DYNAMIC METASURFACE ANTENNAS FOR 6G EXTREME MASSIVE MIMO COMMUNICATIONS

Nir Shlezinger, George C. Alexandropoulos, Mohammadreza F. Imani, Yonina C. Eldar, and David R. Smith

ABSTRACT

Next generation wireless base stations and access points will transmit and receive using an extremely massive numbers of antennas. A promising technology for realizing such massive arrays in a dynamically controllable and scalable manner with reduced cost and power consumption utilizes surfaces of radiating metamaterial elements, known as metasurfaces. To date, metasurfaces are mainly considered in the context of wireless communications as passive reflecting devices, aiding conventional transceivers in shaping the propagation environment. This article presents an alternative application of metasurfaces for wireless communications as active reconfigurable antennas with advanced analog signal processing capabilities for next generation transceivers. We review the main characteristics of metasurfaces used for radiation and reception, and analyze their main advantages as well as their capability to reliably communicate in wireless networks. As current studies unveil only a portion of the potential of metasurfaces, we detail a list of exciting research and implementation challenges which arise from the application of metasurface antennas for wireless transceivers.

INTRODUCTION

The increasingly demanding objectives for 6th Generation (6G) communications have spurred recent research activities on novel transceiver hardware architectures and relevant communication algorithms. Such hardware architectures comprise large numbers of ElectroMagnetic (EM) radiating elements, thus paving the way for Multiple-Input Multiple-Output (mMIMO) communications. A mMIMO system with an arbitrarily large number of antenna elements can provide substantial gains in spectral efficiency with relatively simple signal processing algorithms. This potential has motivated the incorporation of mMIMO technology in the 5G New Radio (NR) interface, and mMIMO transceivers with an extremely large number of antennas are considered to continue being one of the key technologies for 6G communications [1].

With the widespread deployment of Internet of Things (IoT) devices, the number of nodes connected over wireless media is expected to reach the order of tens of billions in the next few years. To address these massive connectivity, high peak device rates, and increased throughput requirements, future wireless networks are expected to transit into dense deployments of coordinating extreme mMIMO transceivers (namely, Base Stations (BSs) and access points equipped with several hundreds or thousands of antenna elements), particularly in urban and indoor environments. While the theoretical gains of densely deployed mMIMO systems are still being unveiled [2], implementing such systems in practice is a challenging task. In particular, realizing transceivers with hundreds, or even thousands, of antenna elements being able to simultaneously serve multiple users, gives rise to a multitude of practical difficulties for conventional sub-6 GHz bands as well as millimeter wave and THz bands. Among those challenges are the high fabrication cost, increased power consumption, constrained physical size and shape, and deployment limitations.

Over the last few years, metamaterials have emerged as a powerful technology with a broad range of applications, including wireless communications. Metamaterials comprise a class of artificial materials whose physical properties, and particularly their permittivity and permeability, can be engineered to exhibit various desired characteristics [3]. When deployed in planar structures (a.k.a. metasurfaces), their effective parameters can be tailored to realize a desired transformation on the transmitted, received, or impinging EM waves [4]. Such structures have been lately envisioned as a revolutionary means to transform any naturally passive wireless communication environment (the set of objects between a transmitter and a receiver constitute the wireless environment) to an active one [5]. Their extremely small hardware footprint enables their cost-effective embedding in various 3D components of the environment (e.g., building facades and room walls/ceilings).

Dynamic Metasurface Antennas (DMAs) have been recently proposed as an efficient realization of massive antenna arrays for wireless communications [6, 7]. They provide beam tailoring capabilities and facilitate processing of the transmitted and received signals in the analog domain in a flexible and dynamically configurable manner using simplified transceiver hardware. In addition, DMA-based architectures require much less power and cost compared with conventional antenna arrays (i.e., those based on patch arrays and phase shifters) eliminating the need for complicated corpo-

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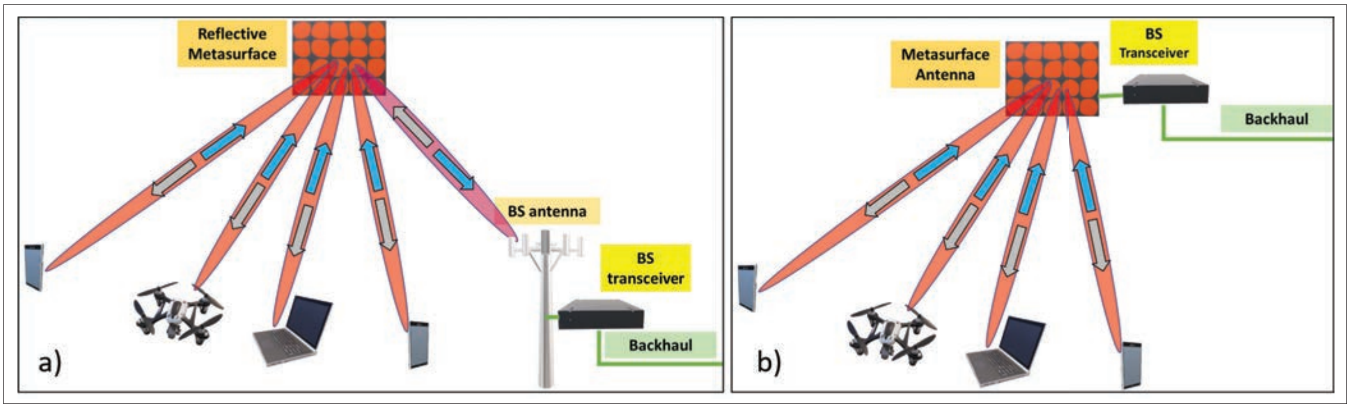

