielectric	Waveguide	A coaxial feed Bottom-fed	Periodic (rotated) metal strip lines	14 GHz		
	[123]	Multiple		✗	✗			Surface wave	A monopole Bottom-fed	C-shaped metallic units	60 GHz		

orthogonal frequency-division multiplexing (OFDM) modulation, etc.) to validate wireless transceiver capabilities. They measured 21.7dBi and 19.1dBi antenna gains at 2.3 GHz and 28.5 GHz, respectively. Afterwards, the work [175] adopted a 1100-element reflecting platform and presented a prototype of HMIMOS aided wireless communications working at 5.8 GHz. The indoor and outdoor field trials showed that more

than 26dB power gains were achieved. Live-streamed 1080p videos can be smoothly played under a 32 megabit-per-second transmission rate over a distance of 500m. In addition, the authors of [176], [177] integrated a 14×14 -element reflecting platform into an ambient backscattering communication system, in which they demonstrated a significant improvement on system performance. Moreover, the authors of [178] used

a 2430-element reflecting platform to form a real-world test-bed. The experiments were performed across two rooms with line-of-sight (LOS) channel between transmitter and receiver, where the experimental results showed that at least 15dB signal power enhancement was observed. Employing a 640-element omni-HMIMOS that is capable of signal reflection and refraction, the authors of [179] built a communication system prototype based on host computer and USRPs. The experiment results validated the full-dimensional communication capability of generating effective beams toward both sides of the omni-HMIMOS. From a more macroscopic perspective, the work [180] implemented an end-to-end interplay between user devices, HMIMOS, and the programmable-wireless-environments control system.

At the end of this section, we select representative studies and provide a summary table with respect to all mentioned physical aspects of HMIMOS for ease of reference. One can find from Table VI for details of each study.

IV. THEORETICAL FOUNDATIONS OF HMIMO COMMUNICATIONS

The enormous physical advances of HMIMOS provide the possibility in boosting the HMIMO communications into reality. However, the corresponding theoretical foundations of HMIMO communications remain to be unveiled. In particular, the channel model of HMIMO systems faces an underlying shift as the dense packing of nearly infinite small radiating elements and the large area deployments of HMIMOS apertures. The DOF (or number of communication modes) of HMIMO systems and the corresponding system capacity are fundamentally transformed. One of the most distinctive transformations is the shifting from the conventional digital-domain to the EM domain. The new domain opens new possibilities for wireless communications and also introduces new issues deserved to be extensively studied, such as EM field sampling and EM information theory. They will not only unveil the fundamental limits of HMIMO communications and facilitate the ultimate performance analysis on HMIMO systems, but also lay the foundation to develop critical enabling technologies. It is quite necessary to present recent advances on these areas. To this aim, we summarize in this section the existing theoretical studies on HMIMO communications with a particular emphasis on the channel modeling, DOF, system capacity, EM field sampling and EM information theory. We embrace each of the contents subsequently as follows.

A. Channel Modeling

According to the physical aspects of HMIMOS presented previously, the transceivers of HMIMO communications are physically implemented via HMIMOS covered with infinitely small radiating elements. They can be mathematically modeled as spatially continuous EM apertures, whereas their EM characteristics cannot be described as those of traditional discrete antenna arrays, but by the current distributions on the transceiving EM planes instead. The classic Rayleigh fading channel model, depicting the independently identical distribution of wireless channels, loses its applicability in

HMIMO communications due to the strong spatial correlations and mutual coupling among infinitely small radiating elements induced by their dense distributions. Another fundamental characteristic of HMIMO channels is revealed as the aperture size becomes large, thereby the communication distances fall within the Fresnel zone that leads to near-field communications. As such, the conventional far-field planar EM wave assumption is no longer valid. Fig. 11 illustrates the schematic of HMIMO communications for a point-to-point HMIMO system. The radiating EM wave is generated by a nearly continuous HMIMOS aperture capable of producing any current distribution. In electromagnetism, the spatial EM wave propagation from a radiating source can be divided into three regions, i.e., the reactive near-field region, the radiative near-field region and the far-field region. The EM components corresponding to each region behave differently. Typically, the amplitudes of EM components fall off as $\frac{1}{r}$, $\frac{1}{r^2}$ and $\frac{1}{r^3}$ in the far-field, the radiative near-field and the reactive near-field regions, respectively. To capture the essence of realistic physical channels, efficient and easy-to-handle channel modeling becomes a critical study area for HMIMO communications.

1) *Wavenumber Domain*: References [30], [181]–[183] proposed to model the HMIMO channel in wavenumber domain. The main idea is utilizing a finite number of sampling points of the wavenumber domain channel for reconstructing the HMIMO channel based on the Fourier expansion, as demonstrated in Fig. 11. Similar to the Fourier transform between the time and frequency domains, the relation between spatial and wavenumber domains is enabled by the Fourier transform as well, such that the spatial domain channel can be characterized by the Fourier transform of the wavenumber domain channel, expressed as [30], [182]

$$h(\mathbf{r}, \mathbf{s}) = \frac{1}{(2\pi)^2} \iiint \iiint a_r(\mathbf{k}, \mathbf{r}) H_a(k_x, k_y, \kappa_x, \kappa_y) a_s(\boldsymbol{\kappa}, \mathbf{s}) \times dk_x dk_y d\kappa_x d\kappa_y, \quad (17)$$

where $H_a(k_x, k_y, \kappa_x, \kappa_y)$ represents the wavenumber domain channel; $a_r(\mathbf{k}, \mathbf{r})$ denotes the receive wave vector; $a_s(\boldsymbol{\kappa}, \mathbf{s})$ reveals the transmit wave vector; and $h(\mathbf{r}, \mathbf{s})$ is the spatial domain channel. As seen from (17), the channel model mainly consists of three parts, namely the transmit wave vector, receive wave vector and the wavenumber domain channel. Therefore, modeling the spatial domain channel can be equivalent to an alternative modeling of the wavenumber domain channel, which is given by [30], [182]

$$H_a(k_x, k_y, \kappa_x, \kappa_y) = S^{\frac{1}{2}}(k_x, k_y, \kappa_x, \kappa_y) W(k_x, k_y, \kappa_x, \kappa_y), \quad (18)$$

where the wavenumber domain channel can be represented by the channel spectral density $S(k_x, k_y, \kappa_x, \kappa_y)$ which is irrelevant to the scattering environment that describes a non-line-of-sight (NLOS) channel, and the antenna arrangement; $W(k_x, k_y, \kappa_x, \kappa_y)$ involves the random characteristics of the channel. The wavenumber domain channel generally has a sparse structure, namely, a finite number of non-zero dominating coefficients. Based on sampling theory, the finite integration area can be sampled uniformly to approximate

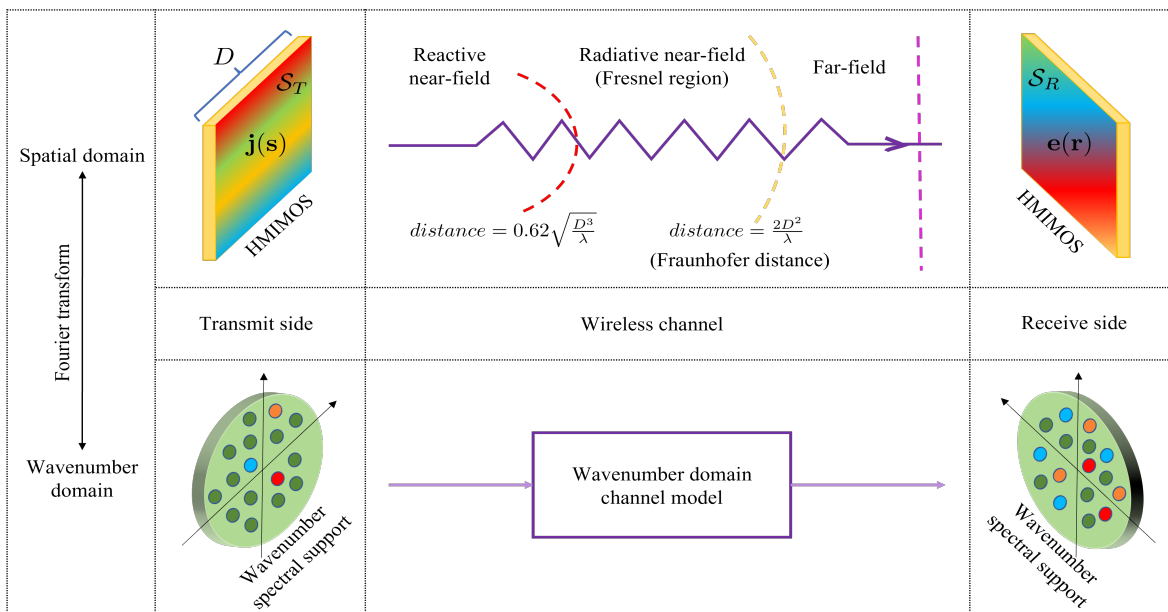


Fig. 11: Schematics of point-to-point HMIMO communications and wavenumber domain channel modeling.

the wavenumber channel domain. The channel approximation accuracy depends on the amount of sampling points. One can obtain a more accurate channel representation via generating more samples, leading to an increase in computational complexity. Based on the approximate wavenumber domain channel, the spatial domain channel can be obtained by taking the Fourier transformation. There are also some other related studies on the derivation of this modeling approach from electromagnetism, such as [184], [185].

2) *Spatial Domain*: In addition to channel modeling in the wavenumber domain, there are also channel modeling studies in the spatial domain. In [186], the authors proposed a spatial domain channel model for a uniform planar array (UPA) based mMIMO system communicating with UEs equipped with single-antenna. The modeling was mainly established based upon the conventional antenna array responses and the angular spread functions that describe multi-path energies and phase distributions. In particular, the study developed a spatial channel correlation model employing directional antennas in a non-isotropic scattering environment.

Reference [187] established a near-field channel model for HMIMO communications operating at THz frequencies and determining the response to incident signals in the radiating near-field using the EM theory. They further derived a closed-form expression on the path loss and beampattern for continuous HMIMOS, which is capable of characterizing the discrete counterpart. The closed-form expression accounting for the reflected electric field facilitates the determination of the received electric field, and also promotes the analysis on the beam focusing capability.

Reference [188] presented the modeling and performance analysis for uniform linear array (ULA) based extremely large-scale MIMO (XL-MIMO) systems based on the near-field spherical wavefront propagation model. The results showed that the receive SNR does not scale linearly with the number

of antennas, while increases with a diminishing return. As this number reaches infinity, the receive SNR tends to be constant. Furthermore, the authors suggested the “critical distance” concept to complement the classic Rayleigh distance that distinguishes near and far fields. Rayleigh distance usually concerns the amplitude difference and ignores the phase difference, while the critical distance considers both amplitude and phase that jointly impact channel condition. This distance definition is of great significance to practical applications. Finally, the authors found that the inter-UE interference can be mitigated not only by the angular separation, but also by the distance separation along the same direction. The channel modeling was later extended to a modular ULA system in [189] and to an UPA system in [190].

The work [191] developed a simple LOS channel model for a point-to-point HMIMO system, which is a special LOS case of [190]. This established channel model is consistent with that of classic mMIMO systems in LOS channels, which is convenient to conduct a fair comparison between HMIMO and mMIMO systems. The developed channel model was then later employed to unveil the power gain and spectral efficiency of a point-to-point HMIMO system. Starting from an EM perspective, the authors of [192] considered the channel modeling of a near-field multi-user HMIMO communication system where triple polarization is exploited. By means of dyadic Green’s function, the authors succeeded in building the channel model and validated its feasibility. Based on the established near-field channel model, two precoding schemes were proposed for mitigating cross-polarization and inter-use interference.

3) *Channel Statistic*: Beyond the channel model itself that is required for assisting signal communications, channel statistics, especially the second-order channel statistics, are also necessary and critical for many applications. For instance, the classic Kronecker channel model is characterized

TABLE VII: Channel modeling of HMIMO communications.

