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Recent Advances of Intelligent Metasurfaces in Wireless Communications

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ABSTRACT: Emerging technologies in future 6G mobile systems are expected to achieve unprecedented access rates and network capacity, but are hindered by high hardware cost and complexity, especially in terms of RF chain requirements. The wireless communication paradigm enabled by programmable metasurfaces, which leverages their ability to precisely manipulate electromagnetic waves, facilitates RF chain-free transmitters and spatial down-conversion receivers, revolutionizing wireless transceiver architectures by simplifying hardware complexity and reducing costs. In this review, we provide the recent advances of intelligent metasurfaces in the applications of wireless communication. We firstly summarize the mainstream realizations of reconfigurable metasurfaces at microwave and then focus on the advances of intelligent metasurfaces with spatial/spatiotemporal modulations. We conclude by analysing the challenges in this research area and surveying new possible directions.

1. INTRODUCTION

Metasurfaces, composed of subwavelength unit cells, have recently drawn increasing interests in both industry and academia [1, 2]. As a two-dimensional (2D) equivalent of the bulky metamaterials, metasurfaces become more popular due to many striking properties of low loss, ultrathin thickness, and convenient fabrication. Researchers can flexibly design metasurfaces, i.e., distributing the subwavelength resonant particles with different geometries and materials on a single layer, to manipulate the propagation and scattering of electromagnetic waves. So far a great number of applications have been facilitated ranging from microwave to optical frequencies, such as carpet cloak, hologram detection, imaging, and optical computing [3–18]. Early metasurfaces were investigated to realize a predefined functionality for a specific electromagnetic mode. It was soon realized that the dynamic adjustability of metasurfaces would greatly enrich the applications of metasurfaces. Therefore, reconfigurable metasurfaces have experienced rapid development [19–23], for example, embedding varactor diodes into metasurfaces and thus controlling the metasurface.

More recently, intelligent metasurfaces have been found to be a promising generation of metasurfaces because they are empowered with intelligence, adaptivity, and automation to satisfy different demands in real time, especially in the fifth-generation (5G) wireless network [24–27]. Recent trends have advanced towards the realization of ultra-high data rates, low energy consumptions, global coverage reliable connectivity, and low latency. Thus, wireless signals are anticipated to exhibit a wider bandwidth and stronger stability, but also suffer from weaker penetration in the propagation [28, 29]. At the same time, the rapid urbanization of construction and randomness in the surrounding environment have further aggravated the contradiction for efficient signal transmission because of complex electromagnetic reflections, scattering, and absorptions before reaching the receiver. To address this challenge, conventional approaches mainly deploy a great number of active nodes in an uncontrollable radio environment, such as base stations and access points, to enlarge network coverage and enhance network capacity. However, such conventional methods may lead to high energy consumption deployment cost and complicate network interference issues. Therefore, it is urgent to develop paradigm-shift methods to achieve the continuous growth of the capacity growth of wireless networks in a green manner.

Intelligent metasurfaces based wireless communication holds great potential to merit 5G communication, future beyond 5G, and the construction of smart cities. Compared with conventional phased array or other active wireless relays, the signal propagation between multiple transmitters and receivers can be flexibly customized to achieve desired manner, which offers a new approach to address the wireless channel fading impairment and interference issue. Intelligent metasurfaces greatly relieve the heavy reliance on high-complexity, energy-consuming radio-frequency hardware at base stations. In contrast, intelligent metasurfaces manipulate the received signal in a passive manner without complex active transmitting modules. It thus allows the intensive deployment of communication equipment convenient in a green manner. Artificial intelligence algorithms are a driving force that enable fast forward prediction and inverse design of intelligent metasurfaces [30–32]. Apart from this, the study of intelligent metasurfaces is promising for many other applications, including target localization and electronic surveillance.

In this review, we provide a survey of the recent advancements of intelligent metasurfaces for the application of wireless communication. We summarize different methods to realize re-