FIGURE 1. Two applications of reconfigurable metasurfaces in the downlink (gray arrows) and uplink (blue arrows) of multi-user mMIMO wireless communications: a) as nearly passive reflective surfaces; and b) as active transceiver antenna arrays.

rate feed and/or active phase shifters. DMAs may comprise large numbers of tunable metamaterial antenna elements that can be packed in small physical areas [8] for a wide range of operating frequencies. These combined features, that is, their ability to realize flexible antenna architectures with a massive amount of elements of reduced size, cost, hardware complexity, and power consumption, makes DMAs an appealing technology for the extreme mMIMO transceivers of 6G wireless networks. In contrast to passive metasurfaces that have received extensive attention recently [5], the potential and capabilities of metasurfaces as active mMIMO antenna arrays, as well as their associated challenges and future research directions, have not yet been properly treated in the wireless communication literature.

In this article, we discuss the promising application of DMAs as mMIMO transceivers for future wireless communications. We commence with a brief introduction of metasurfaces considered for wireless communications, highlighting the differences between their nearly passive and dynamic antenna counterparts. We then present the unique properties of DMAs as transceiving structures with Analog and Digital (A/D) processing capabilities. We elaborate on the relationship between DMAs and conventional hybrid A/D mMIMO architectures, which are based on phase shifters for analog processing [9] and discuss the main advantages and challenges of using DMA-based BSs for mMIMO communications. A simulation study evaluating the ability of DMAs to reliably communicate with reduced numbers of Radio Frequency (RF) chains by exploiting their inherent analog signal processing flexibility is detailed. We also present experimental results demonstrating the strong potential benefits of DMAs for wireless communications. The article is concluded with a description of open problems in this area of research and a discussion of future directions toward unveiling the potential of DMAs for 6G wireless communications.

Metasurfaces for Wireless Communications

Metamaterials comprise a class of artificial materials in which macroscopic structured elements mimic the atoms or molecules. Each metamaterial element behaves as an electric or magnetic polarizable dipole, the collection of which can often be characterized by an effective permittivity and permeability. These dipole moments can be engineered so as to achieve desired EM properties [3]. The underlying idea behind metamaterials is to introduce tailored inclusions in a host medium to emulate diverse targeted responses. When metamaterial elements are distributed over a planar surface, they are often referred to as metasurfaces [10]. Such 2-Dimensional (2D) structures support the individual tuning of each metamaterial element, allowing the metasurface to carry out different functionalities, such as radiation, reflection, beamforming, and reception of propagating EM waves [4]. The ability to stack a large number of elements in a limited surface area allows metasurfaces to achieve highly directed and/or focalized signaling enabling holographic beamforming [2]. The properties of each element can often be externally controlled, yielding a dynamic metasurface, also referred to as a reconfigurable intelligent surface [5].

Two main types of dynamically tuned metasurfaces have been considered recently in the context of wireless communications, as illustrated in Fig. 1. These are passive reflective surfaces [5] and active antenna arrays [7]. The former type builds upon the capability of metasurfaces to generate reconfigurable reflection patterns. The common application of such passive metasurfaces is to facilitate and improve communication between the BS and multiple users in urban or indoor settings by effectively modifying EM signal propagation. The deployment of a metasurface enables the communication system as a whole to overcome harsh non-line-of-sight conditions and improve coverage. To achieve this goal, the metasurface can be placed within small distances from the BS or the users, without increasing transmission power. Such reflective surfaces do not implement conventional relaying techniques (i.e., neither power amplification nor baseband signal processing) [5], but only reflect the impinging signal in a controllable manner. Passive reflective metasurfaces can also be part of an overall transceiver design (similar to a reflectarray), making it possible to embed information in its configurable reflection pattern in the form of reflection modulation [11]. Nearly passive reconfigurable intelligent surfaces require some level of control to alter the impinging EM wave in light of the dynamic wireless environment. This is achieved by embedding a digital control unit, which is capable