Channel modeling	Ref.	System model	Aperture type	Channel type	Main contributions
Wave-number domain	[181] [182]	Single UE BS: HMIMOS, UE: HMIMOS	Continuous planar surface, ULA, UPA	NLOS (Far-field)	Describe the 3D small-scale fading as a Fourier plane-wave spectral representation and present a discrete representation for EM field via Fourier plane-wave series expansion.
	[183] [30]	Single UE BS: HMIMOS, UE: HMIMOS	UPA	NLOS (Far-field)	Present a 4D plane-wave representation of channel response in arbitrary scattering and provide a low-rank semi-unitarily equivalent approximation of the spatial EM channel.
	[185]	Downlink multiple UEs BS: HMIMOS, UEs: HMIMOS	UPA	NLOS (Far-field)	Extend the 4D plane-wave representation of channel response in arbitrary scattering to the multi-user scenario, where each UE is equipped with an HMIMOS.
Spatial domain	[186]	Single UE BS: HMIMOS, UE: Single-antenna	UPA	NLOS (Far-field)	Provide a channel model for holographic mMIMO with the consideration of non-isotropic scattering and directive antennas
	[188] [189] [190]	Single/multiple UEs BS: XL-MIMO array UE: Single-antenna	ULA, UPA, continuous planar surface	LOS (Near-field)	Investigate channel modeling and performance analysis of XL-MIMO communications based on the generic spherical wavefront propagation model.
	[191]	Single UE BS: HMIMOS, UE: HMIMOS	Continuous planar surface	LOS (Near-/far-field)	Develop a simple channel model for LOS holographic-input holographic-output system, which is consistent with that for conventional LOS mMIMO systems.
	[192]	Downlink multiple UEs BS: HMIMOS, UE: HMIMOS	UPA	LOS (Near-field)	Establish a near-field LOS channel model based on the dyadic Green's function considering an utilization of triple polarization, and propose two precoding schemes.
Channel statistic	[186]	Single UE BS: HMIMOS, UE: Single-antenna	UPA	NLOS (Far-field)	Establish spatial channel correlation for holographic mMIMO with respect to non-isotropic scattering and directive antennas.
	[193]	Single UE BS: Single-antenna UE: XL-MIMO array	ULA	NLOS (Near-field)	Present an analysis on near-field spatial correlation with an emphasis on one-ring scatter distribution, including the far-field spatial correlation as a special case.
	[194] [195]	Single UE BS: λ , UE: RIS	UPA, quasi-continuous planar surface	NLOS (Near-/far-field)	Derive a 4D sinc function depicted joint small-scale spatial-temporal correlation model in isotropic scattering and extend it to an extra consideration of mutual coupling effect.

by the second-order channel statistics (i.e., spatial channel correlations), and many wireless applications [196]–[199] are facilitated based on the second-order statistics.

In order to derive an effective and accurate depiction on this information, reference [186] developed a spatial channel correlation model characterized based on antenna array responses and angular spread functions. As such, the spatial channel correlation model is then connected to array geometry and channel environment. According to the derived result and analysis of spatial correlation matrix, the authors presented a novel channel estimation approach without the full knowledge of such channel statistics.

Furthermore, the work [193] examined the near-field spatial correlation of an XL-MIMO, employing the non-uniform spherical wave characteristics. Therein, the near-field spatial correlation, depicted by power distribution of scatters, is relevant to both incident angles and scatters' distances. The authors derived an integral expression of spatial correlation to demonstrate the distance influence. The results revealed a non-stationarity of the spatial correlation.

Considering both spatial and temporal correlations, reference [194] investigated a joint spatial-temporal correlation model in the consideration of the isotropic scattering. This model is characterized by a four-dimensional (4D) sinc function, which can be simplified to the spatial-only correlation at any time instant that was later adopted for DOF analysis of an RIS-aided communication system. Later, the authors of [195] extended the spatial correlation analysis for a quasi-continuous aperture with a particular consideration of the mutual coupling effect.

For ease of reference, we list representative studies of channel modeling for HMIMO communications in a summary table, as demonstrated in Table VII.

B. Performance Analysis

1) *DOF*: The DOF represents the number of communication modes of EM fields which reveals how many independent data streams can be transmitted simultaneously by the wireless propagation media. It is capable of indicating the optimal communication of an HMIMO system and should be determined to fully understand the limitations. Since the mathematical modeling of HMIMO transceivers shifts from the conventional discrete antenna array to the continuous EM surface, and the far-field region tends to be near-field, the DOF of HMIMO systems is accordingly varying that needs to be examined. In the following contents, we list up-to-date research for DOF of HMIMO communications, show their considered scenarios, and present their main results.

Pioneer studies were conducted in [200], [201] for investigating the DOF of an LIS-based HMIMO system, where an LIS communicates with multiple single-antenna UEs in LOS channels. The authors derived that the DOF of such a system tends to be $\frac{2}{\lambda}$ per meter for UEs with 1D layout, and $\frac{\pi}{\lambda^2}$ per square meter for UEs designed in 2D and 3D layouts, where λ represents the wavelength.

Later, the studies [202], [203] explored the DOF of a point-to-point LIS-based HMIMO system, where an LIS communicates with a small intelligent surface (SIS) in arbitrary configurations, with a particular emphasis on the near-field communication. They contributed the optimal communication between LIS and SIS as an EM-level eigenfunction problem which is conventionally solved by time consuming and less instructive numerical computations, and then presented an approximate but accurate closed-form expression of the DOF that facilitates the computations and unveils underlying optimal communications. The obtained results indicated that the DOF of LOS channel is determined only by geometric factors normalized to the wavelength, and can be higher than 1. Exploiting the DOF for achieving optimal communications, references [204],

[205] proposed a beamspace modeling, describing generic orientations and near-field operating conditions, for defining the communication modes and determining its DOF, as well as deriving the closed-form basis set between transceivers that guarantees a near-optimal communication without complicated weights' configurations for precoding/combing and exhaustive numerical computations.

Conversely, the authors of [206] put an emphasis on a far-field isotropic scattering environment and analyzed the spatial DOF of a point-to-point HMIMO system. They examined the DOF for 1D linear, 2D planar and 3D volumetric apertures, respectively, based on the newly derived 4D Fourier plane-wave series expansion of the channel. The results provided a guideline of discrete radiating elements spacing to achieve the DOF, which is $\frac{\lambda}{2}$ for 1D apertures, and $\frac{\lambda}{\sqrt{\pi}}$ for 2D apertures. The work was then extended to a more general study on the relation between DOF and Nyquist sampling under arbitrary propagation conditions in [207]. This was performed by modeling the EM wave propagation to a corresponding linear system, for which multidimensional sampling theorem and Fourier theory are applied for analysis. The study showed that the DOF per unit of area is the Nyquist samples per square meter for large antenna surfaces. With further consideration in the presence of evanescent waves, reference [208] studied the spatial DOF for near-field HMIMO communications using the Fourier plane-wave series expansion. It mainly focused on the isotropic scattering environment while is capable of being extended to the non-isotropic case. The study revealed that the evanescent waves can be further exploited to add extra spatial DOF and increase the system capacity.

According to [194], the authors explored the DOF through a specially developed joint spatial-temporal correlation model for isotropic scattering environment. Therein, they noticed that the spatial DOF decreases with an increase of the number of antennas of HMIMO transceivers, which seems counter-intuitive. An additional explanation of this anomalous phenomenon was presented in [195] via utilizing the power spectrum of the spatial correlation function. With a particular emphasis on the existence of mutual coupling, this study presented an analysis on the effective spatial correlation as well as the eigenvalue structures of the spatial correlation matrix in terms of different radiating element intervals, by leveraging a specially designed metric that indicates the inter-element coupling strength. The corresponding results revealed the connection between eigenvalues and evanescent waves which are potentially beneficial for near-field communications.

2) *Capacity*: For the emerging communication systems of HMIMO, the intrinsic system capacity is key to investigate its potential. Since HMIMO exhibits strong mutual coupling effect due to numerous of radiating elements and behaves differently in near-field and far-field regions, therefore, the fundamental limits require to be uncovered and novel performance evaluation methods should be developed. In this regard, we overview the contemporary studies on capacities of HMIMO communications for demonstrating the recent progresses of this area. To be specific, we classify the advances based on different channel state, namely, capacity of LOS channel and capacity of channel with presence of NLOS. The details are

expanded as follows.

Capacity of LOS Channel: In this category, the LOS channel between HMIMO transceivers does not include any scatter that affects the wave propagation. Under this condition, references [200], [201] first presented pioneer studies on the system capacity of HMIMO communications implemented by LIS. Therein, the studies focused on the uplink system capacity for multiple single-antenna UEs experiencing LOS channels, where the capacities for UEs on line/plane shapes or in a cube shape were derived. The reference provided an asymptotic limit on the normalized capacity as the terminal density increases and the wavelength approaches zero, which was derived as $\frac{P}{2N_0}$ where P denotes the transmit power per volume unit and N_0 is the noise spatial power spectral density.

Another recent work [191] investigated the system capacity of a LOS point-to-point HMIMO system based on a dedicatedly developed channel model. The authors presented comparison results of HMIMO over conventional MIMO, indicating that the considered HMIMO system is capable of achieving up to π^2 times higher power gain than the conventional LOS MIMO system with a same surface area. This extra power induced by HMIMO system can interpreted to up to 3.30 bits/s/Hz spectral efficiency gain.

The authors of [209] studied the receive power for LIS enabled HMIMO downlink transmission communicating with single UE in an LOS environment. The investigation was proceeded by presenting a new mathematical communication model that captures system the impedance for both isotropic and planar antenna elements. The work was later extended to multiple single-antenna UEs in [210], where radiated and received powers were characterized by expressions derived using a circuital description of the LIS-based HMIMO system accounting for super-directivity and mutual coupling. With specially designed matched filter (MF) and weighted MMSE transmitters, the authors verified the variation of sum-rate in terms of radiating element spacing, ohmic losses, and mutual coupling among UEs.

In [211], the authors assessed the uplink spectral efficiency of an LIS communicating with two single-antenna UEs, with an emphasis on the near-field communication. They validated the uplink spectral efficiency using maximum ratio combining (MRC) and minimum mean squared error (MMSE) combining schemes, and showed that MMSE combining is superior to MR combining in achieving high spectral efficiency by mitigating the interference. The results indicated that channel estimation errors degrade MMSE fast. The study also demonstrated the impact of polarization mismatch on the spectral efficiency.

With a particular focus on the XL-MIMO system, the authors of [188] studied the receive SNR of an ULA BS enabled single/multi-user system under a LOS near-field environment depicted based on the spherical wavefront model. They derived the close-form expression of the receive SNR for optimal MRC and maximum ratio transmission (MRT), encompassing the conventional uniform plane wave assumption as a special case. The study was later extended to a modular ULA system in [189], and to an UPA system in [190] with a suggested unified modeling for discrete antenna array and continuous surface.

In addition to the previously theoretical analyzes on system

TABLE VIII: Performance analysis of HMIMO communications.

Performance analysis	Ref.	System model	Aperture type	Channel type	Main contributions
DOF	[200] [201]	Uplink multiple UEs BS: LIS, UE: Single-antenna	/	LOS (Near-/far-field)	Derive the DOF, harvested per meter deployed surface, for 1D linear, 2D planar, and 3D cubic terminal deployments.
	[202] [203]	Single UE BS: LIS, UE: LIS	Continuous planar surface	LOS (Near-field)	Derive the DOF as well as show it is only determined by geometric factors and is larger than 1 in near-field region.
	[204] [205]	Single UE BS: LIS, UE: SIS	ULA	LOS (Near-field)	Propose a beamspace modeling that defines the communication modes and determines the DOF.
	[206]	Single UE BS: HMIMOS, UE: HMIMOS	ULA, UPA	NLOS (Far-field)	Investigate the DOF based on the 4D Fourier plane-wave series expansion of the HMIMO channel.
	[207]	Single UE BS: HMIMOS, UE: HMIMOS	/	/	Study the relation between DOF of HMIMO system and Nyquist sampling.
	[208]	Single UE BS: HMIMOS, UE: HMIMOS	UPA	NLOS (Near-field)	Reveal that evanescent waves can be exploited to increase extra spatial DOF.
	[194] [195]	Single UE BS: X, UE: RIS	UPA, quasi-continuous planar surface	NLOS (Near-/far-field)	Study the DOF with and without the presence of mutual coupling effect.
Capacity	[200] [201]	Uplink multiple UEs BS: LIS, UE: Single-antenna	/	LOS (Near-/far-field)	Derive capacity for 1D, 2D and 3D terminal deployments, as well as present the asymptotic limit of normalized capacity.
	[191]	Single UE BS: HMIMOS, UE: HMIMOS	Continuous planar surface	LOS (Near-/far-field)	Compare current LOS holographic-input holographic-output system with conventional LOS MIMO systems in terms of capacity and power gain.
	[209]	Single UE BS: LIS, UE: Single-antenna	UPA	LOS (Near-field)	Analyze receive power based on a designed mathematical communication model that depicts the mutual coupling of radiating elements.
	[210]	Downlink multiple UEs BS: LIS, UE: Single-antenna	UPA	LOS (Near-field)	Examine receive power by a circuitual description of the system, and evaluate sum-rate with respect to antenna spacing, ohmic losses, and inter-UE mutual coupling.
	[211]	Uplink two UEs BS: LIS, UE: Single-antenna	UPA	LOS (Near-/far-field)	Assess uplink spectral efficiency using MRC and MMSE combing schemes in the near-field region.
	[188] [189] [190]	Single/multiple UEs BS: XL-MIMO arrays UE: Single-antenna	ULA, UPA, continuous planar surface	LOS (Near-field)	Investigate the receive SNR of XL-MIMO systems based on the generic spherical wavefront propagation model.
	[212]	Single UE BS: LIS, UE: single-antenna	UPA	LOS (Near-/far-field)	Analyze the effect of hardware impairments on the achievable rate using a simplified receiver structure.
	[213]	Downlink multiple UEs BS: RHS, UE: Single-antenna	UPA	LOS (Far-field)	Study the effect of quantization on the sum-rate and present a lower bound in terms of quantization.
	[183] [30]	Single UE BS: HMIMOS, UE: HMIMOS	UPA	NLOS (Far-field)	Evaluate the capacity of a point-to-point HMIMO system based on the built 4D Fourier plane wave representation of the channel model.
	[185]	Downlink multiple UEs BS: HMIMOS, UEs: HMIMOS	UPA	NLOS (Far-field)	Study system capacity using MRT and ZF precoding schemes based on the 4D Fourier plane wave representation of HMIMO channel for multiple UEs.
	[214] [215]	Uplink/Downlink multiple UEs BS: DMA, UE: Single-antenna	UPA	NLOS	Study uplink and downlink capacities of DMA-based HMIMO system based on a specially designed mathematical model of DMA.
	[216]	Uplink multiple UEs BS: LIS, UE: Single-antenna	UPA	NLOS (Far-field)	Asymptotically analyze uplink data rate under channel estimation errors, interference channels, and hardware impairments.
	[217]	Uplink multicell multiple UEs BS: LIS, UE: Single-antenna	UPA	NLOS (Far-field)	Evaluate the spectral efficiency of a multi-LIS multicell system in presence of pilot contamination, and derive an asymptotic bound.