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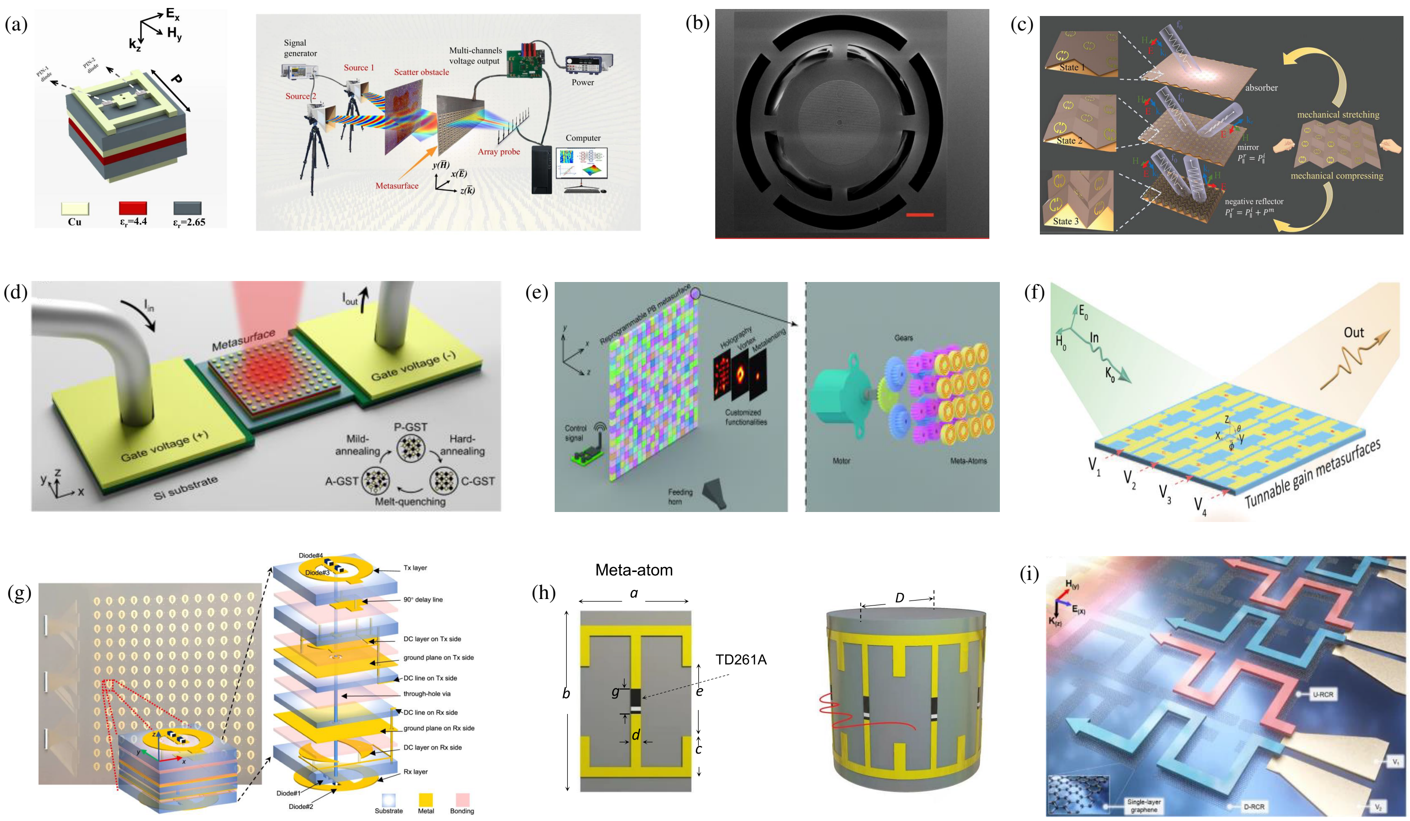

FIGURE 1. Reconfigurable metasurfaces studies. (a) High-efficiency tunable transmission metasurfaces for adaptive focusing in complex environment based on supervised-evolving learning algorithm [35]. (b) MEMS-tunable dielectric metasurfaces [41]. (c) Origami reconfigurable metasurfaces [43]. (d) Reprogrammable phase-change metasurface [50]. (e) Mechanically reprogrammable Pancharatnam Berry metasurface [38]. (f) Negative resistance induced reconfigurable gain metasurfaces [16]. (g) Transmissive reconfigurable metasurfaces [34]. (h) Gain metasurfaces and single-channel superscatterer [15]. (i) Single-pixel reconfigurable graphene metasurface [22]. Figures reproduced with permission from: (a) Ref. [35], Copyright 2023, Springer Nature; (b) Ref. [41], Copyright 2018, Springer Nature; (c) Ref. [43], Copyright 2019, Springer Nature; (d) Ref. [50], Copyright 2022, Springer Nature; (e) Ref. [38], Copyright 2022, SPIE & CLP; (f) Ref. [16], Copyright 2024, American Physical Society; (g) Ref. [34], Copyright 2024, Springer Nature; (h) Ref. [15], Copyright 2022, Springer Nature; (i) Ref. [22], Copyright 2024, Springer Nature.

configurable metasurfaces at microwave by embedding active components. Then, we focus on how to reshape the wireless communication environment by using intelligent metasurfaces with spatial/spatiotemporal modulations. Finally, we provide an outlook for future directions.

2. PHYSICAL REALIZATION OF INTELLIGENT METASURFACES

Although passive metasurfaces exhibit effectiveness in diverse scenarios, there exists a compelling imperative to imbue them with tunability to augment their functional capabilities. As a corollary, substantial efforts have been focused on the development of tunable metasurfaces endowed with the capacity to actively manipulate EM waves through external stimuli (Fig. 1). These tunable designs epitomize post-fabrication reconfigurable attributes and harbor considerable potential across a diverse spectrum of applications. The selection of a suitable modulation technique involves considerations such as materials compatibility and operating speed. Accessing certain physical phenomena may require ultrafast modulation techniques like photo-carrier excitation or optical nonlinearities in metals and semiconductors. Alternatively, slower modulation mechanisms like electrical gating or mechanical actuation can find applications in reconfigurable devices. Extensive research has been conducted on tunable metasurfaces employing a variety of tuning mechanisms. There are different categories about tunable metasurfaces, such as those based on functionality and applications. Here, we mainly talk about tunable metasurfaces in the logic of tuning methods.