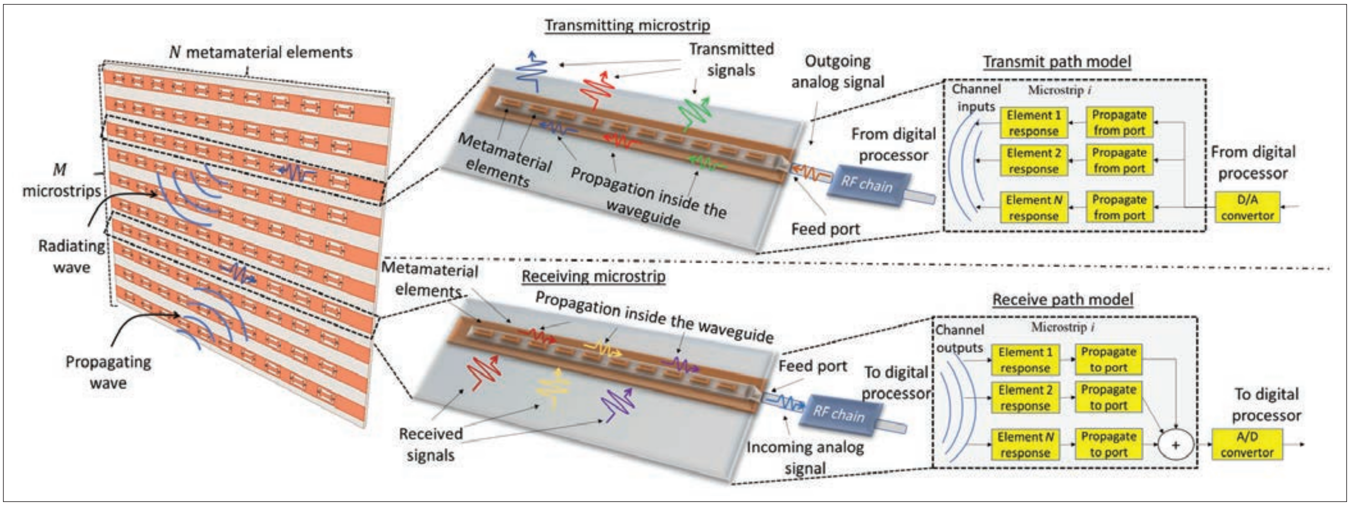

FIGURE 2. An *N*-element DMA consisting of M microstrips, where each microstrip is implemented as an 1D waveguide. The upper right part and the lower right part of the figure illustrate their operations during transmission and reception, respectively, along with their equivalent signal path models.

of tuning the metamaterial elements to obtain desired reflection patterns.

DMAs comprise an additional recent usage of metasurfaces for communication as mMIMO antenna structures. This application exploits their ability to realize planar, compact, and low cost dynamically tunable massive antenna arrays [7], which can be deployed in current and future BSs and access points. As such, a DMA-based BS will consist of a multitude of radiating metamaterial elements that can transmit and receive communication signals over the wireless channel. By dynamically tuning the EM properties of the DMA elements, one can control the analog beampattern for transmission and reception. Unlike passive reflective metasurfaces, which are the focus of considerable research attention lately, the usage of metasurfaces as active mMIMO antennas is a relatively new area of research. To understand the potential of DMAs for mMIMO systems, we discuss in the following section the architecture, properties, advantages, and drawbacks of using DMAs for transmitting and receiving communication signals.

DMAs for Massive MIMO Communications

In this section, we discuss the application of metamaterial-based planar antenna arrays in wireless communication systems. We first detail the architecture of DMAs and their main characteristics in the context of communications, and then elaborate on its operation when deployed for mMIMO BSs. Finally, some representative numerical evaluations are presented together with experimental results.

DMA Hardware Architecture

DMAs consist of a multitude of reconfigurable metamaterial radiating elements that can be used both as transmit and receive antennas. Those elements are placed on a waveguide through which the signals to be transmitted, and the received waveforms intended for information decoding, are transferred. The transceiver digital processor, which generates the outgoing signals and processes the received signals, is connected to the waveguide through dedicated input and output ports, respectively. In general, DMAs can use 2D waveguides connected to several input/output ports [6]. However, the common DMA architecture, on which we focus in this article, consists of multiple separate waveguide-fed element arrays, referred to as *1-Dimensional (1D) waveguides*, each connected to a single input/output port, as illustrated in Fig. 2. Such waveguides can accommodate a large number of radiating elements, which are commonly sub-wavelength spaced, allowing each input/output port to feed a multitude of possibly coupled radiators. Since this waveguide is typically designed to be single mode and the wave can only propagate along one line, its analysis is much easier than 2D waveguides (such as parallel plate waveguides), where a scattered wave from each element propagates in all directions. Furthermore, ensuring isolation between different ports is easier in 1D waveguides than in multiple ports of a 2D waveguide. A common implementation of 1D waveguides is based on *microstrips*, as illustrated in Fig. 2.