capacity, reference [212] studied the achievable rate of a receiving LIS system in the present of correlated hardware impairments. It modeled the correlation by means of distance between considered points on the LIS surface, based on which the closed-form expression of the achievable rate was derived. Reference [213] examined how quantization of an amplitude controlled reconfigurable holographic surfaces (RHSs) impacts the sum-rate of a downlink RHS-assisted multi-user system. They presented a lower bound of the sum-rate in terms of the quantization, and unveiled the required minimum quantized bits accordingly.

Capacity with presence of NLOS Channel: In this category, the channel between HMIMO transceivers includes scatters that influence the wave propagation. To present an exact depiction from an EM perspective, references [30], [183] investigated the system capacity of a point-to-point HMIMO system based on the 4D Fourier plane wave representation of HMIMO channels with arbitrary spatially-stationary scattering. Particularly, instead of using the conventional spatial domain channel model, the wavenumber domain channel was established to capture the essence of the physical channel and

used to evaluate the system capacity for rectangular volumetric arrays. Based on this basis, the authors of [185] extended the Fourier plan wave representation of HMIMO channels to the scenario including multiple UEs with each equipped by an HMIMOS, based on which they investigated the system capacity using the MRT and zero-forcing (ZF) precoding schemes, respectively. The study revealed that large spectral efficiency can be achieved by packing more radiating elements on HMIMO transceivers. Moreover, as spaces among antennas reduced, strong mutual coupling reduces the spectral efficiency under a fixed number of radiating elements.

By characterizing multi-path channel model using a linear filter characterized by multiple channel tips, the authors of [214] and [215] studied the uplink and the downlink system capacities of an HMIMO system, respectively, in which a dynamic metasurface (DMA) implemented BS communicates with multiple single-antenna UEs. The authors derived the uplink/downlink capacities based on a specifically designed mathematical model of the DMA. They unveiled the fundamental limits under different weight configurations of DMA.

Moreover, the authors of [216] analyzed the uplink data rate

for an LIS based HMIMO system in an asymptotic manner. They assumed an LOS desired channel interfered by spatially correlated Rician fading channels. In particular, the study put an emphasis on a practical scenario where channel estimation errors, interference channels, and hardware impairments are considered. Under these settings, the theoretical bound was presented, which demonstrates that the noise, interference from estimation error, hardware impairments, as well as the NLOS paths can be eliminated with the increase of antennas. Later, the work [217] evaluated the spectral efficiency of a multi-LIS system in the presence of pilot contamination. The authors derived its theoretical bound asymptotically, which can be utilized for determining pilot training length and number of UEs. The study suggested that the system spectral efficiency is limited by the pilot contamination as well as both inter and intra-LIS LOS interference no matter how large the number of antennas become.

Lastly, to provide a panoramic view of performance analysis, we sum up related studies to a summary table, as demonstrated in Table VIII.

C. EM Field Sampling

Since EM waves modulated by HMIMO are continuous in space, they have to be sampled and discretized for digital processing, which is related to the sampling of spatial EM field aiming at retaining the maximum EM information with the minimum samples.

Preliminary explorations of EM field sampling was carried out in [218] [219], investigating the non-redundant representation of spatially continuous EM fields using a limited number of samples. A recent study on EM field sampling for LIS-based HMIMO system was conducted in [201]. For a LOS uplink LIS-based BS serving multiple single-antenna UEs, the authors showed that the hexagonal sampling lattice is capable of optimally minimizing the surface area while retaining one independent signal dimension for each spent antenna. The authors in [207] further investigated EM propagation characteristics in different scenarios with planar HMIMOS. The optimal Nyquist sampling theorem in the spatial domain and the spatial DOF were derived accordingly. It is concluded that sampling at the Nyquist rate allows to fully capture DOF of EM field with minimum number of samples. Specifically, the authors demonstrated the redundancy of conventional half a wavelength interval sampling approach. Based on this observation, the authors extended the proposed spatial domain Nyquist sampling to the non-isotropic scattering environment, and made a preliminary design of the Nyquist sampling matrix for the complex environment to derive sampling efficiency. Employing prior knowledge of the scattering conditions, they derived an elongated hexagonal sampling structure for achieving an efficient representation. The results revealed that a reduction of 13% samples per square meter is realized compared to half a wavelength sampling for isotropic propagation, and more sample reduction is expected for non-isotropic propagation.

D. EM Information Theory

EM information theory is an interdisciplinary framework to evaluate the fundamental limits of wireless communications

with a fusion of EM wave theory and information theory. The conventional information theory is typically adopted in far-field assumption, however, as communication frequency and array size increase significantly in future communications, the near-field range dependent of antenna arrays in EM theory is dominant, which motivates EM information theory that takes into account the near-field effects.

1) *Near-Field Communications for HMIMO*: Since the future 6G communications incorporate large size HMIMO arrays and millimeter wave/terahertz communication frequencies, the near-field regime becomes the main applicable scenario. A widely adopted metric to determine the boundary between the far-field and near-field regions is the Rayleigh distance, also known as the Fraunhofer distance [220]. Specifically, the area larger than the Rayleigh distance is defined as the far-field region, where the impinging EM waves can be approximated as plane waves. Conversely, the area smaller than Rayleigh distance is defined as the near-field region, where the plane waves approximation is not applicable any more. In this regime, the emitted EM waves are modeled as spherical waves [220], which poses challenges to the conventional communication architecture, such as tractable channel modeling and theoretical performance analysis.

The primary challenge comes from the nonlinear phase embedded in near-field communications. Specifically, in the near-field region, the physical geometry of each path seriously influences phase information, which is exactly the difference in near-field and far-field modeling [221]. Only through the combination of distance information and phase variants, the effective techniques can achieve favorable performance gain in near-field region, such as the beam focusing and energy enhancement. Secondly, the conventional theoretical validation is not applicable to near-field communications. For example, it has been proved that the SNR grows linearly with the number of antenna array elements N in mMIMO transceivers and half-duplex relay systems. However, [222] proved that this power scaling holds only in far-field regime and tapers off in near-field region. Thirdly, spatial broadband effect occurs in near-field results in unsynchronized reception and high frequency selection [223]. This effect deteriorates with the increase in communication frequency and antenna aperture, resulting in serious time delay and phase shifts.

Therefore, near-field wireless communications require novel techniques in analysis and applications. In [193] the authors investigated the near-field spatial correlation of a large-scale antenna array adopting non-uniform spherical wave representation, and a novel integral expression to characterize near-field spatial correlation that generalized the conventional far-field case was proposed. [224] specifically investigated beam focusing techniques in near-field to achieve significant rate improvement and reliable communications among UEs in the same angular direction simultaneously, which is not feasible in far-field beam focusing techniques. [225] designed phase shifts to flatten the beam focusing gain across frequencies and mitigate the near-field beam splitting effect. [223] also proposed a phase-delayed focusing method to overcome spatial broadband effect.

However, the above techniques are mainly adopted in con-

TABLE IX: EM field sampling and EM information theory.

Theoretical aspects	Ref.	System model	Aperture type	Channel type	Main contributions
EM field sampling	[201]	Uplink multiple UEs BS: LIS, UE: Single-antenna	/	LOS (Near-/far-field)	Analyze the optimal sampling lattice for LIS design and show that the hexagonal sampling lattice minimizes the surface area optimally under some constraint.
	[207]	Single UE BS: HMIMOS, UE: HMIMOS	/	/	Present the optimal Nyquist sampling in spatial domain, and design efficient sampling structure that captures the EM field.
EM information theory	[193]	Single UE BS: Single-antenna, UE: XL-MIMO arrays	ULA	NLOS (Near-field)	Investigate near-field spatial correlation in the presence of arbitrary scatters for mMIMO systems using non-uniform spherical wave model.
	[224]	Downlink multiple UEs BS: MIMO, UE: Single-antenna	UPA	LOS (Near-field)	Investigate beam focusing in near-field communications and design different configurations for corresponding antenna structures.
	[221]	Uplink multiple UEs BS: Metasurface antenna, UE: Single-antenna	UPA	NLOS (Near-field)	To address near-field and dual-wideband effect, a channel model including both effects is developed, and an HMIMO-aided uplink beam combining algorithm is proposed.
	[205]	Single UE BS: LIS, UE: SIS	ULA	LOS (Near-field)	Propose focusing function to design the current distribution on the surface of the HMIMO array and deriving received electric field expression in near-field communication scenario
	[226]	Single UE BS: XL-MIMO arrays, UE: Single-antenna	ULA	NLOS (Hybrid-field)	Develop hybrid-field communication channel model, study a hybrid channel estimation problem, and suggest a corresponding approach.

ventional antenna arrays, which suffer from costly hardware design or other drawbacks. Fortunately, the intelligent processing of EM waves in HMIMO opens up opportunities to achieve better performance including higher spectral efficiency and superior beam focusing at lower cost. A few of works focused on the application of HMIMO in near-field. For example, [221] first proposed a near-field channel model and designed an HMIMO-assisted beam combining algorithm that effectively reduces the rate loss due to the non-ideal near-field effect, resulting in a higher sum-rate compared to the conventional framework. In particular, the authors demonstrated that the sum-rate performance of the proposed system is almost unaffected by mutual coupling, even when the antenna interval is sub-wavelength, which is commonly adopted in HMIMO scenarios.

2) *Hybrid-Field Communications for HMIMO*: Another feasible communication scenario in HMIMO communications is the hybrid-field case. As mentioned before, with the boost of HMIMO aperture and frequency, the traditional far-field assumption is no longer viable. However, the near-field assumption may also not be practicable as well. To be specific, the HMIMO array aperture at the transmitter side of BS can be relatively large in practical deployment, but the aperture at UE side is limited, resulting in constrained array size. Therefore, from the perspective of transmitter side, UEs are located within its near-field range that the spherical wave representation should be considered, while for UEs, the transmitter is positioned in its far-field area where the plane wave assumption holds. This was also mentioned in [205], i.e., the transmitter is much larger than each receiver at UEs, thus, the transmitter is located in far-field region of UEs while the UE is located in near-field region of the transmitter. Under such circumstance, both near-field and far-field coexists, i.e., the hybrid field communications appears. Hybrid-field communications triggers a natural question: is it possible to analyze both near-field and far-field in the same manner? Surprisingly, the answer is yes. Although the near-field and far-field communications possess distinct characteristics, these two fields still show some common traits to be investigated using the comparable techniques. For example, the polar domain channel characterized

by polar angles and radial distance is applicable to both near- and far- fields, which motivates the further investigation of hybrid field communications for HMIMO. Reference [226] revealed the possible hybrid field characteristics for HMIMO arrays, i.e., some scatters far away from the BS are in far-field region instead of near-field any more, while those scatters relatively close to the BS are actually in near-field region, thus the mixed field channel is generated considering both conventional far-field and near-field path components.

In the final of this section, we present a summary table in Table IX, encompassing relevant studies of EM field sampling and EM information theory.