2.1. Tuning Via Lumped Elements

Tunable lumped electronic components, with input impedance adjustable biasing voltage, provide an effective means to create tunable metasurfaces, particularly beneficial for microwave applications. Metasurface unit cells can integrate active components like diodes or transistors, receiving biasing through either direct current (DC) or radio frequency (RF) modulation. DC biasing signal typically induces changes in the impedance of the diodes, whereas RF biasing signal functions as a temporal or spatiotemporal modulation signal for modifying effective permittivity or conductivity over time. Finally, real-time full control of the metasurface can be achieved by a field-programmable gate array (FPGA) or a computer processor potentially running deep learning algorithms. For instance, a tunable metasurface utilizing PIN diodes has been proposed, enabling real-time control over deflection, diffusion, and polarization [33]. Furthermore, a transmissive 2-bit reconfigurable metasurface with a reconfigurable power router has been designed to enable object detection and localization [34]. Moreover, a tunable metasurface, based on a PIN diode and driven by a supervised-evolving learning algorithm, has been demonstrated for a neuro-metasurface focusing system [35], as depicted in Fig. 1(a). Through the use of varactor diode modulation and tuning, researchers have demonstrated a dynamic metasurface capable of independently modifying both the magnitude and phase of an electrically thin surface [36]. Each meta-atom can be individually tuned by incorporating pin or varactor diodes, not only allowing for continuous tuning but also unlocking exciting applications such as metalens [37, 38] and orthogonal angular momentum [39, 40]. However, it is crucial to note that tuning via lumped elements may not be suitable for applications beyond the GHz range, considering the operating frequency limitations of varactors and PIN diodes.

2.2. Mechanical Tuning

Mechanically tunable metamaterials are engineered structures that undergo deformation, rotation, buckling, folding, and snapping in response to applied mechanical forces, rather than altering their material properties. Microelectromechanical systems (MEMSs) emerge as viable choices for implementing mechanically tunable metamaterials because of their reconfigurable mechanical structures, minimal power requirements, and alignment with complementary metal-oxide-semiconductor (CMOS) technology. MEMS-tunable varifocal lenses have been designed composed of a converging and a diverging metasurface lens [41], as shown in Fig. 1(b). Another mechanism to realize mechanically tunable metamaterials is the stretching of flexible substrates. This is because the near-field and far-field interactions among antennas are highly responsive to alterations in their spacing. Based on this concept, a tunable metasurface has been proposed that can switch among distinct holographic images through substrate stretching [42]. Kirigami/Origami, the art of cutting paper, has also been effectively applied to optical tuning via structural configurations of constitutive unit cells. Origami reconfigurable metasurfaces enable the continuous tuning of the EM wavefront, either absorbing light energy or modulating light momentum, by transitioning the meta-structures from folded to unfolded configurations [43], as shown in Fig. 1(c). Furthermore, a mechanically tunable metasurface inspired by origami tessellation has been designed by a self-assembled 2D porphyrinic metal-organic framework formed by Zn nodes and flexible porphyrin linkers [44]. Microfluidics has been employed to create mechanically tunable metamaterials, as their optical responses undergo reversible changes when empty channels are filled with microfluidics. For example, a simple approach for achieving real-time tunable structural colors has been proposed through the incorporation of titanium dioxide (TiO_2) metasurfaces into the microfluidic channel that is tuned by introducing various solvents [45]. Twisted metasurfaces are a promising method to enhance the ability of dynamical manipulation by harnessing the uncorrelated structural twist [46–48]. While the potential of mechanically tunable metasurfaces for active photonics is significant, their effectiveness relies on precise integration with machinery and components to enable accurate control.

2.3. Phase-Change Materials

Phase-change materials (PCMs) such as germanium-antimony-telluride ($Ge_2Sb_2Te_5$, also called GST) and vanadium dioxide (VO_2), have been prominently employed to realize tunable metasurfaces because they exhibit reversible phase transitions in response to external stimuli. These materials are particularly noteworthy for their ability to induce unit-scale changes in refractive index during structural and electronic phase transitions. A substantial variation in the optical and electronic properties can be seen when GST undergoes reversible transitions between amorphous and crystalline phases induced by heating, electrical, or optical stimuli. An on-chip electrical switching platform is presented that is capable of binary switching and quasi-continuous tuning for $Ge_2Sb_2Se_4Te$ (GSST)-based tunable metasurfaces, enabling dynamic optical beam steering [49]. Furthermore, an optically tunable metasurface is proposed based on GST to realize reconfigurable optical devices showcasing examples such as writable focusing devices, holograms, and a resonant metamaterial [50], as shown in Fig. 1(d). Moreover, a phase change materials-based metasurface has been demonstrated for photonic routing in the near-infrared region [51]. VO_2, another prominent PCM, is distinguished by its ability to undergo a reversible metal-to-insulator transition upon heating. The insulator-to-metal transition in VO_2 can be induced either by direct heating [52], optical pumping [53], or electrical bias [54]. Unlike GST, VO_2 exhibits volatile (latching) phase transitions. The insulator-to-metal transition in VO_2 allows it to exhibit a broad range of electrical resistivities and complex refractive indices. This emphasizes its substantial potential in the development of tunable metasurfaces. A thermally tunable broadband absorber is presented based on VO_2 phase transitions in near-to mid-infrared regions [55]. Furthermore, an electrically tunable VO_2-based metasurface has been demonstrated for phase modulation in the near-infrared wavelength range.