When DMAs are deployed as receive antennas, the signals captured at each metamaterial element propagate through the corresponding waveguide to the output port, where they are acquired and forwarded to the digital unit for baseband processing. In a DMA-based transmit antenna array, the signals to be radiated from its metamaterial elements are fed to each waveguide via its input port. The relationships among the radiating signals and those captured/fed at the input/output port of each waveguide are determined by the following two properties arising from the DMA architecture:

- Each metamaterial element acts as a resonator whose frequency response is described by a Lorentzian equation [4]. The parameters of the resonant circuit, that is, its oscillator strength, damping factor, and resonance frequency, are externally controllable and can be configured in run-time for each element individually. An illustration of the normalized magnitude of the element response achieved for several different resonant frequencies is depicted in Fig. 3. This figure demonstrates that the elements can be tuned to exhibit diverse responses, varying from bandpass to frequency flat filters.

- In each waveguide, the signal has to travel between the feed port and each metamaterial element. Consequently, the signals propagating along the waveguide accumulate different (frequency dependent) phases for each metamaterial element.

A detailed mathematical description of the resulting equivalent model for each DMA waveguide, which arises from the aforementioned properties, can be found in [7, 12], and is also illustrated in the right part of Fig. 2. As shown in this figure, the input/output port is connected to a set of radiating elements via a reconfigurable filter encapsulating the joint effect of the propagation inside the waveguide and the externally controllable frequency response of the metamaterial element.

DMA-Based mMIMO Transceivers

Similar to conventional massive antenna arrays, DMAs interface the electronic circuitry of a mMIMO transceiver with the EM waveforms propagating over the wireless channel. However, their application in mMIMO BSs induces several unique characteristics, which follow from the DMA structure discussed in the previous section. First, the number of independent data streams that can be processed by a DMA-based BS in the digital domain is typically much smaller than the number of its metamaterial-based antenna elements. In particular, a DMA consisting of M waveguides (e.g., the 1D waveguides in Fig. 2 termed as microstrips), each embedded with L metamaterial antenna elements, allows the transceiver to process M data streams, while utilizing in total $N = ML$ metamaterial elements. Consequently, DMA-based transceivers implement a form of hybrid A/D beamforming, since part of the processing of the transmitted and received signals is carried out in the analog domain, as an inherent byproduct of the waveguide-fed metamaterial array architecture. Such hybrid processing, which requires additional dedicated hardware in conventional mMIMO architectures, allows the BS to utilize an amount of metamaterial elements that is much larger than the number of the digitally processed data streams. This inherent expansion upon transmission and compression in reception is typically desirable in mMIMO BSs as a method to reduce the number of costly RF chains [9], while achieving increased beamforming gain, as well as to facilitate efficient operation under low quantization requirements [13]. Despite their similarity, there are several key differences between the equivalent model of DMAs as a hybrid A/D signal processing system, and conventional hybrid A/D beamforming architectures based on phase shifter networks [9]. These differences include controllable frequency selectivity, hardware savings, as well as power and cost savings, as detailed in the following.

In DMA-based transceivers, each metamaterial antenna element can exhibit a broad range of frequency responses with various combinations of amplitude and phase values, ranging from frequency selective to frequency flat profiles. These profiles are externally controllable for each element separately. This implies that DMA-based mMIMO BSs implement dynamically reconfigurable and frequency selective hybrid A/D beamforming by tuning their elements to impart different levels of attenuation and phase shift on the transmitted and received signals. Consequently, DMA-based BSs can be treated as hybrid A/D beamforming systems which do not require additional dedicated analog combining circuitry, while offering increased flexibility, compared to conventional hybrid A/D beamforming architectures consisting of interconnections of frequency static phase shifters and switches [9].