V. ENABLING TECHNOLOGIES OF HMIMO COMMUNICATIONS

Since HMIMOS only provide a basic physical entity in implementing HMIMO communications, it is necessary to develop corresponding physical-layer enabling technologies to drive HMIMOS for approaching the fundamental limits of HMIMO communications. To this purpose, critical physical-layer technologies, such as channel estimation, and beamforming in holographic settings, are especially of significant. However, designing these enabling technologies encounters fundamental differences compared to those designs in conventional mMIMO communication systems. The differences mainly come from the revolution of HMIMOS over mMIMO in following aspects.

Firstly, the hardware and working mechanism of HMIMOS, as shown in Section II-B, Section III and Section VI-A, are totally different from that of mMIMO arrays. This will inevitably cause a distinct mathematical model for depicting the working process of HMIMOS, and will also introduce different practical constraints. Different mathematical model and practical constraints will significantly affect the designs for enabling technologies. Secondly, the approximately continuous aperture of HMIMOS, covered by uncountable infinite small radiating elements, opens up the possibility to direct manipulate EM waves by generating any arbitrary current distribution in a holographic mean. It will enable the conventional digital signal processing to be processed in EM domain. As such,

conventional signal processing for mMIMO will suffer from an ultra-high computational complexity due to the massive number of radiating elements. In addition, mutual coupling, mitigated in mMIMO arrays, is unavoidable emerged due to the ultra-dense distribution of radiating elements. Conventional transceiver designs will be invalid, thereby mutual coupling should be considered in enabling technologies designs for HMIMO communications. Lastly, the low power consumption and low-cost characteristics of HMIMOS facilitate fabrication of large area continuous apertures, allowing transceivers communicating in near-field region. Not only the angle information but also the distance information between transceivers can be exploited to assist near-field communications, which is far away from the conventional far-field assumption that is the basis in designing enabling technologies for mMIMO communication systems.

In overall, the new features bring significant differences in designing enabling technologies for HMIMO communications, compared with previously designed physical-layer technologies for mMIMO communications. This poses many challenges, while at the same time, also motivates new technology designs. In the following of this section, we focus on newly emerged enabling technologies of HMIMO communications, with a particular emphasis on holographic channel estimation, and holographic beamforming/beam focusing.

A. Holographic Channel Estimation

Similar to channel estimation in conventional mMIMO communication systems, it is also required in HMIMO communication systems for accurate decoding and recovery of the transmitted signal at the receiver end. At the same time, HMIMO channel estimation is more complicated than the traditional discrete uncorrelated antenna array scenario because in HMIMO, the transceiver is mathematically modeled as a continuous EM surface with inter-element coupling. Conventional estimation methods based on pilot transmission lead to unacceptably large overhead and the far-field assumption usually assumed in wireless systems till now, does not necessarily apply for HMIMO due to the size of the surfaces.

Early work by the authors in [227], introduced an LIS in a wireless communication system which consists of a BS and a UE, formulated the constrained channel estimation (CE) optimization problem and developed a Lagrange multiplier and dual ascent-based estimation scheme to solve the problem and obtain the closed-form expression for the combined channel parameters iteratively. Cramér-Rao lower bounds (CRLBs) were computed and numerical results compared this technique with least-squares (LS) in low SNR. In order to compensate for the fact that passive intelligent metasurfaces have no signal processing capabilities, [228] developed a cascaded channel estimation technique for the large intelligent metasurface-assisted mMIMO system comprising a two-stage algorithm that includes the generalized bilinear message passing for matrix factorization and the Riemannian manifold gradient-based algorithm for matrix completion. [229] proposed a convolutional neural network (CNN)-based image denoising architecture, called denoising CNN, for estimating the direct

and cascaded channel in a LIS-assisted MISO communication system and showed its performance gains over the simple LS.

The nature of HMIMOS apertures, consisting of a large number of unit elements, densely spaced, which require large amounts of time to be trained, imposes a severe CE overhead. [230] studied the achievable rate of an LIS-assisted single-input single-output communication system for an increasing number of elements, accounting for the pilot overhead of an LS channel estimator. Compressed sensing (CS) methods have been employed to reduce the CE training periods. The authors of [231], have developed a method to estimate a broadband, THz, mMIMO channel with holographic RIS. It comprises two-stages, a downlink coarse grouping and a finer-grain CS-based uplink stage that exploits the sparsity of the THz MIMO channel in the angular and delay domains. They derived the beam pattern for a holographic RIS and showed that the beam pattern of an ideal holographic RIS can be approximated by that of an ultra-dense RIS. [61] employed an LIS with the majority of its elements being passive and a few randomly distributed active elements. This architecture enabled the developments of a CS tool to construct the channels at all the antenna elements from the sampled channels seen only at the active elements as well as a deep learning tool to learn how to predict the optimal LIS reflection matrices directly from the sampled channel knowledge, which represents what we call environment descriptors.

CS algorithms exploiting channel sparsity in the angular domain rely on far-field channel models whereas for HMIMO apertures which are large in physical size, the near-field region, where the angle domain is not sparse, appears to be dominant. In [232], [233], the angle domain is replaced by the polar domain, in which both far- and near-field are sparse. A polar-domain simultaneous orthogonal matching pursuit algorithm is proposed for the near-field CE. In order to tackle the HMIMO near-field CE, [234], implemented a subarray-wise CS-based CE method and a scatterer-wise method to explore the near-field non-stationary channel. The multipath channel is modeled with the last-hop scatterers under a spherical wavefront and the large aperture array is divided into multiple subarrays. Numerical results demonstrate that the subarray-wise method can achieve an excellent mean square error performance with low complexity, whereas the scatterer-wise method can accurately position the scatterers and determine the non-stationary channel.

[226] proposes a hybrid far- and near-field channel for XL-MIMO, where some scatterers are in the far-field and some in the near-field. The hybrid-field CE scheme deployed, individually exploits the channel sparsity of its far- and near-field components in the angular and polar domains respectively.

In [235], the authors propose a channel estimation scheme based on a parametric physical channel model for LOS dominated communication in mmWave and THz wave bands. The proposed channel estimation scheme exploits the specific structure of the radiated beams generated by the continuous surface to estimate the channel parameters in a dominated LOS channel model. It considers both the far-field and near-field regions by partitioning the continuous aperture into tiles for which the far-field assumption holds. It is numerically

TABLE X: Holographic channel estimation.

Ref.	Uplink/ downlink	Aperture type	Channel type	CE approach	Main contributions
[227]	Downlink	/	NLOS (Far-field)	Lagrange multiplier, dual ascent method	Present Lagrange multiplier and dual ascent-based estimation scheme and obtain the closed-form expression for the combined channel parameters iteratively.
[228]	Downlink	ULA	NLOS (Far-field)	Sparse matrix factorization, matrix completion	Estimate cascaded channel for large intelligent metasurface-aided mMIMO systems.
[229]	Uplink	/	NLOS (Far-field)	CNN-based non- linear channel estimator	Estimate direct and cascaded channel in an LIS-aided MISO communication system.
[230]	Uplink	/	NLOS (Far-field)	LS estimator	Investigate the number of LIS elements that maximizes the average achievable rate.
[231]	Downlink /uplink	UPA, continuous planar surface	LOS/NLOS (Far-field)	CS-based method	Two-stage CE, a downlink coarse grouping and a finer-grain CS-based uplink stage that exploits the sparsity of the THz MIMO channel in angular and delay domains.
[61]	Downlink	UPA	NLOS (Far-field)	CS-/deep learning- based methods	Constructs the channels at all the antenna elements from the sampled channels seen only at the active elements and learns how to predict the optimal LIS reflection matrices directly from the sampled channel knowledge.
[232] [233]	Uplink	ULA	NLOS (Near-field)	CS-based method	Near-field channel estimation by exploiting the polar-domain sparsity.
[234]	Uplink	ULA	NLOS (Near-field)	Subarray-/scatterer-wise CS-based methods	The multipath channel is modeled with the last-hop scatterers under a spherical wavefront and the large aperture array is divided into multiple subarrays.
[226]	Downlink	ULA	NLOS (Hybrid-field)	CS-based method	The hybrid-field CE scheme deployed, individually exploits channel sparsity of its far- and near-field components in the angular and polar domains.
[235]	Uplink	UPA, continuous planar surface	LOS (Near-/far-field)	Parametric model based method	Channel estimation scheme based on a parametric physical channel model for LOS dominated communications in mmWave and THz wave bands.
[186]	Uplink	UPA	NLOS (Far-field)	Array geometric information- aided subspace method	Provide a spatial channel correlation model and suggest an array geometric information aided subspace CE approach.

demonstrated that the proposed estimation scheme significantly outperforms other benchmark schemes under poor scattering.

[186] argues that with the large number, closely deployed unit elements of the HMIMO surface, the rank of the spatial correlation matrix needed for MMSE channel estimation, decreases. Instead, an LS estimator that also exploits the array geometry to identify a subspace of reduced rank that covers the eigenspace of any spatial correlation matrix. The proposed estimator outperforms the LS estimator, without using any user-specific channel statistics.

Lastly, we list relevant studies of holographic channel estimation in Table X for ease of reference.

B. Holographic Beamforming and Beam Focusing

The approximately continuous aperture of HMIMOS, where the spacing of radiating elements tends to be much less than half a wavelength, facilitates the capabilities in achieving both higher spatial resolution and stronger EM wave operability compared with conventional discrete antenna arrays. In addition, the continuous aperture is likely to become large, which opens up the opportunity of near-field communications, in which an extra distance dimension is introduced for assisting communications on the basis of the conventional angle dimension. With those fundamental changes, the traditional beamforming technologies are facing a transformation from the conventional angle-dependent manner to the holographic joint distance-angle fashion. Alternatively, conventional beamforming, only achieving the angular level of energy focus, namely, the transmitted energy is focused to a certain transmitting angle, will potentially shift to the near-field holographic beam focusing, capable of realizing precise location energy focus exploiting both distance and angle information. In the subsequent contents of this subsection, we will present recent

advances on holographic beamforming and beam focusing with a macroscopic classification as follows.

1) *DMA Input-Output Response Based Work*: In this group, the most past studies are performed on the basis of the input-output response model of a DMA, one of the typical HMI-MOS that can be utilized for realizing DMA-based HMIMO communication systems. Fig. 12 presents a demonstration on the receive modeling of the input-output response of a microstrip line of DMA. Each radiating element corresponds a tuning weight, and the input signal corresponding to each radiating element propagates along the microstrip line together with other signals. This propagation is modeled via a linear multi-tap filter. Using the established input-output response model, intended holographic beamforming/beam focusing can be implemented by properly configuring the DMA weights.

To this aim, [215] and [214] first formulated a mathematical model for DMA-based mMIMO systems and designed efficient alternating optimization (AO) algorithms to dynamically configure the DMA weights for the achievable sum-rate maximization in the uplink and downlink case, respectively. The AO algorithms were designed by approaching an optimally derived unconstrained configuration, based on which DMA weights with practical constraints can be obtained. Later, both [236] and [237] extended the use of DMAs in wideband setups, such as OFDM systems, using low resolution analog-to-digital converters (ADCs) by jointly optimizing the DMA weights along with the dynamic range of the ADCs and the digital processing, under a given bit constraint. Employing a different optimization object, [238] studied the energy efficiency maximization problem in single-cell multi-user mMIMO systems, by jointly optimizing transmit precoding matrices of UEs and DMA weights of the BS, based on Dinkelbach's transform and AO method. This effort was later extended in [239] for further exploiting both instantaneous and statistical channel state information (CSI) in designing the joint transmit precoding

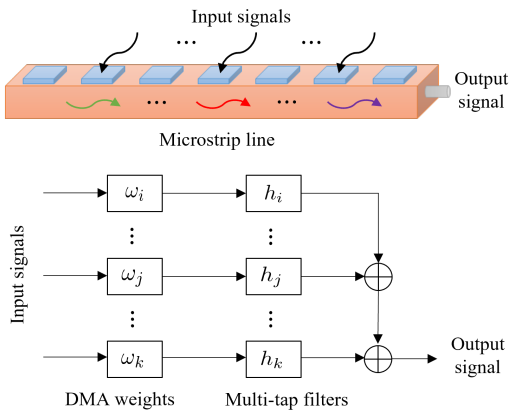


Fig. 12: Modeling of the input-output response of a microstrip line of DMA (take the receive side as an example).

and DMA weights.