2.4. Intelligent Metasurfaces with Spatial Modulation

The essence of intelligent metasurfaces in the applications of wireless communication is to steer electromagnetic waves and thus construct a smart radio environment by distributing a number of metasurfaces in the surrounding [56–63], as shown in Fig. 2. This capability makes intelligent metasurfaces particularly useful in addressing coverage gaps and enhancing signal strength in wireless networks. By deploying intelligent metasurfaces in strategic locations, it is possible to redirect and amplify signals, thereby improving coverage in areas that are typically challenging for traditional communication infrastructure. First, one of the primary applications of intelligent metasurfaces in wireless communication is to overcome physical ob-

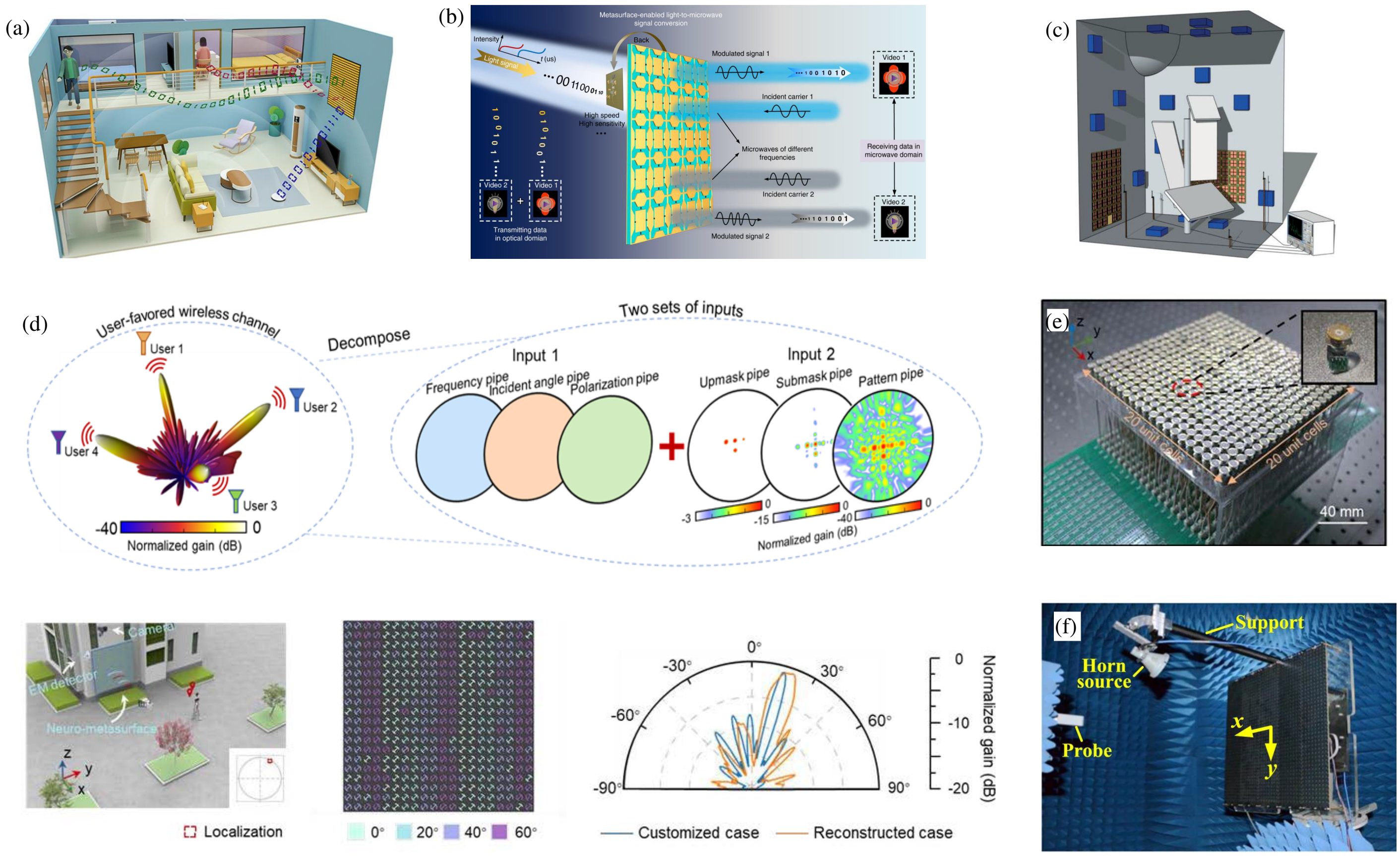

FIGURE 2. Intelligent metasurfaces based wireless communication with spatial modulation. (a) Metasurface-assisted massive backscatter wireless communication with commodity Wi-Fi signals [58]. (b) A light-to-microwave transmitter for wireless communications [62]. (c) Analog computation with Wi-Fi waves in an indoor room [60]. (d) The input wireless channel is decomposed into two sets of inputs including input 1 (frequency, incident angle, polarization pipes) and input 2 (upmask, submask, and pattern pipes) [57]. (e) Mechanical neuro-metasurfaces [57]. (f) Programmable metasurface with dynamic polarization, scattering and focusing control [56]. Figures reproduced with permission from: (a) Ref. [58], Copyright 2022, Springer Nature; (b) Ref. [62], Copyright 2022, Springer Nature; (c) Ref. [60], Copyright 2018, American Physical Society; (d), (e) Ref. [57], Copyright 2022, The American Association for the Advancement of Science; (f) Ref. [56], Copyright 2016, Springer Nature.