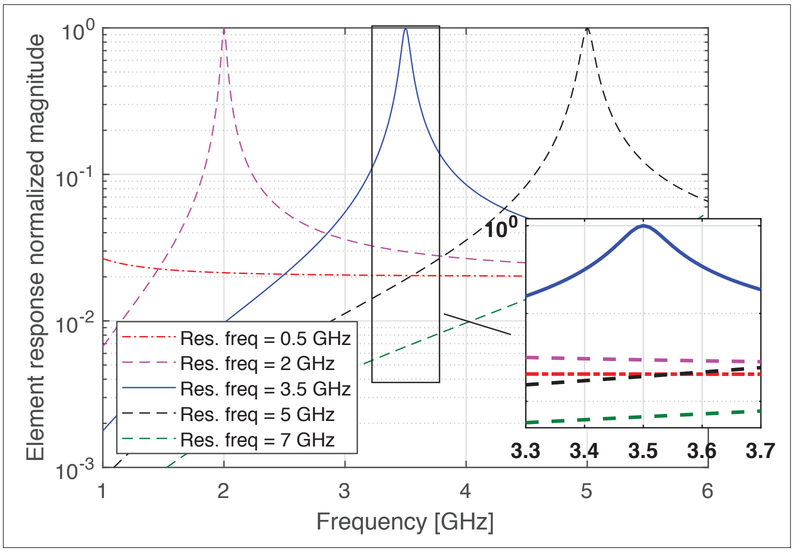

FIGURE 3. The normalized element response magnitudes for different settings of the Lorentzian resonant frequency (Res. freq) as functions of the operating frequency in GHz.

Furthermore, DMAs provide similar beamforming capabilities to those achievable with typical phased array antennas, but with much lower power consumption and cost. To better illustrate this point, we note that the radiation pattern formed by a DMA is the superposition of the radiated field from many metamaterial radiators, whose complex amplitude are determined by two factors: the tunable resonance response of the elements and the phase accumulated by the guided wave. Using simple holographic techniques, the tuning states of the metamaterial elements can be designed to form beams in any direction of interest. Since the tuning of metamaterial elements is usually accomplished with simple components, such as varactors, it requires minimal additional power for beam steering. This is in contrast to many common antenna arrays which use active phase shifters that consume significant power. The beamforming capability of DMAs is heavily dependent on the sub-wavelength spacing of metamaterial elements. This is due to the fact that the metamaterial elements amplitude and phase cannot be tuned separately. To augment this limited design space, one can utilize the phase accumulation of the feed wave as it travels between different elements. A densely sampled waveguide thus provides enough degrees of freedom to form any desired beamforming pattern.

Numerical and Experimental Results

The DMA architecture facilitates the implementation of massive amounts of metamaterial elements in simple, energy-efficient, compact, and low-profile design configurations, irrespective of the operating frequency. The planar physical shape of DMAs makes them suitable for installations in urban and indoor environments, and the inherent expansion/compression induced by their waveguide-fed architecture reduces the number of required expensive RF chain circuits. However, this expansion/compression, which stems from the fact that the transceiver can access the signals only at each waveguide's input/output ports, reduces the achievable performance compared to a fully-digital transceiver which is capable of simultaneously accessing the signals transmitted and received from each antenna element separately. In particular, this performance reduction follows from the DMA requirement for fewer digital streams than antenna elements, and is a common characteristic of hybrid A/D beamforming architectures.

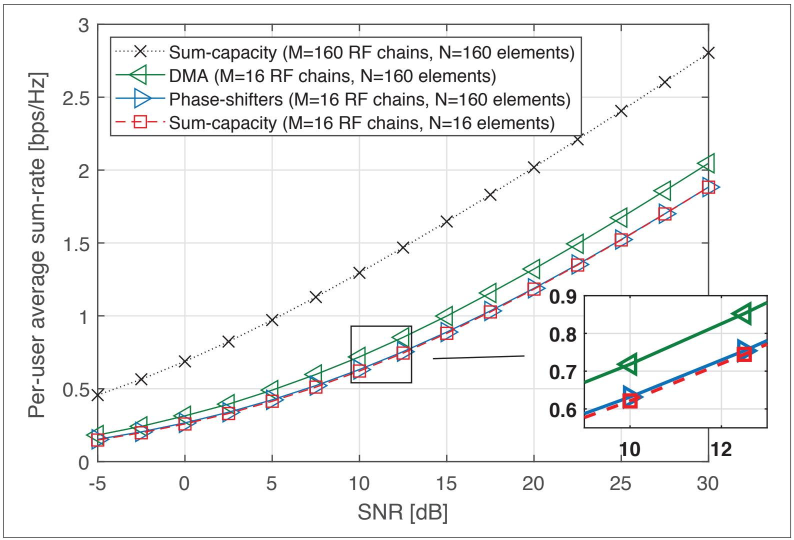

FIGURE 4. Achievable uplink sum-rate performance in bps/Hz versus the SNR in dB for a 160-antenna mMIMO BS with 16 RF chains serving simultaneously 64 users within a cell with 400m radius based on [7]. For the DMA architecture, each of the $M = 16$ microstrips includes $L = 10$ unit metamaterial elements. In the fully-connected hybrid A/D beamformer, the phase-shifter network interconnects each antenna element to all RF chains.