With a particular focus on the beam focusing in near-field scenario, a mathematical model for DMA-based near-field multi-user MIMO systems was proposed in [240], incorporating both the feasible processing of DMAs as well as the propagation of the transmitted EM waves in near-field wireless communications. Then, the joint optimization of the DMA weights dictating its transmission pattern, and the digital precoding vector was considered, in order to maximize the sum-rate when operating in near-field, while accounting for the specific Lorentzian-form response of metamaterial elements. Moreover, exploiting the great potential of beam focusing in near-field wireless power transfer (WPT), [241] presented a mathematical model for DMA-based radiating near-field WPT systems, characterized the weighted sum-harvested energy maximization problem of the considered system, and proposed an efficient solution to jointly design the DMA weights and digital precoding vector. Lastly, in [221], an algorithmic framework was proposed to design the beam combining for the near-field wideband holographic metasurface antennas (HMA)-assisted XL-MIMO uplink transmissions based on a spherical wave-based channel model that simultaneously takes into account both the near-field and dual-wideband effects. The HMA-based beam combining problem was first formulated, which is challenging due to the nonlinear coupling of high dimensional HMA weights and baseband combiners, and then a sum-mean-square-error minimization-based algorithmic framework was developed.

2) *Mutual Coupling Based Work*: This group mainly describes a specific classification of recent studies that focus on characterizing mutual coupling mathematically, examining its influence, and further exploiting it for achieving super-directivity based on coupling-aware transceiver designs. Fig. 13 shows a circuit modeling of a multi-port network consisting of a transmitter and multiple receivers. It depicts the connection between voltage and current by means of impedance which captures the mutual coupling of radiating elements, the mutual coupling of UEs and also the propagation effects.

Reference [209] first focused on the single user downlink LIS communication scenario and studied two models for the

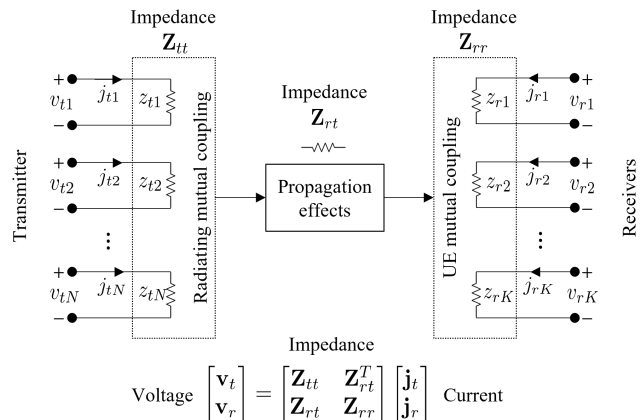


Fig. 13: Circuit model of a multi-port network consisting of a transmitter and multiple receivers.

LIS: one based on a discrete model with isotropic antennas and one that is a collection of closely spaced planar antenna elements. For both models, the expression for the mutual coupling was derived and the precoding vector from the coupling-aware MF was provided. The coupling-aware precoding showed that the super-directivity can be potentially achieved as the spacing of radiating elements becoming small. Later, [210] investigated the LIS-based multi-user MIMO communication scenario taking into account mutual coupling, super-directivity and near-field effects. The LIS design was based on the infinitesimal dipoles and two coupling-aware transmission schemes were proposed: MF and WMMSE under practical limitations, such as the limited radiated power and existence of ohmic losses. The authors showed that those practical limitations cannot be neglected in achieving the super-directivity. Following this direction, another recent work [242] proposed a coupling-aware beamforming scheme for achieving the super-directivity of a nearly continuous surface. They further presented how to obtain the coupling matrix which is used for coupling-aware beamforming.

3) *Holographic Principle Based Work*: This group encompasses recent studies of holographic beamforming under the guidance of holographic principle as demonstrated previously in *Holographic LWA based EM Holography* in Section II-B. As shown in Fig. 14, reference waves, loaded by RF chains, propagate along the substrate and thus excite each radiating element with a specific weight to finally form intended object waves. The weights are amplitude-controlled and tuned based on the interference pattern. Based on this model, representative studies are listed as follows.

In [243], an RHS-assisted wideband OFDM downlink single-user scenario with frequency selective channels was considered, focusing on the achievable data rate maximization problem by jointly optimizing the digital and the holographic beamforming, respectively, according to an amplitude control optimization algorithm. An interference pattern multiplexing based scheme was developed to diminish the beam squint issue arising from the frequency selectivity. Subsequently, [244] introduced an iterative joint optimization algorithm for the digital beamforming at the BS and the holographic

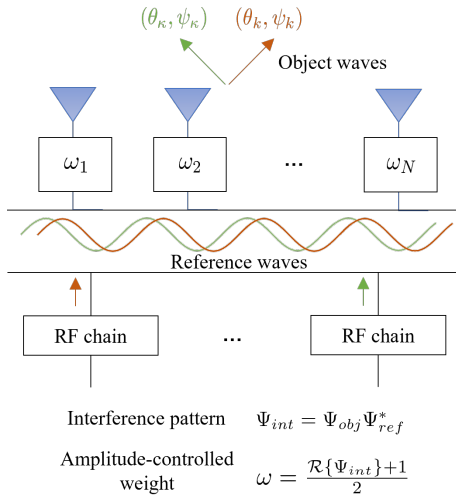


Fig. 14: Holographic principle guided transmissions (take the transmit side as an example).

beamforming at the RHS for a downlink multi-user scenario, aiming to maximize the achievable sum-rate. In order to handle the resulting complex-domain optimization problem subject to unconventional real-domain amplitude constraints, coupled with the superposition of the radiation waves from different radiation elements as well as the overall coupling between the radiation elements simultaneously with the propagating surface, the closed-form optimal holographic beamforming scheme was also derived. By simulation results it was shown that the RHS was capable of accurate beam-steering with low side-lobes. In addition, [245] proposed a joint beamforming optimization technique to maximize the sum-rate in an RHS-assisted downlink multi-user communication system. Specifically, an AO algorithm solving the digital beamforming sub-problem at the BS by ZF beamforming with power allocation, the holographic beamforming sub-problem at the RHS via fractional programming, and the receive combining sub-problem at the UEs by a coordinate ascent approach, was developed. Lastly, [246] proposed a new type of space-division multiple access, called holographic-pattern division multiple access (HDMA) along with a multi-user holographic beamforming scheme for HDMA. Theoretical analysis resulted in an optimal holographic beam pattern through which the sum-rate with simple ZF precoding can achieve the asymptotic capacity of the HDMA system.

In addition, [247] extended the work to satellite communications. An uplink RHS-aided communication system comprising one UE and multiple low-earth-orbit (LEO) satellites was considered and a sum-rate maximization problem was formulated. ZF digital beamforming was applied at the UE and holographic beamforming was optimized at the RHS via dynamic programming. The satellites' positions were predicted according to the temporal variation law. Simulation results showed the superiority of the RHS-aided system compared to the traditional phased antennas in terms of the achieved sum-rate as well as the cost, and proved the technique's robustness against tracking errors of the satellites' positions. Furthermore, the authors of [248] formulated an integrated sensing

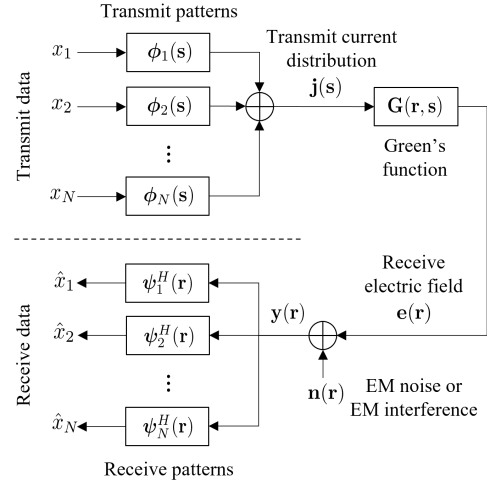


Fig. 15: EM level modeling of point-to-point HMIMO communications.

and communication problem in an RHS-assisted scenario for simultaneously detecting multiple radar targets and serving multiple UEs. The beamforming gains towards the directions of the targets were maximized, minimizing in parallel the cross-correlation among these directions with an iterative algorithm. Theoretical analysis for the maximum beamforming gain lower bound was conducted and simulation results revealed the superiority of the holographic beamforming scheme over traditional MIMO systems.

4) *EM Level Model Based Work*: Beyond above mentioned groups of mathematical model spurred studies, another branch, aiming to modeling the communication system in an EM level, is emerged. Fig. 15 exhibits an EM level modeling of point-to-point HMIMO communications, where the transmit data are carried by dedicated transmit patterns, and the transmit current distribution is generated accordingly. At the receive end, electric field can be captured and further used to decode the data by means of receive patterns. Based on this EM level model, it is possible to design dedicated patterns, capable of generating any current distributions for a continuous HMIMOS, for maximizing the communication performance from an EM perspective. The patterns can be also interpreted as basis functions as described in [33]. Based on this EM level model, emerging studies are listed as follows.

Firstly, [31] built an EM level transmission model for a point-to-point HMIMO communication system, and analyzed the optimal pattern achieved in specific conditions. Furthermore, to provide a simple and practical pattern design, it introduced a suboptimal wavenumber-division multiplexing (WDM) scheme for LOS HMIMO, inspired by OFDM, assuming that the spatially-continuous transmit currents and received fields are represented using the Fourier basis functions. Due to the non-finite support (in the spatial domain) of the EM channel, WDM cannot provide non-interfering communication modes. The orthogonality among the communication modes (in the wavenumber domain) is achieved with WDM only when the size of the receiver grows infinitely large, due to the unbounded support of the channel response in the spatial

TABLE XI: Holographic beamforming and beam focusing.

Category	Ref.	Uplink/downlink	Multiple UEs	Channel type	Optimization approach	Main contribution
DMA input-output response based work	[214]	Uplink	Yes	NLOS	Closed-form solution, AO algorithm	Formulate a mathematical model for DMA-based uplink mMIMO systems, characterize the achievable sum-rate, and design holographic beamforming for different DMA setups, considering frequency-flat/selective channels.
	[215]	Downlink	Yes	NLOS	Closed-form solution, AO algorithm	Formulate a mathematical model for DMA-based downlink mMIMO systems, and design various holographic beamforming schemes for different DMA setups, considering frequency-flat/selective channels.
	[236] [237]	Uplink	Yes	NLOS	Greedy algorithm, AO algorithm, fractional programming	Extend the use of DMAs in OFDM systems using low resolution ADCs, as well as jointly optimize the DMA weights and the dynamic range of ADCs, under a given bit constraint.
	[238]	Uplink	Yes	NLOS (Far-field)	Dinkelbach's transform, AO algorithm	Study the energy efficiency optimization of a single-cell multiuser mMIMO system by a joint optimization of the UEs' transmit precoding and the BS DMAs' weights.
	[239]	Uplink	Yes	NLOS (Far-field)	Dinkelbach's transform, AO algorithm	Examine the joint transmit precoding and DMA weights in energy efficiency maximization of a multi-user uplink system, exploiting either instantaneous or statistical CSI
	[240]	Downlink	Yes	LOS (Near-field)	AO algorithm, Riemannian gradient	Formulate a mathematical model for DMA-based near-field multi-user MIMO systems, depicting both feasible processing of DMAs and near-field EM wave propagation, and joint design digital precoding and DMA weights.
	[241]	Downlink	Yes	LOS (Near-field)	AO algorithm, Riemannian gradient	Present a mathematical model for DMA-based radiating near-field WPT systems, characterize the weighted sum-harvested energy maximization problem, and joint design digital precoding and DMA weights.
	[221]	Uplink	Yes	NLOS (Near-field)	Weighted MMSE transform, AO algorithm, minorization-maximization	Formulate the HMA-based beam combining problem for XL-MIMO communications, and design the beam combining for the near-field wideband XL-MIMO uplink transmissions assisted by HMA
Mutual coupling based work	[209]	Downlink	No	LOS (Near-field)	Closed-form solution (MF)	Formulate a mathematical model of mutual coupling for LIS, and provide a coupling-aware MF scheme for isotropic and planar antenna elements.
	[210]	Downlink	Yes	LOS (Near-field)	Closed-form solution (MF, weighted MMSE)	Present coupling-aware MF and weighted MMSE designs for LIS-based multi-user system, accounting for super-directivity and mutual coupling effects along with near field propagation
	[242]	/	/	LOS (Far-field)	Closed-form solution	Propose a coupling-aware beamforming design for achieving super-directivity, and present a feasible method to obtain the coupling matrix.
Holographic principle based work	[243]	Downlink	No	NLOS (Far-field)	AO algorithm	Maximize the achievable data rate via a joint design of hybrid digital and holographic beamforming, while mitigating the beam squint loss.
	[244]	Downlink	Yes	NLOS (Far-field)	Closed-form solution, AO algorithm	Propose to jointly optimize a hybrid digital-holographic beamforming scheme to maximize the sum-rate.
	[245]	Downlink	Yes	NLOS (Far-field)	Closed-form solution, fractional programming, AO algorithm	Propose a joint digital-holographic beamforming and receive combining optimization scheme to maximize the sum-rate in an RHS-assisted downlink multi-user communication system.
	[246]	Downlink	Yes	LOS (Near-field)	Closed-form solution, (Lagrangian multiplier)	Propose a new type of space-division multiple access, HDMA, design a holographic beamforming scheme to maximize the capacity in an RHS-assisted downlink multi-user communication system.
	[247]	Downlink	Yes	LOS (Far-field)	Closed-form solution (ZF), dynamic programming	Present a joint digital and holographic beamforming scheme to maximize the sum-rate for an uplink RHS-aided communication system comprising one UE and multiple LEO satellites.
	[248]	Downlink	Yes	NLOS (Far-field)	Semidefinite relaxation, AO algorithm	Propose a hybrid digital-holographic beamforming scheme that jointly performs sensing and communication, and theoretically provide a lower bound on the maximum beamforming gain.
EM level model based work	[31]	/	No	LOS (Far-field)	Closed-form solution (Fourier basis)	Formulate a mathematical model in EM level for continuous aperture based point-to-point HMIMO system, and design a suboptimal WDM scheme realizing a practical HMIMO communication.
	[249] [250]	Downlink	Yes	LOS (Far-field)	Weighted MMSE transform, AO algorithm	Formulate a mathematical model in EM level for continuous aperture based multi-user HMIMO system, and design the corresponding patterns for UEs that maximize the sum-rate.
	[192]	Downlink	Yes	LOS (Near-field)	Gaussian elimination, block diagonalization	Propose a near-field LOS channel model using dyadic Green's function, and present two precoding schemes for cross-polarization and inter-user interference eliminations.
Others	[251]	Uplink	Yes	LOS (Far-field)	Closed-form solution (MRT, ZF)	Explore if MRT is sufficient when transmitting to multiple UEs or if more advanced methods, such as ZF, is needed to deal with interference when transmitting from an LIS.
	[211]	Uplink	Yes	LOS (Near-field)	Closed-form solution (MRC, MMSE)	Signal and interference terms are numerically analyzed as a function of the position of the transmitting devices with both MRC and MMSE schemes.
	[252]	Downlink	No	LOS (Near-field)	AO algorithm, greedy searching	Formulate a mathematical model of XL-MIMO based near-field distance-aware precoding system, and jointly design the analog and digital beamformers.