stacles that block or attenuate signals. For instance, intelligent metasurfaces can be deployed on walls, buildings, or other structures to reflect and redirect signals around obstacles, ensuring that they reach intended receivers without significant loss of strength. This capability is particularly useful in urban environments where buildings and other structures can create significant coverage gaps. Second, intelligent metasurfaces can significantly improve indoor coverage by redirecting outdoor signals into buildings and enhancing signal strength within indoor environments. By strategically placing intelligent metasurfaces on building exteriors or within rooms, it is possible to ensure that signals penetrate deeper into indoor spaces, providing better coverage and higher data rates for indoor users. This application is particularly beneficial in scenarios where traditional indoor coverage solutions, such as distributed antenna systems (DAS), are not feasible due to cost or complexity. Third, in outdoor environments, intelligent metasurfaces can be used to fill coverage gaps created by natural obstacles such as trees, hills, or other terrain features. By deploying intelligent metasurfaces on existing infrastructure, such as streetlights or utility poles, it is possible to redirect signals around these obstacles, ensuring continuous coverage for mobile users. This approach can enhance the overall user experience by reducing dropped calls and improving data connectivity in challenging outdoor environments. Fourth, intelligent metasurfaces can dynamically adjust beamforming patterns to track mobile users and provide optimal signal strength as they move through the coverage area. By continuously monitoring the location and movement of users, intelligent metasurfaces can reconfigure the reflection patterns to maintain strong and reliable connections. This dynamic capability is particularly useful in high-mobility scenarios, such as vehicular communication or drone-based applications, where users frequently change positions. Fifth, in addition to improving coverage, intelligent metasurfaces can also enhance network capacity by enabling more efficient use of the available spectrum. By dynamically adjusting the reflection and transmission properties of the metasurface, it is possible to create multiple spatial channels, effectively increasing the capacity of the wireless network. This capability is particularly important in dense urban environments where spectrum resources are limited, and the demand for high-speed data services is high.

Refs. [61, 62] used programmable metamaterials composed of unit cells with 0 and π phase responses, termed "0" and "1" elements. By arranging these elements in controlled sequences, various EM wave manipulations can be achieved. For example, periodic coding sequences can direct incident beams into specific directions. One can further extend to an n-bit digital-coding metasurface by carefully engineering the reflection phase using multiple PIN diodes or varactor diodes. The ability to digitally control and program the EM wave response of these materials paves the way for innovative applications and more versatile functionalities in various technological domains. Yang and colleagues presented a novel programmable metasurface capable of dynamically controlling polarization, scattering, and focusing of electromagnetic waves [56], as shown in Fig. 2(f). The metasurface is designed with tunable elements that can be adjusted in real-time, offering unprecedented flexibility in manipulating wavefronts. This innovation opens up new possibilities for applications in areas such as wireless communications, imaging systems, and electromagnetic wave management. The authors demonstrated the effectiveness of their design through both theoretical analysis and experimental validation, showcasing the potential of programmable metasurfaces in advancing modern technology.

For dynamic wireless channel management and autonomous adaption to user requirements, the idea of homeostatic metasurfaces has been proposed [57], as illustrated in Fig. 2(d). These are planar arrays driven by deep learning, consisting of numerous active elements, whereas each active element introduces independent modulation of amplitude, phase, and polarization to the incident EM waves. These neuro-metasurfaces mitigate dependence on traditional radio frequency components and showcase two notable characteristics: they remove the necessity for iterative computations and human intervention. Furthermore, an intelligent metasurface system has been proposed to perform both target tracking and wireless communications. This involves integrating computer vision with a convolutional neural network (CNN) for the automatic detection of moving target locations. Additionally, the dual-polarized digital programmable metasurface (DPM) , integrated with a pre-trained artificial neural network (ANN), facilitates intelligent beam tracking and wireless communications [59]. Moreover, the concept of reinforcement learning (RL) has been introduced to drive the programmable metasurface for on-site control of wireless links [63]. For proof of concept, a system has been designed to manipulate commodity wireless links. Through experiments, it has been demonstrated that the proposed RL-driven programmable metasurface (PM) significantly enhances the quality of the wireless link across multiple scenarios, irrespective of the varied positions of the transmitter and receiver.

2.5. Intelligent Metasurfaces with Spatiotemporal Modulation

Spatiotemporal metasurfaces leverage the duality of space and time to achieve unprecedented control over electromagnetic waves, representing a cutting-edge advancement in the field of optics and electromagnetics [64–68]. Traditional metasurfaces manipulate light by structuring materials spatially, but spatiotemporal metasurfaces extend this capability by incorporating temporal modulation. This dual-domain control opens up new possibilities for dynamic and adaptive optical devices. Combining spatial structuring with temporal modulation allows for more complex and versatile control of light. This includes effects such as wavelength shifts emulating the Doppler effect, Lorentz nonreciprocity, time-reversed optical behaviour, and negative refraction. Spatiotemporal metasurfaces represent a significant leap forward in the control of electromagnetic waves, combining spatial and temporal modulation to achieve dynamic and adaptive optical functionalities. This technology has the potential to revolutionize various fields, including telecommunications, imaging, and sensing, by providing lightweight, compact, and power-efficient components for active wavefront shaping.