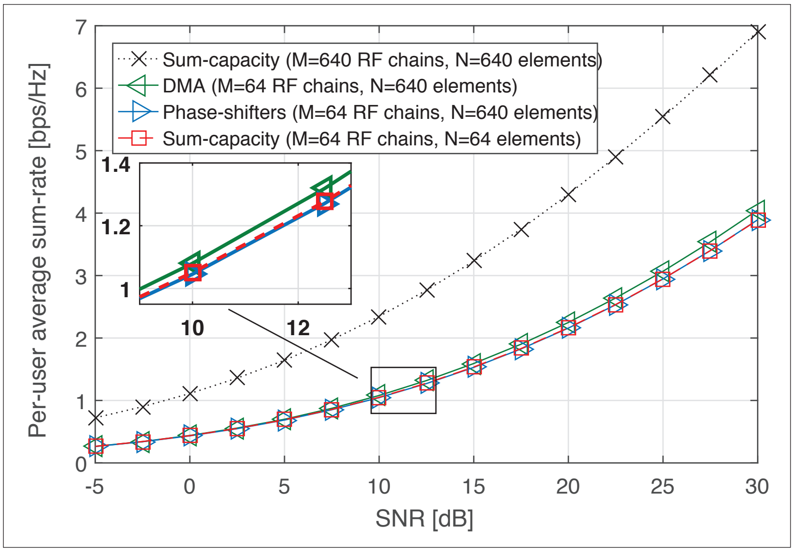

FIGURE 5. Achievable uplink sum-rate performance in bps/Hz versus the SNR in dB for a 640-antenna mMIMO BS with 64 RF chains serving simultaneously 64 users within a cell with 400m radius based on [7]. For the DMA architecture, each of the $M = 64$ microstrips includes $L = 10$ unit metamaterial elements. In the fully-connected hybrid A/D beamformer, the phase-shifter network interconnects each antenna element to all RF chains.

To evaluate the effect of the aforementioned properties on the performance of DMA-based mMIMO BSs, we depict in Figs. 4 and 5 the achievable uplink sum-rate performance of narrowband communications at 3.5GHz carrier frequency as a function of the operating Signal-to-Noise Ratio (SNR). The achievable sum-rate is computed by treating the uplink wireless channel as a multiple access channel, and thus the number of RF chains is not restricted to be larger than the number of users. In these figures, the same performance with a fully-connected hybrid A/D architecture is included, as well as the sum-capacity of the uplink channel when the number of BS antennas equals the number N of receiving elements and when it equals the number M of receive RF chains. The corresponding simulation scenario is based on the channel model detailed in [7, Sec. IV], which considers a rich scattering environment where the locations of the users within the cell are uniformly randomized, and the spatial correlation due to the sub-wavelength element spacing is obtained via the Jakes' model. Specifically, the scenario simulated consists of 64 user terminals uniformly distributed in a single cell of 400m radius that simultaneously communicate in the uplink direction with a mMIMO BS having $N = 160$ and $N = 640$ antenna elements in Figs. 4 and 5, respectively. For the DMA architecture, $L = 10$ unit metamaterial elements are coated upon each of the $M = N/L$ waveguides (microstrips in this case). With the fully-connected hybrid A/D beamforming architecture, all antenna elements are attached via phase-shifter networks to each of the M RF chains.

As observed in Figs. 4 and 5, the DMA architecture yields sum-rate performance closer to the sum-capacity with $M = N$ than conventional hybrid A/D architectures based on fully-connected networks of phase shifters. This advantage follows from the previously discussed capability of DMAs to implement different forms of analog signal processing, offering additional flexibility compared to conventional phase shifters. The rate gains of DMAs with M RF chains and $N = ML$ elements over the sum-capacity when the BS has M antennas indicates that connecting each RF chain to a microstrip with multiple elements can notably improve the communication rate compared to using each RF chain to feed a single antenna. While the numerical results are presented here for uplink communications, similar observations have been reported for the downlink case as well as for communications with low-resolution analog-to-digital converters [12].

Despite the growing interest in using reconfigurable metasurfaces (either as an intelligent reflector or a transceiver) to augment wireless communication systems, very few experimental studies have been conducted. Most experimental studies focus on verifying the possibility to model each tunable metamaterial radiator as a polarizable dipole, and optimize their tuning states to form desired beams. For instance, the DMA configuration illustrated in Fig. 2 consists of an array of microstrips, each comprised of a 1D waveguide-fed metasurface. An experimental implementation of such a dynamic 1D waveguide-fed metasurface, based on [14, 15], is shown in Fig. 6. This waveguide is fashioned with metamaterial elements with two different (inter-