domain. Later, in [249], [250], a pattern design for continuous HMIMOS enabled multi-user communication system is investigated to maximize the information modulated on EM waves. The authors modeled the system in EM level, and proposed a pattern-division multiplexing method accordingly. Specifically, the authors first construct a communication architecture between continuous surface HMIMOs from EM theory, and then project the orthogonal continuous current functions carrying information at transceiver side onto a Fourier orthogonal basis, thus transforming the design of orthogonal continuous current functions into a design problem of their projection length on a finite orthogonal basis, thus enabling optimization of the problem and realizing a significant capacity improvement over the existing WDM scheme. In addition, another recent study in [192] suggested two precoding schemes for a multi-user HMIMO communication system, where near-field and triple polarization were considered. The two precoding schemes are respectively responsible for cross-polarization elimination and inter-user interference mitigation. This study was performed based on a specially established near-field channel model by means of the dyadic Green's function.

5) *Others*: Some other studies were developed as well. For example, [251] studied the beamwidth and sidelobes of a transmitting LIS, which can be considered as a continuous surface. A comparison has been made between employing MRT and ZF schemes, in order to mitigate the interference deriving from the LIS's closed spaced antennas in a two-user scenario, under the far-field, LOS wireless channel assumption. It was shown that ZF and MRT perform equally well when the number of antennas reaches its asymptotic limit, while MRT is sub-optimal for practical LIS sizes. Following [251], reference [211] showed that when the distance between UE and LIS is comparable to the size of LIS, the near-field assumption holds. Both MRC and MMSE combining schemes were considered to study the uplink spectrum efficiency of two UEs communicating with an LIS with varying antenna spacing, effective antenna areas and loss from polarization mismatch. MMSE combining was proved to be superior when employing a practically large LIS. Besides, the authors of [252] examined a near-field LOS XL-MIMO communication system, and presented a distance-aware precoding structure which can flexibly configure RF chains depending the DOF of

near-field channel. A corresponding distance-aware precoding algorithm was designed to adaptively fit the DOF variation along with the change in distance.

In the final of this subsection, we list recent studies of holographic beamforming and beam focusing in Table XI for ease of reference.

VI. COMPARISONS AND EXTENSIONS

A. Comparisons with Conventional Technologies

In this subsection, we will compare HMIMO communications with conventional technologies, such as RIS/IRS-aided communications and mMIMO communications. We first briefly interpret RIS/IRS as the passive type of HMIMOS from a macroscopic perspective, and then put an emphasis on the comparison between HMIMO and mMIMO in regard to the hardware, directivity, coverage, capacity and energy efficiency. We detail each content as follows.

1) *Comparison with RIS/IRS*: Complying with [39], we consider RIS/IRS as the passive type of HMIMOS which are capability-limited in sensing and computing, as well as are generally controlled by BS over a dedicated control link. They are mainly used as passive reflectors by deploying between transceivers for realizing an intelligent and environmentally programmable communication system. In the following, we interpret RIS/IRS in comply with HMIMOS from a holographic working principle perspective. As demonstrated in Section III, the feeds used for exciting reference waves can be placed in different positions, namely integrated into the surface and located externally of the surface. RIS/IRS belong to the latter scenario. Specifically, from a more macroscopic perspective, the reference wave can be EM signals emitted by one/more BSs or other communication nodes, which are refracted or reflected by the HMIMOS to generate specific radiations. Under such an interpretation, the existing RIS/IRS and their expansions can be regarded as HMIMOS, such that the introduced “transmitter-RIS/IRS-receiver” link enables the underlying communications to be viewed as in a holographic principle guided fashion. Once the radiating elements of RIS/IRS are suitably adjusted, the resulting pattern constructed by effective radiating units can be considered as the required hologram for achieving a desired radiation.

2) *Comparison with mMIMO*: As one of the most important enablers for 5G wireless communications, mMIMO work through deploying a large number of antennas capable of supporting multiple parallel streams and achieving signal power enhancement. HMIMOS can be considered as a brand-new extension of conventional mMIMO, but introduce many differences and bring unique characteristics. We compare HMIMOS with conventional mMIMO, list their main diversities from a hardware perspective first, and discuss main comparisons in terms of communication metrics. It should be emphasized that the HMIMOS we focus on here are mainly used as transceivers which is in comply with the working mode of conventional mMIMO antenna arrays.

Hardware Perspective: It should be first noted that for HMIMOS the size of radiating elements and the distance between two adjacent elements are in subwavelength that is

generally much smaller than free space wavelength [43]. While for conventional mMIMO antenna arrays, the spacing between adjacent radiating elements should be in half a wavelength to reduce the mutual coupling, which leads to a much larger aperture size when integrating more radiating elements. From a sampling perspective, the densely packing of radiating elements results in a signal over-sampling, enabling a great potential of direct manipulation on EM fields. Packing a large amount of radiating elements, HMIMOS commonly exhibit an almost spatially continuous aperture in 2D planer shapes, and they can be potentially fabricated in almost any required shape, as shown in III-E. However, the conventional mMIMO antenna arrays with limited shape extensibility are mainly popular in spatially discrete aperture, and mostly deployed in ULAs.

Next, we show the differences in details via plain block diagrams of HMIMOS and conventional mMIMO antenna arrays. Without loss of generality, we present block diagrams for transmitters, and omit block diagrams for receivers that can be depicted in a similar way. We omit the TCA based HMIMOS for brevity and mainly take the LWA based HMIMOS for demonstration as these schemes are totally different from the perspective of working principle in implementing amplitude and phase tuning. Take a look at Fig. 16(a), one can see that the schematic of HMIMOS has a waveguide to sustain propagation of reference waves that are excited by the outputs of external RF chains. There are also a large amount of radiating elements with each controlled by a tuning element. The tuning elements enable a controllable capacitance that is responsible for modulating radiating elements coupled by reference waves, and manipulate amplitude and phase of each radiating signal for generating desired beams. The mapping from inputs to radiated signals is realized by a large number of low-cost and energy efficiency tuning elements (e.g., PIN diodes), and a small amount of RF chains. Oppositely, such a mapping of mMIMO antenna arrays can be implemented in three typical schematics, namely fully-digital, fully-analog and hybrid analog-digital processing, as shown in Fig. 16(b)(c)(d). The fully-digital schematic relays on a large amount of RF chains to enable a fully-digital processing, with each RF chain output connected to one radiating element. The enormous number of RF chains incurs high cost and large power consumption for mMIMO systems. Differently, the fully-analog schematic deals with such problems by connecting each radiating element with a phase shifter and then a power amplifier. Only one single RF chain is used to supply signals to all power amplifiers. Compared to the fully-digital schematic, the fully-analog schematic mitigates the cost and power consumption problems via sacrificing communication performance, i.e., from supporting multi-stream transmission to only one stream transmission. To find a balance between fully-digital and fully-analog schematics, the hybrid analog-digital schematic applies phase shifters and power amplifiers as well for connecting a large number of radiating elements to a small amount of RF chains [196], [253]–[256].

Comparing conventional mMIMO antenna arrays with HMIMOS, it is emphasized that even the fully-analog schematic with least cost and power consumption cannot comparable to HMIMOS because the phase shifters and power

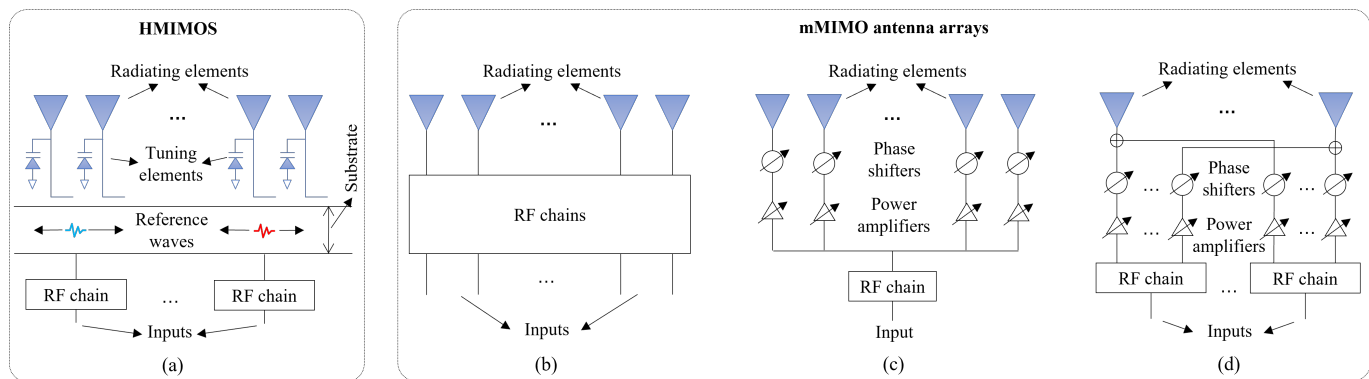


Fig. 16: Block diagrams of HMIMOS and conventional mMIMO: (a) HMIMOS block diagram; (b) conventional mMIMO with fully-digital processing; (c) conventional mMIMO with fully-analog processing; and (d) conventional mMIMO with hybrid analog-digital processing.

amplifiers are still costly and power hungry compared to the low cost and energy efficiency tuning elements. Moreover, a thoroughly comparison between HMIMOS and phased array antennas was conducted by Pivotalcommware company in [257], where the results showed that the cost and power consumption of HMIMOS are 1/10 and 1/3 of that of the phased array antennas, respectively.

Directivity and Coverage: Directivity is a key parameter for depicting antenna arrays. It describes the concentration of antenna radiating pattern in a particular direction. It can be used to compute the antenna array gain by further multiplying the antenna efficiency. For conventional mMIMO antenna arrays, the array gain is proportional to the number of packed radiating elements. However, this array gain is enhanced and has potential to reach the square of the number of radiating elements for HMIMOS, due to strong mutual coupling created by almost infinite small radiating elements densely packed in subwavelength spacing that is much smaller than half a wavelength. The mutual coupling, considered to be harmful in conventional mMIMO design, fundamentally transforms, and is possible to be exploited in achieving the super-directivity, a phenomenon that describes the significantly higher array gains obtained by HMIMOS compared to that of mMIMO antenna arrays equipped with identical number of radiating elements [29]. We fortunately see that some recent studies on mutual coupling and the incurring super-directivity were performed in [209], [210], [242]. These investigations presented newly designed communication models accounting for mutual coupling effects and super-directivity, based on which coupling-aware transmitter designs were developed. The results revealed that properly exploiting mutual coupling in transmitter designs indeed facilitates the realization of super-directivity, and it is important to study and design, under realistic factors, e.g., antenna efficiency and ohmic losses, for achieving the super-directivity.