Intelligent spatiotemporal metasurfaces provide new possibilities for steering signal in both time and space and constructing simplified-architecture wireless communication systems, such as PSK and QAM transmitters, as shown in Fig. 3. Traditional communication components can be mimicked by intelligent spatiotemporal metasurfaces, with the features of low cost and low power consumption. A new wireless communication scheme with both space- and frequency-division multiplexing enabled by spatiotemporal metasurfaces was put forward, which can be used for multichannel wireless communication system [66]. Spatiotemporal metasurfaces are realized by inputting different time-varying signals into metasurfaces to produce different harmonic waves. These harmonic waves are manipulated to different users. In this way, different users can simultaneously receive different signals.

Index modulation is a promising technique that enhances spectral efficiency and anti-interference capabilities by embedding part of the information, such as subcarriers, antennas, and time slots, into the transmitted signal. The authors leverage the unique properties of spatiotemporal metasurfaces to implement this modulation method [67], as shown in Fig. 3(d). By generating and harvesting different harmonic waves, additional bits are provided for index modulation. To further enhance the system's intelligence, tandem neural networks are employed to link the propagation paths of harmonic waves with the time-varying sequences required by the metasurfaces. The paper discusses the generalization of neural network inputs for vague targets and simulates multiuser scenarios using two wireless channels and harmonic waves to demonstrate the effectiveness of the proposed index modulation technique.

2.6. Other Applications

Intelligent metasurfaces can be used for many other interesting applications, such as dynamic recognition based on neuro-metamaterials (Figs. 4(a) and 4(b)) and intelligent self-adaptive invisibility cloak [69–75]. Ideal invisibility cloak should be like natural chameleon that can rapidly and automatically adjust its internal structure to remain invisible at all times. Chameleon has three key components to realize camouflage, i.e., photon-sensitive cell, central nervous system, and pigment cell. To replicate this mechanism, an intelligent cloak can be constructed using an electromagnetic detector, a deep learning sys-