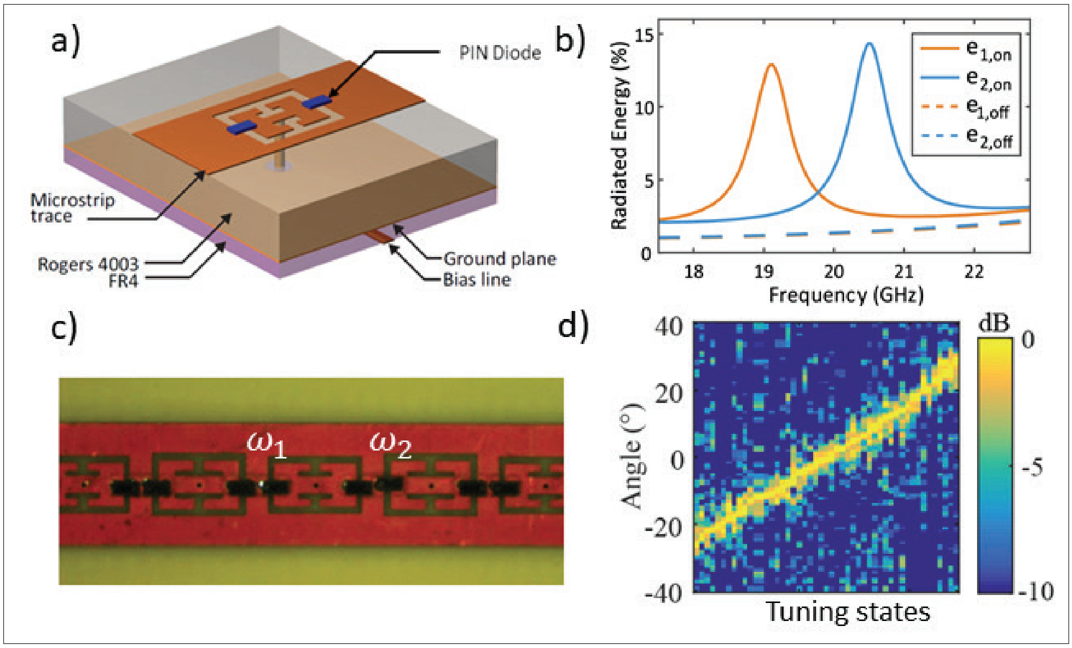

FIGURE 6. An experimental implementation of a dynamic 1D waveguide-fed metasurface: a) Detailed circuitry of a reconfigurable metamaterial element. b) The simulated response of the metamaterial element, where the impact of the PIN diodes to render the element in radiating ($e_{1,on}$ and $e_{2,on}$) and non-radiating ($e_{1,off}$ and $e_{2,off}$) states are shown. c) A close-up view of a sample 1D DMA with metamaterial elements having two different resonance frequencies. (a), (b) and (c) are adapted with permission from [15] © The Optical Society. d) Beamforming capability of the fabricated 1D DMA © [2017] IEEE. Reprinted, with permission, from [14].

The hardware architecture of DMAs enables efficient implementation of extreme mMIMO transceivers, which renders this concept a strong candidate technology for the physical layer of 6G communications. However, DMAs come with certain design challenges that need to be carefully addressed, while giving rise to new opportunities.

leaved) resonant frequencies. Each element is loaded with two PIN diodes as shown in Fig. 6a, which render the metamaterial element radiating and non-radiating. This makes it possible to achieve the different frequency selective profiles shown in Fig. 6b, which faithfully match the configurable Lorentzian model used in our achievable rate simulations in Figs. 4 and 5. In Fig. 6c we provide close-up view of the fabricated 1D DMA, whose experimental ability to form beams in different directions is shown in Fig. 6d. These experimental results validate their equivalent model as frequency selective hybrid architectures, while showcasing the potential of DMA-based mMIMO transceivers in forming multiple directed beams.

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OPEN RESEARCH CHALLENGES

As previously discussed, the hardware architecture of DMAs enables efficient implementation of extreme mMIMO transceivers, which renders this concept a strong candidate technology for the physical layer of 6G communications. However, DMAs come with certain design challenges that need to be carefully addressed, while giving rise to new opportunities. In the following, we list some of the most important related research challenges to date.

Frequency-Selective Analog Beamforming: Current theoretical studies and algorithmic designs for DMAs focus either on narrowband communications or ignore their capability to dynamically configure the frequency-selective profile of each unit metamaterial element. This unique property, which does not exist in any conventional hybrid A/D beamforming architecture, provides increased flexibility for the design of wideband operation by matching the spectral behavior of each element to optimize the equivalent wideband channel. The resulting unique model also gives rise to important theoretical questions regarding the fundamental limits of DMA-based transceivers, in terms of their maximal achievable reliable communication rate, as well as the dependence of the achievable rate on the number of metamaterial elements. Consequently, the true potential of DMA-based mMIMO systems in achieving reliable and ultra high rate communications is not yet fully explored.