The coverage of an HMIMO system is expected to be enlarged compared with conventional mMIMO systems. As stated previously, the super-directivity of HMIMOS can be potentially achieved, resulting in a higher antenna array gain over mMIMO antenna arrays. Therefore, the coverage of an

HMIMO system can be further expanded over mMIMO systems for a same transmit power. To the best of our knowledge, the increase of coverage promoted by super-directivity has not been unveiled, and a future study should be performed. While a prior study for reliability analysis of an LIS-based HMIMO system was carried out in [258]. The authors analyzed the outage probability of LIS that can characterize the coverage, and provided a comparison of outage probabilities between LIS and mMIMO. The results showed that the LIS always achieves lower outage probabilities than those of mMIMO.

Capacity and Energy Efficiency: The capacity offered by an HMIMO communication system is envisioned to have a further increase over conventional mMIMO systems. First of all, the low-cost and low power consumption of HMIMOS make it possible to distribute more radiating elements than mMIMO for an identical aperture area. As revealed from recent studies, this can lead to the super-directivity in HMIMOS that can produce a higher array gain to increase the receive signal power, leading to a higher receive SNR compared with mMIMO. Following the Shannon capacity formula, this increase in receive SNR will offer an extra increase in capacity. This increase needs to be further explored. We see that some recent studies provided discussions on array gain [201] and power gain [203] for LIS based communication systems. Another up-to-date work [191] conducted a direct comparison between LOS HMIMO and LOS mMIMO in terms of power gain and spectral efficiency gain in a point-to-point communication setting, which showed an up to π^2 times higher power gain and a corresponding 3.30 bits/s/Hz spectral efficiency gain can be achieved. Secondly, the low-cost and low power consumption of HMIMOS also facilitate fabricating of extremely large apertures which is impossible to research for conventional mMIMO antenna arrays. The large area apertures boost increase in DOF and promote communications shifting from the far-field region to the near-field region, where both distance and angle can be exploited for assisting communications. Recent research showed that the DOF of an HMIMO communication system can be higher than 1 (i.e., the DOF of far-field mMIMO systems) in near-field LOS propagation channel [203], which

TABLE XII: Comparison between HMIMO and mMIMO.

Metrics	HMIMO	mMIMO
Aperture	Nearly continuous aperture	Discrete aperture
Mutual coupling	Ultra-high	Low (neglectable)
Antenna array gain	High (super-directivity)	Low
Beam modes	Polarization and OAM modes	Mainly polarization modes
Number of beam modes	Infinite modes theoretically (OAM modes)	Two modes (linear/circular polarization)
Communication model	EM level model (Helmholtz equation, Green's function, Fresnel Kirchhoff diffraction). Circuit model (Impedance based mutual coupling)	Mathematical perspective model (Rayleigh scattering)
Communication region	Near-field & hybrid near-far field	Far-field
Multiplexing space	Nearly infinite and continuous	Limited and discontinuous
Multiplexing resolution	High (follow diffraction limit)	Low (limited by bandwidth & beam width)
Sampling theory	Spatial sampling	Nyquist time/frequency sampling
Signal processing domain	EM domain & hybrid EM-digital domain	Digital domain
Mathematical tools	Kolmogorov information theory, functional analysis, random process & probability theory	Shannon information theory, random process & probability theory

can be exploited to promote the capacity. The extra DOF is contributed to evanescent waves in near-field region [208]. Finally, we emphasize that the great potential of HMIMO communications can be more significant in serving multiple UEs, which is characterized in twofold. On the one hand, the enlarged coverage of an HMIMO communication network allows more UEs to be covered in an effective communication area that satisfies a required communication reliability. This will contribute an enhanced network capacity. On the other hand, the extra distance dimension introduced in near-field communications can be exploited for distinguishing signals corresponding to different UEs, which can increase network capacity with an augmented capability in communicating with more UEs simultaneously.

The energy efficiency of an HMIMO communication system is supposed to be increase compared with mMIMO systems. Since HMIMOS are implemented by low-cost and low power consumption devices which are totally distinct from mMIMO antenna arrays tuned by power-hungry phase shifters and power amplifiers, as demonstrated in *Hardware Perspective*. Meanwhile, HMIMOS can offer a potentially augmented performance over mMIMO antenna arrays. It is natural to conclude that HMIMO communications are potentially feasible solution in reaching energy efficiency 6G. However, the fundamental limit of energy efficiency for HMIMO systems is not unveiled. Recently, some studies for realizing an DMA-enabled energy efficiency communication system were performed in [238], [239], in which the results showed DMAs can offer higher energy efficiency over mMIMO antenna arrays.

Other Comparisons and Summary: Beyond the above comparisons, various differences between HMIMO and mMIMO arise and the full potential of HMIMO communications is on

the way to be unveiled. To present a more panoramic view, we list a complete comparison table between HMIMO and mMIMO in Table XII. Besides the mostly mentioned differences in aperture, mutual coupling and antenna array gain, we would like to emphasis that the beam modes supported in HMIMO systems will be much more abundant than mMIMO, tending to support from conventional polarization modes to newly OAM modes owing to the powerful capabilities of HMIMOS in EM wave manipulations. This will contribute to the revolution of wireless communications from mMIMO to massive modes, enhancing system capacity significantly in specific situations [259], [260]. In addition, the modeling of HMIMO communication systems should encompass physical phenomena, such as, EM wave propagation, mutual coupling, which are generally neglected in mMIMO modeling. For example, mMIMO channel modeling is mostly performed from a mathematical perspective by depicting wireless environment based on Rayleigh scattering. This, however, is invalid in HMIMO communications with essential physical phenomena incorporated. One possible solution is modeling from an EM perspective, where EM fields follow the Helmholtz equation; wireless channel can be described via Green's function; and Fresnel Kirchhoff diffraction models the light propagation. Another direction is via circuit modeling that can capture mutual coupling effects of HMIMO communication system, providing a possible analysis manner. Future HMIMO communications are mostly considered to be occurred in near-field or hybrid near-far field regions, which is totally different from mMIMO, assuming that communications occur in far-field regions. Compared with mMIMO with limited and discontinuous multiplexing spaces, as well as low multiplexing resolutions limited by signal bandwidth

and beam width, HMIMO communications have potential to reach nearly infinite and continuous multiplexing space with high multiplexing resolution (follow diffraction limit). This mainly contribute to the powerful capability of HMIMOS in recording and reconstruction of EM fields in a holographic fashion. Since HMIMOS open the era of signal processing in EM domain, conventional digital domain signal processing of mMIMO tends to face a paradigm shift. Signal processing of HMIMO communications can be performed in EM domain or hybrid EM-digital domain. As such, sampling theory, mainly applied to time and frequency domains in mMIMO, will be possibly moved to the spatial domain. For instance, wavenumber domain channel modeling of HMIMO should be discretized by proper spatial sampling. This is also necessary to pattern designs of EM level system model for maximizing the communication performance. Lastly, for fully understanding, analyzing and designing HMIMO communications, new mathematical tools are essential. Shannon information theory, random process and probability theory, popular mathematical tools in mMIMO analyzes and designs, are not enough for HMIMO communications. Kolmogorov information theory, functional analysis are expected to be beneficial in unveiling full potential of HMIMO communications.

B. Various Extensions

The powerful capabilities of HMIMOS and the proven benefits introduced in HMIMO communications bring great potentials when integrating them into various extensions. In the following of this section, we elaborate several potential HMIMOS applications relevant to 6G, that are valuable to be further investigated. The applications included but not limited to are: (i) MmWave and THz communications; (ii) WPT, wireless energy harvesting (WEH), simultaneous wireless and information power transfer (SWIPT) and wireless powered communication network (WPCN); (iii) Sensing, localization, positioning, and tracking; (iv) Satellite, UAV and vehicular communications; as well as (v) other miscellaneous applications.

1) *MmWave and THz Communications*: By deploying HMIMOS in mmWave and THz communications, one can obtain a communication system with potential benefits, such as simplifying transceiver hardware architecture, offering high data rates and reliable low latency for seamless virtual reality (VR) experiences, as well as conquering large propagation path loss to obtain extended signal transmission distance and coverage range. More specific, in [261], the authors study two mMIMO transmitter architectures enabled by HMIMOS that are illuminated by few nearby active antennas with each connected to a dedicated RF chain. Such an architecture facilitates an energy-efficient system capable of transmitting a phase-shifted version of incident signals from few active antennas with an exploitation of the array gain introduced by scaled up passive radiating elements. Based upon the architectures and comply with their constraints, two precoders are designed and the power consumption model considering imperfections is developed. Simulation results valid the energy efficiency and scalability of HMIMOS for being promising

candidates in building mMIMO/umMIMO communications. Next, in [262], the authors investigate a wireless VR network empowered by HMIMOS BSs working on THz frequencies, where high data rates and reliable low latency for seamless VR experience are required. To this aim, a risk-based framework is suggested for data rate and reliability assurance, and a corresponding policy-based reinforcement learning (RL) algorithm enabled by a recurrent neural network (RNN) is developed for solving such a problem. The results show a high accuracy and fast convergence of the RNN. Enlarging signal propagation distance and coverage range in THz communications, the authors of [263] deploy multiple passive HMIMOS for assisting signal transmissions between a BS and single-antenna UEs, in which they propose a deep RL based hybrid digital and analog beamforming design for realizing a multi-hop communication. The deep RL based scheme is proven to be a state-of-the-art method for solving multi-hop NP-hard problem with a 50% increase in coverage range compared with the zero-forcing beamforming without HMIMOS assistance. Moreover, the authors of [231] investigate HMIMOS aided THz mMIMO communications, in which HMIMOS with continuous or quasi-continuous apertures are considered. They theoretically derive the beam pattern of HMIMOS with continuous apertures and reveal a satisfied approximation on such a beam pattern by practically feasible ultra-dense HMIMOS. Based upon this continuous HMIMOS aided system, a close-loop channel estimation, including a coarse downlink together with a finer uplink channel estimations, is suggested to capture the broadband channels. The superiority of HMIMOS is shown in simulations.

2) *WPT, WEH, SWIPT and WPCN*: By using either active holographic beamforming/beam focusing or passive beamforming/beam focusing, HMIMOS are capable of enhancing the strength of received signals at receivers. Such capabilities bring a great potential in improving energy efficiencies of communication systems assisted by WPT and WEH, allowing a beneficial SWIPT capability within WPCNs. Particularly, the authors of [264] realize a high transmission efficiency near-field WPT utilizing an HMIMOS whose radiating element layout and tuning states are configured through the holographic principle. Recently in [241], the authors present an exploitation of spherical wavefront for near-field WPT, in which HMIMOS weights and the digital precoder are jointly designed after solving a weighted sum-harvested energy maximization problem. The results show the improvement in energy transfer efficiency. Furthermore, two prototypes of HMIMOS validating near-field WPT at 5.8 GHz are fabricated and tested in [265] and [266], respectively. Taking advantage of WEH from information signals, an autonomous HMIMOS without dedicated power supply is investigated in [267], for which the design is implemented via dividing unit cells of HMIMOS into two subsets that are responsible for energy harvesting and beamforming, respectively. Efficient subset allocation policies are proposed for solving formulated problems with a suggested feasibility of autonomous HMIMOS. Building up WPT and WEH capabilities, passive HMIMOS assisted SWIPT systems are particularly investigated [268], [269], in which different optimization problems, such as the maximization of weighted

sum power or the maximization of weighted sum-rate, complying with distinct constraints, e.g., signal-to-interference-plus-noise ratios of information receivers or energy harvesting requirements of energy receivers, are established and solved based upon the alternating optimization algorithm or the block coordinate descent algorithm. A further extension on multiple passive HMIMOS aided SWIPT communications is studied in [270] with transmit power minimized under different quality-of-service constraints. In [271], the authors investigate passive HMIMOS assisted WPCNs by jointly designing radio resource allocation and passive beamforming under an energy efficiency maximization optimization.