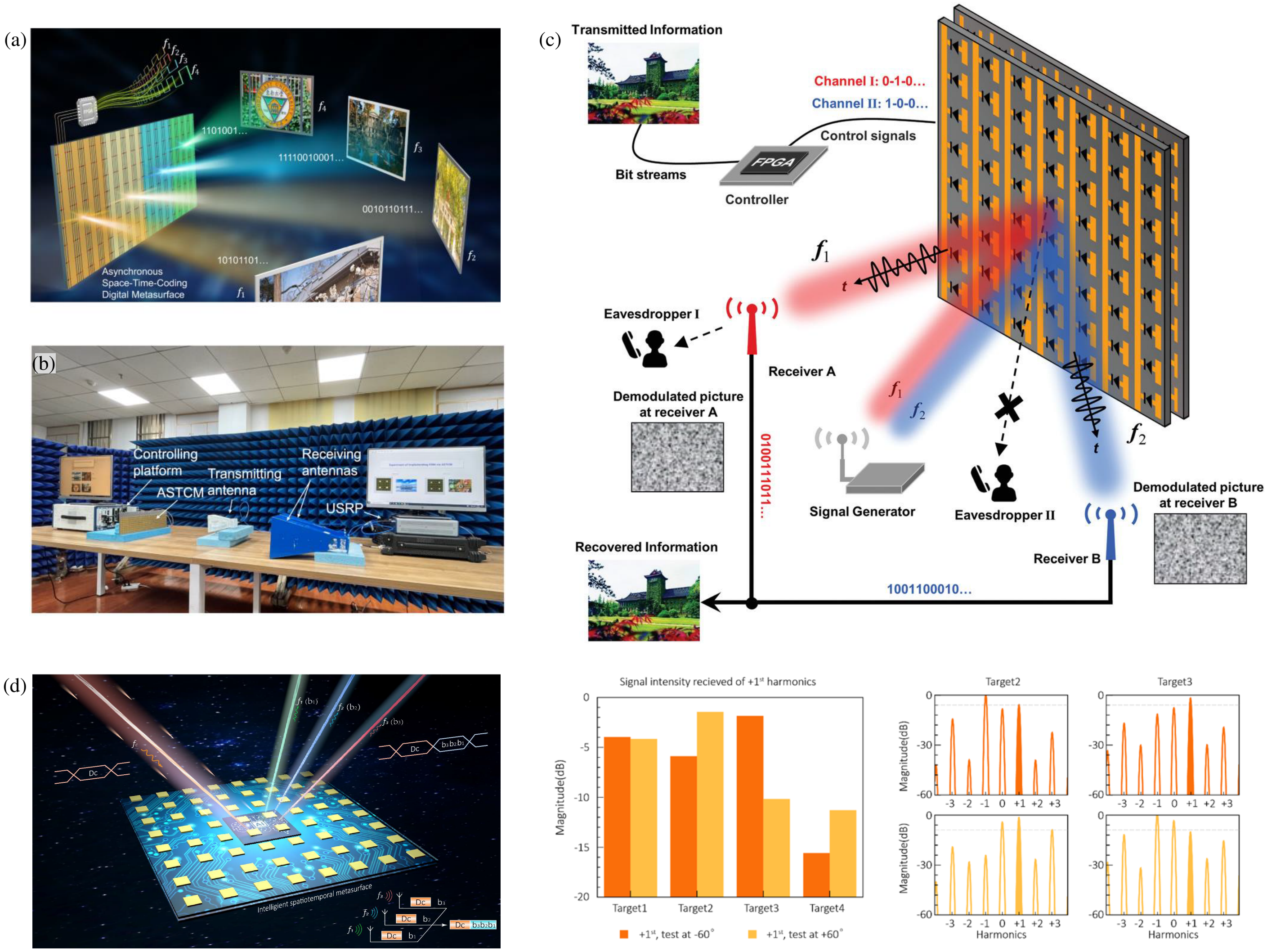

FIGURE 3. Intelligent metasurfaces based wireless communication with spatiotemporal modulation. (a), (b) Multi-frequency signals based on asynchronous space-time-coding digital metasurface [64]. (c) Physical level information encryption [68]. (d) Index modulation with intelligent spatiotemporal metasurfaces [67]. The system is enabled by a built-in inverse-design agent that automates spatiotemporal metasurfaces for different application demands. Figures reproduced with permission from: (a), (b) Ref. [64], Copyright 2023, Springer Nature; (c) Ref. [68], Copyright 2022, Wiley-VCH; (d) Ref. [67], Copyright 2023, Wiley-VCH.

tem, and reconfigurable metasurfaces. First, the electromagnetic detector senses incoming waves and the surrounding environment in real-time, providing essential inputs for the system [76–78]. Second, the deep learning system functions as the chameleon's central nervous system, determining how to adjust the scattered field around the object. Third, the reconfigurable metasurface implements the deep learning system's instructions. Each element within the metasurface includes an active component that dynamically adjusts the local reflection spectrum.

In the experiment, under various randomly-set landforms and illumination conditions, the measured near-field distributions matched those of the pure background, demonstrating that the intelligent cloak effectively conceals the hidden object [24]. To emphasize its real-time and dynamic capabilities, an experiment was conducted with an intelligently cloaked vehicle moving freely over a randomly uneven landform. Throughout this process, a receiving antenna continuously collected the scattered field. Remarkably, the amplitude of the time-varying signal remained almost unchanged, making the antenna unable to detect the presence and movement of the cloaked vehicle, in stark contrast to the uncloaked scenario. This method was further generalized to three-dimensional intelligent cloaked vehicle equipped with thousand-level reconfigurable full-polarization metasurfaces [72].

Very recently, an autonomous aeroamphibious invisibility cloak has been demonstrated, featuring integrated perception, decision, and execution modules [73], as shown in Figs. 4(c) and 4(d). This cloak is capable of maintaining invisibility across diverse and dynamic backgrounds while neutralizing external stimuli. The key physical innovation lies in the spatiotemporal modulation applied to tunable metasurfaces, which shapes the scattering field in both spatial and frequency domains. To intelligently control these spatiotemporal metasur-