Wireless Channel Estimation and Tracking: To date, studies on DMA-based communications assume that the transceiver has full channel knowledge. In practice, however, the channel coefficients need to be efficiently estimated, which is a

Experimenting with DMAs for communications in indoor scenarios is an important future step in unveiling their potential as mMIMO transceivers. Finally, although conceptually feasible, DMAs for communications in the high millimeter wave (around 60 GHz) and THz (above 100 GHz) bands are still in relatively early stages of research.

challenging task with hybrid A/D receivers. When channel estimation is carried out in a time-division duplexing manner, DMAs offer the possibility of tuning their elements to facilitate channel estimation via pilot signals, and to adapt in a manner which optimizes data reception in light of the estimated channel. The design and analysis of efficient algorithms for DMA-based BSs, which have to estimate features of the wireless channel and reliably communicate, have not yet been properly treated in the literature.

Hardware Design and Experimentation: A large body of fabricated designs and experimental work is still required in order to transit the DMA concept into an established technology for future extreme mMIMO BSs with hundreds or thousands of metamaterial elements. The experimental studies detailed in the previous section are an important first step which demonstrates the feasibility of this concept. Yet, the performance and other implications of using DMA-based transceivers need be tested in a broad range of wireless setups. To date, most experimental studies of DMAs are geared toward imaging and radar systems.

In particular, several key operation properties of DMAs should be thoroughly tested to fully understand their potential for mMIMO communications. First, one needs to quantify the level of correlation among the signals received by different metamaterial elements on the same waveguide as well as different waveguides. The impact of this correlation on the overall response needs to be investigated. In the example discussed in the previous section, the tuning of the metamaterial elements is optimized based on certain communication criteria. However, the resulting pattern may introduce more correlation or result in low SNR (for example, in a scenario where the resulting pattern is directed toward directions other than the intended users). The co-design of the metamaterial elements tuning states with the resulting pattern is another important factor that needs to be examined. When used as a transmitter, the possibility of the high amplitude RF signal (the carrier) to push the tunable component of each metamaterial element into a nonlinear regime needs to be investigated. This nonlinearity can cause intersymbol or intercarrier interference. Furthermore, experimenting with DMAs for communications in indoor scenarios is an important future step in unveiling their potential as mMIMO transceivers. Finally, although conceptually feasible, DMAs for communications in the high millimeter wave (around 60 GHz) and THz (above 100 GHz) bands are still in relatively early stages of research.

Finally, DMAs usually employ resonant metamaterial elements which are coupled to waveguides. The added losses due to the resonant response of the metamaterial elements and the dielectric and conductive losses inside the waveguides can reduce the efficiency of DMAs in comparison to conventional antennas. However, the overall power consumption of a system based on DMAs can be much less since they can operate without conventional active phase shifters or use fewer RF chains. Furthermore, DMAs offer a flexible design space where the antenna efficiency can be optimized. For example, the DMA can be implemented using hollow waveguides, circumventing waveguide losses all together. One can thus consider link power budget analysis of DMA-based communication systems and designing DMAs that satisfy desired efficiency criteria as an important future direction.

Hybrid Passive and Active Metasurfaces: As discussed in the introduction, the emerging concept of reconfigurable metasurfaces, with both its passive and active counterparts, is lately gaining increased interest for both controllable reflection and transmission/reception. It is reasonable to envision hybrid passive and active reconfigurable metasurfaces, notably strengthening the design flexibility for such surfaces and their performance gains in programmable wireless environments. For instance, having such a hybrid metasurface acting as a receiving device can significantly facilitate channel estimation, which is currently a major challenge and a source of substantial overhead in purely passive metasurfaces. In addition, hybrid metasurfaces will enable more advanced relaying strategies, overcoming the dominating impact of pathloss in their passive versions.

Use Cases and Applications: The use cases and applications where DMAs can provide substantial improvement compared to current architectures have not yet been thoroughly identified. For example, their planar shape and reduced size for a small number of RF chains facilitate their deployment in indoor environments, like buildings, malls, train stations, and airports. In such setups, DMAs are expected to communicate with multiple users in close line-of-sight conditions, possibly operating in the near-field regime. Such near-field scenarios bring forth the possibility of beam focusing, namely, the ability to focus the signal toward a specific location. This is in contrast to conventional beamforming in far-field conditions, where multiple directive beams can realize orthogonal links in the same indoor or outdoor area.

CONCLUSION

DMAs are an attractive radiating technology for next generation wireless systems, making it possible to realize dynamically controllable mMIMO antennas of reduced cost and power consumption compared to conventional arrays. In this article, we surveyed some of the key properties of DMAs in the context of mMIMO systems, including their operation model during their transmission and reception, tunable frequency selective profile, beam steering capabilities, as well as advantages and drawbacks compared to conventional arrays. We concluded with a set of key open research directions, which are expected to pave the way in unveiling the full potential of using active metasurfaces in 6G wireless communications.

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The use cases and applications where DMAs can provide substantial improvement compared to current architectures have not yet been thoroughly identified. For example, their planar shape and reduced size for a small number of RF chains facilitate their deployment in indoor environments, like buildings, malls, train stations, and airports.