3) *Sensing, Localization, Positioning, and Tracking:* With a complete exploration of their capabilities, one can expect that HMIMOS have a great potential in assisting the realization of other attractive functionalities of 6G, such as sensing, localization and tracking. First of all, sensing is an important capability that perceives the wireless environment states. In order to mitigate spectrum congestion, the authors of [248] introduce HMIMOS in promoting the integrated sensing and communication performance, in which an amplitude-controllable holographic beamformer is optimized, and a lower bound on the maximal beam pattern gain is theoretically analyzed. They show that more than 50% increase of beamforming gain can be achieved with a reduced cost when comparing to the same size MIMO array. Exploring the benefit of passive HMIMOS in spectrum sensing, the authors of [272] evaluate the detection probability in an asymptotic fashion with the statistically configured passive HMIMOS. Under this setting, equivalent channel gains are provided and an insight on the required number of reflecting elements of HMIMOS for achieving a near 100% detection probability is theoretically analyzed. Integrating spectrum sensing and learning capabilities into semi-active HMIMOS, the framework of spectrum learning aided HMIMOS is presented in [273]–[275]. Capitalizing on this spectrum learning ability, they are capable of reflecting useful signals while ignoring interfering signals based on an intelligent ‘think-and-decide’ process. Beyond wireless sensing, wireless localization and positioning are envisioned as an essential function of 6G shifting from the previous add-on feature. The approximately continuous aperture of HMIMOS enables the road to reach a high localization resolution. To this end, the authors of [276] study the fundamental limits of holographic positioning in the near-field regime. A CRLB is computed based on a combination of EM propagation theory and estimation theory, considering several cases such as with/without prior knowledge of source orientation and a specific type of source location. [277] utilizes multiple receiving RISs comprising a new large one that acts as an HMIMO receiver, in order to perform 3D localization. Additionally, passive HMIMOS aided localization is studied in [278] obtaining the CRLB of ultimate localization and orientation, and providing a closed-form phase configuration of passive HMIMOS for joint communication and localization. The near-field positioning is extended to near-field position and velocity tracking for a moving object in [279], inside of which posterior CRLB is derived and different Bayesian tracking algorithms are studied with respect

to the accuracy and complexity under cases e.g., parameter mismatches and abrupt trajectory changes. HMIMOS are also expected to constitute an enabling technology for simultaneous localization and mapping (SLAM), according to which a map of the environment is being build and the user can self-localize with respect to the map. The authors in [280] propose a RIS-enabled framework for SLAM without any access points.

4) *Satellite, UAV and Vehicle Communications:* Making use of the excellent characteristics, e.g., low size, weight, cost, power consumption, and flexible aperture shapes, as well as powerful capabilities, it is prospected that HMIMOS are capable of assisting satellite, UAV and vehicular communications by mitigating their facing challenges, such as power constraint, severe path loss, and hardware limitations, etc. More specific, in [247], the authors apply HMIMOS to LEO satellite communications to enable HMIMO communications. They design a temporal variation law guided LEO satellite tracking scheme, eliminating the overhead of satellite positioning, and also develop a tracking error robust holographic beamforming algorithm for sum-rate maximization. In assisting the air-to-ground communication, the authors of [281] utilize HMIMOS, capable of simultaneously transmitting and reflecting on both sides of the aperture, to support a maximal sum-rate. A joint optimization of UAV trajectory as well as active and passive beamformings is conducted subject to the flight safety, maximum flight duration and minimum data rates of ground UEs. An RL framework and a worst-case performance guaranteed distributionally-robust RL algorithm are developed accordingly. Utilizing a similar simultaneously transmitting and reflecting HMIMOS for improving double fading effect faced in vehicular communications, the authors of [282] jointly design BS digital beamforming and HMIMOS analog beamforming based on imperfect CSI for minimizing the transmit power of BS. Specific transmission protocol is presented for achieving the CSI acquisition with low channel training overhead. Resource allocation is optimized based on alternating optimization and constrained stochastic successive convex approximation algorithms. Furthermore, the authors of [283] propose to deploy conformal HMIMOS on vehicle surface to release blockage impact. They theoretically give the phase pattern of a cylindrical HMIMOS via generalizing the conventional planar HMIMOS and prove the benefits.

5) *Other Miscellaneous Applications:* Beyond the previously mentioned extensions, the emergence of HMIMOS, especially the passive HMIMOS, spurs a vast of research combinations by introducing HMIMOS to various areas, including physical layer security [284]–[286], index modulation [287]–[289], non-orthogonal multiple access [290]–[292], cognitive radio [293]–[295], ambient backscattering communications [74], [296], [297], full duplex wireless communications [298]–[303], cell-free network [304]–[306], mobile edge computing [307]–[311], federated learning [312]–[314], and machine learning aided applications [315]–[318]. It should be emphasized that these studies consider the application of HMIMOS mainly as passive reflectors, incorporating in conventional communication systems, such as MIMO and mMIMO. It is rare to see that a communication system employs HMIMOS as active transceivers and utilizes the holographic principle to

enable above appealing HMIMO communications. As such, theoretical analyzes and practical algorithms of HMIMO communications for these cross-domain areas remain to be unveiled.

VII. RESEARCH CHALLENGES AND FUTURE DIRECTIONS

We describe the recent advances of HMIMOS and HMIMO communications, and show their great potentials in future 6G era by embracing the physical aspects of HMIMOS, theoretical foundations and enabling technologies of HMIMO communications. It should be noted that this area is still in its initial stage, where several research challenges should be carefully addressed and mitigated for making HMIMOS and HMIMO communication practical. The grand challenges will bring new opportunities as future directions. In the following of this section, we present and discuss some of the most critical research challenges of HMIMOS and HMIMO communications.

A. Physical Level Design and Experimentation

To date, various HMIMOS structures are designed based on different holographic design methodologies, which demonstrates the conceptually feasibility. It remains however a vast of unveiled questions for practical implementations. For example, in LWA based HMIMOS, the substrate performing as the role of a waveguide exhibits a signal loss effect in reference wave propagation, such that the radiated signals of all radiating elements leaked from the substrate experience different attenuated reference waves, which will lead to biased transmission and reception compared to the lossless substrate. Furthermore, the generated fields by radiating elements have an inevitable influence back toward the reference wave propagated along the substrate. These non-ideal hardware imperfections influence the aperture size design of HMIMOS, which will be more critical as HMIMOS becoming large. The practical imperfections should be carefully tested and compensated. Another critical question is that the dense deployment of radiating elements will unavoidably introduces strong mutual coupling that decreases the radiation efficiency and performance. The mutual coupling must be effectively characterized and should be suppressed or properly exploited by exploring advanced hardware structures. It should be further emphasized that HMIMOS hardware design and optimization become challenging as the aperture size and radiating elements going large. The complexity mainly arises from EM numerical computations that usually involve with a large number of variables to be optimized, namely, aperture size, the number of radiating elements and various practical imperfections. Hence, efficient methods and strategies should be designed. We see from existing studies that the current HMIMOS are designed and fabricated for only supporting single or less multiple beams that is far away from the practical requirements that dozens of UEs or more should be served simultaneously through different concurrent beams. The hardware design to enable large multiplexing capability of HMIMOS should be further studied. On the other hand, in TCA based HMIMOS, the key challenge in

physical level design mainly arise from the holographic RF-optical mapping, where the phases of parallel optical beams, mapped from the corresponding RF signals, are sensitive to tiny environment variations, such as temperature, vibration, airflow and sound, which decreases the mapping performance. Stable holographic RF-optical mapping should be examined. To promote HMIMOS for practical use, experimenting with HMIMOS for realistic communications under various setups should be performed to validate their potentials.

B. Holographic Fundamental Limits

1) *Exploiting HMIMO Limit in EM Regime*: The realistic information transmissions are carried by EM waves which however exhibit distinct behaviors in near-field and far-field regions. Disappointingly, although Shannon's theory provides a solid foundation for modern wireless communications, it still reaches its bottleneck in HMIMO communications due to complicated characteristics involved in EM transmissions, thus hampers the straightforward adoption of Shannon's theory in HMIMO limit analysis. For example, the transmitted EM waves exhibits constructive or destructive phenomena at different observation points in Fresnel zones [319]. How to combat destructive interference and fully exploit constructive effect through holographic communications design is a challenging task. Fortunately, HMIMOS enable flexible phase shift design, thus, a proper phase shift design may be an effective solution. There are also other feasible methods to deal with this problem, which require further investigations.

Moreover, a general EM information theory should be established by considering both time domain and spatial domain signals. Specifically, there is a slight asymmetry between information in time domain and in spatial domain [320]. In time domain, the capacity of communications could be improved with an increase of observation time. Similarly, in space-domain, the capacity of communications could be also improved by enlarging the size of HMIMOS. However, different from the infinity observation time, the size of antennas is limited. Thus, in such case, how to obtain the bound of communications in spatial domain poses new challenge to theoretical analysis in holographic systems. Only with the full knowledge of EM waves, one can fully exploit the potential of holographic systems, which requires industrious work to connect classic information theory and critical EM wave transmission.

2) *Sampling in Near-Field*: Considering distinguishable characteristics in near-field and far-field regions, the sampling of EM waves to reconstruct EM fields is necessary in effective signal processing. Specifically, there exists a minimum number of samples in spatially continuous EM field for accurate reconstruct without losing too much information. However, the EM field sampling is still in its infancy and no unified and accepted mathematical conclusion is reached. [207] investigated Nyquist sampling in reconstructing an EM field by solving circle/ellipse packing problems. The authors proposed that conventional signal processing techniques for bandlimited signals can be applied to EM fields due to a fundamental space-time duality [207]. However, the near-field space in wavenumber domain is typically infinite, thus, the

mentioned sampling method is not feasible. Therefore, how to sample in near-field at an arbitrary low reconstruction error is challenging. In addition, the tractable relationship between the truncation error and sampling points in near-field is also valuable to be explored.

C. Holographic Signal Processing

1) *Holographic Channel Estimation*: The extremely large number of radiating elements incorporated in HMIMOS entails prohibitive pilot overheads, therefore, an effective channel estimation method has become a crucial issue. There are many works investigating channel estimation of massive parameters, which can be categorized mainly into two groups, i.e., estimating the general channel model at high pilot expense [186], or estimating the sparse channel model at low pilot overheads [233]. However, both methods suffer from expensive pilot cost or performance loss. Specifically, the former one is applicable to a general channel model since the pilots are long enough to estimate all unknown variables, while the latter one takes advantages of sparsity to adopt less pilots in channel estimation as the number of unknown parameters reduces. In fact, the sparsity is not available in general framework, resulting in estimation performance degradation. Consequently, a cost efficient channel estimation method using lower overheads in a generic system model is tricky. Besides, developing new channel estimation approaches consistent with newly built channel models is necessary and has significant potential in realizing high accurate channel estimates.

2) *Holographic Beamforming and Beam Focusing*: HMIMOS can achieve spatially continuous apertures and high beam pattern gains since it incorporates compact radiating elements, which entitles holographic beamforming. Various holographic beamforming schemes were proposed in wireless communications [248], [270], [321], however, the existing work mainly focuses on angle-aware beamforming schemes, i.e., UEs with close elevation/azimuth angles are difficult to be distinguished. Therefore, designing effective beamforming schemes in such scenarios is demanding. Capable of realizing a simultaneous distance-angle-aware functionality, holographic beam focusing tends to be critical for near-field communications as HMIMOS becoming large. Designing valid beam focusing approaches, especially based on newly established theoretical foundations, is of great significance. In addition, since HMIMOS consist of excessively large number of radiating elements, conventional beamforming design cannot be applied directly, especially the high computational ZF schemes. Accordingly, low-complexity beamforming designs for HMIMO communications is vital to enable practical systems. Moreover, the mutual coupling existing in dense HMIMOS inevitable degrades the performance by directly applying the conventional beamforming schemes. Consequently, coupling-aware beamforming/beam focusing schemes are substantial for HMIMO communications. There are also some other state-of-the-art issues in beamforming achieved by HMIMO systems, for example, how to generate multi-beam with the lowest side-lobe to detect active UEs.

VIII. CONCLUSIONS

In this paper, we have presented a comprehensive overview of the key features and recent advances of HMIMO wireless communications. We first presented a multitude of holographic applications and listed representative holographic technology roadmaps for future HMIMOS-based communications. We then emphasized on three main components of HMIMO communications, namely, physical aspects of HMIMOS and their theoretical foundations, as well as enabling technologies of HMIMO communications. In the first component, we embraced the physical aspects of HMIMOS in terms of their hardware structures, holographic design methodologies, tuning mechanisms, aperture shapes, functionalities, as well as representative state-of-the-art prototypes. In the second component, we presented theoretical foundations of HMIMO communications with respect to channel modeling, DOF, and capacity limits, and overviewed the HMIMOS capability for EM-field sampling, as well as the resulting emerging research area of EM information theory. In the last component communications, we presented recent advances on physical-layer HMIMO-enabling technologies, and in particular, on holographic channel estimation and beamforming/beam focusing. We also compared HMIMO communications with conventional technologies, especially mMIMO communications, and discussed a variety of extensions of HMIMOS. We finally presented a comprehensive list of technical challenges and open research directions that we believe they will drive unprecedented research promotions in the future.

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