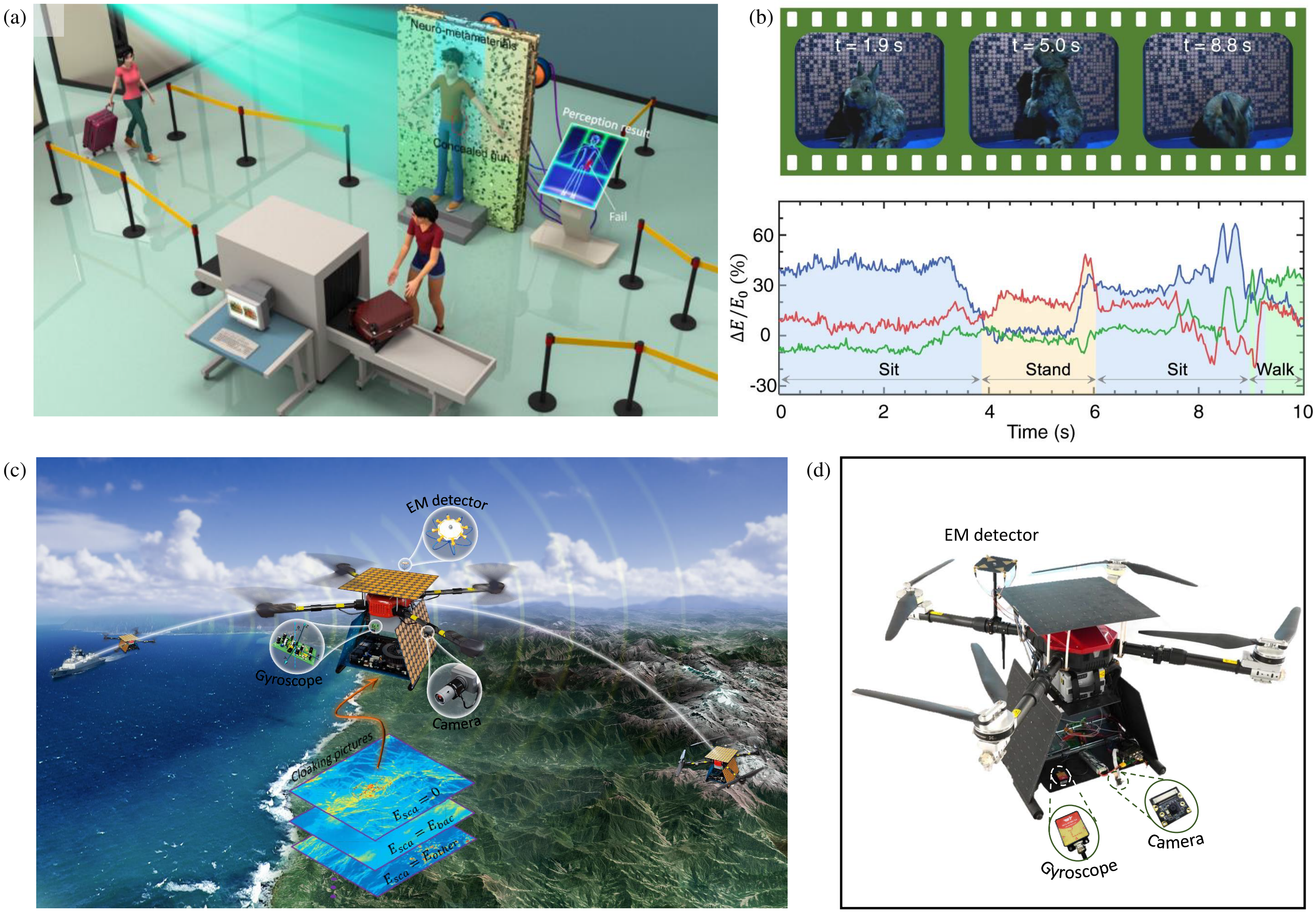

FIGURE 4. Intelligent metasurfaces enabled other applications. (a) Neuro-metasurfaces that can be applied for dynamic recognition [11]. (b) Real-time recognition of the rabbit's postures rabbits [11]. (c) Autonomous aeroamphibious invisibility cloak [73]. Such drone is equipped with perception, decision, and action functionalities to allow it to self-adapt to kaleidoscopic environments and offset external detection. Generation-elimination network is integrated to output the optimal spatiotemporal metasurfaces through maximum probabilistic inference. (d) Experimental intelligent invisible drone [73]. Figures reproduced with permission from: (a), (b) Ref. [11], Copyright 2022, Springer Nature; (c), (d) Ref. [73], Copyright 2024, SPIE & CLP.

faces, a stochastic-evolution learning approach is introduced that automatically converges on the optimal solution through maximum probabilistic inference. In a fully autonomous experiment, we implemented this concept on an unmanned drone, demonstrating adaptive invisibility in three distinct environments — sea, land, and air — with a similarity rate of up to 95%.

3. CONCLUSION

Recent advancements in intelligent metasurfaces have fundamentally transformed the field of wireless communications. These developments have introduced innovative technologies and methodologies that address the limitations of existing communication systems and pave the way for future advancements. Intelligent metasurfaces, through their ability to precisely control electromagnetic wave properties such as phase, amplitude, and frequency, have emerged as critical components in next-generation wireless networks. The transition from passive programmable to intelligent metasurfaces has been a significant breakthrough, enabling real-time manipulation of electromagnetic waves and fostering the development of advanced communication devices. The integration of these metasurfaces with microprogrammed control units and field-programmable gate arrays has significantly enhanced their versatility and functionality, allowing for dynamic and adaptive communication strategies. These intelligent metasurfaces have introduced novel transceiver architectures that improve signal processing efficiency and network performance. For instance, time-domain-coding and space-time-coding metasurfaces systems represent new approaches to enhancing spectral efficiency and energy utilization in wireless networks. The impact of these advancements is evident across various applications, from smart radio environments that mitigate the challenges of wireless channel conditions to innovative methods for path loss modelling and network optimization. The ability of intelligent metasurfaces to address issues such as high-frequency signal coverage, energy efficiency, and system capacity has marked a significant step forward in the development of future-generation (B5G/6G) communication systems. Looking ahead, the potential of intelligent metasurfaces extends far beyond their current applications. Ongoing research and technological developments are expected to unlock new capabilities and refine existing techniques, such as the assistance of deep learning algorithms to drive metasurfaces [79–85]. Future research directions should focus on exploring these new opportunities, and interdisciplinary researchers should work together to solve practical implementation challenges, and further expand the role of intelligent metasurfaces in shaping the future of wireless communication, such as the global inverse design of large-scale distributed metasurfaces [86], encryption communications [87, 88], and the metasurface deployment in complex environment [89]. By enabling sophisticated control over electromagnetic waves and fostering the development of innovative communication architectures, these advancements are set to redefine the landscape of future wireless networks, including physical layer security, wireless power transfer, and mobile edge computing. We also anticipate the envision of directly processing wireless signal at the physical space [90–93]. The ongoing research and technological progress in this field hold the promise of even greater achievements and applications in the coming years [94, 95].

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