Reconfigurable Surfaces for Wireless Communications

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***Abstract*—Reconfigurable surfaces have recently attracted the interest of researchers in wireless communications. In this paper, we overview the potential applications of reconfigurable surfaces in wireless communications and discuss their design requirements for emerging wireless applications.**

***Index Terms*—Metamaterials, reconfigurable intelligent surfaces, holographic surfaces, index modulation, backscattering.**

I. Introduction

During the last few years, reconfigurable surfaces have received major attention from the wireless community. In this context, a reconfigurable surface is a dynamic metasurface, i.e., a metamaterial-made electromagnetic object whose thickness is much smaller than the wavelength and the other dimensions of the surface [1]. Wireless researchers are studying these surfaces extensively with focus on their electromagnetic and communication-theoretic modeling [2], [3], and signal processing and optimization challenges [4], including the impact of channel estimation and control overhead for enabling their dynamic configuration [5]. In this paper, we provide an overview of the potential applications of reconfigurable surfaces in wireless communications and discuss their specific features for several emerging potential applications.

II. Relay-Type Surfaces: Reconfigurable Intelligent Surfaces

One of the most studied applications of dynamic metasurfaces in wireless communications is their use as relay-type surfaces, i.e., reconfigurable intelligent surfaces (RIS). RISs are currently being investigated within an industry specification group of the European telecommunications standards institute (ETSI)[1]. Relay-type surfaces have the main feature of being nearly-passive, i.e., they are not equipped with power amplifiers, digital signal processing units, and RF chains. They are constituted by two main components: a large number of passive scatterers and the corresponding electronic circuits to enable the reconfigurability. The main motivation of deploying nearly-passive surfaces lies in the desire of telecommunication operators to offer blanket coverage when the deployment of regular full-stack cells is not possible (e.g., no availability of backhaul) or may not be economically viable[2].

Examples of possible uses of relay-type surfaces are illustrated in Fig. 1. Specifically, these surfaces can be utilized (1) to control the multipath without relying on complex multiple-antenna transmitters and receivers; (2) to provide coverage in blind-spot areas that are difficult to reach; as well as (3) to enhance the rank of ill-conditioned wireless channels. While the first two case studies are well explored in the literature, the third case study is less investigated. Indeed, it is often argued that relay-type surfaces may be beneficial only in deployment scenarios where a sufficiently reliable line-of-sight (LOS) link is not available. In the presence of a LOS link, however, a relay-type surface provides a digitally controllable scatterer that is located geographically apart from the transmitter and receiver, and that, under some conditions, results in a well-conditioned concatenated channel, e.g., when the two constituent (LOS and reflected) paths have a sufficient angular separation [6, Section 7.2.5].

[1]https://www.etsi.org/committee/1966-ris?jjj=1665239878113.

[2]https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3988.

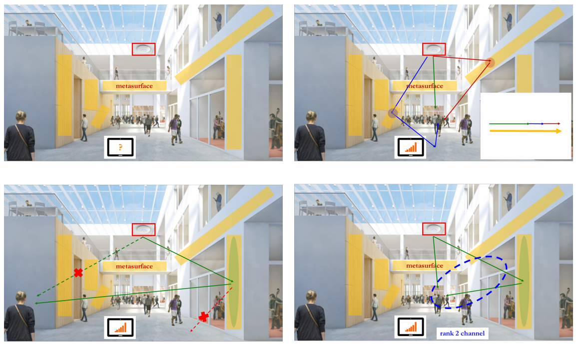

Fig. 1. Relay-type surfaces: Nearly-passive dynamic metasurfaces that are utilized for controlling the multipath through beamsteering or focusing; for overcoming coverage holes through smart reflections or refractions; and for increasing the rank of rank-deficient channels by capitalizing on the presence of geographically distant digitally controllable scatterers.

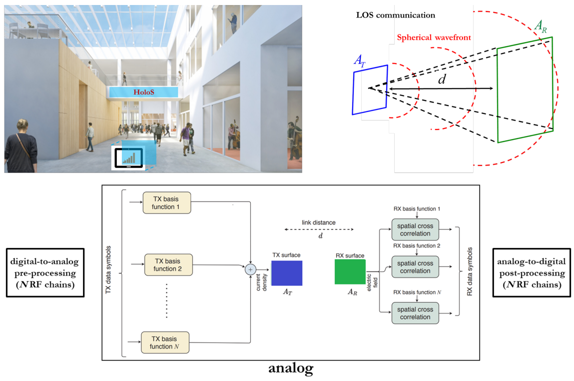

Fig. 2. MIMO-type surfaces: Active dynamic metasurfaces that are utilized to realize hybrid multiple-antenna transceivers with a limited number of RF chains compared to the number of scattering elements, and to enable multi-mode communication even in LOS channels.

III. MIMO-Type Surfaces: Holographic Surfaces

A less studied but emerging application of dynamic metasurfaces is the implementation of multiple-input multiple-output (MIMO) transceivers that enable multi-mode communication (spatial multiplexing) in LOS propagation conditions and in the absence of rich scattering (multipath). As shown in Fig. 2, this is possible by capitalizing on the spherical curvature

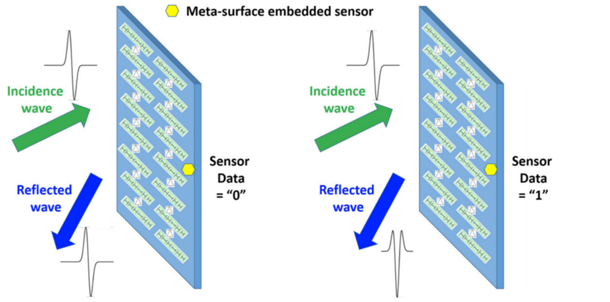

Fig. 3. Information surfaces for backscattering: Nearly-passive dynamic surfaces that are utilized to encode data onto their reconfigurable features, such as the waveform of the reflected wave, without the need to creating new radio waves and using additional transmit power.

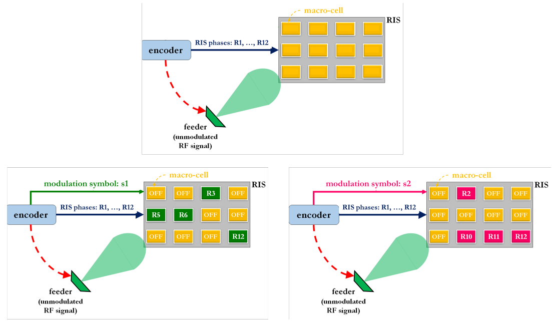

Fig. 4. Information surfaces for index modulation: Nearly-passive dynamic surfaces that are utilized to modulate data by using one single-RF chain and by encoding the information symbols onto their reconfigurable features, such as the subset of activated scattering elements used for beamsteering.

of the electromagnetic waves in the radiative near-field of the surfaces. Holographic surfaces are dynamic metasurfaces that are active, i.e., they are equipped with RF chains, power amplifiers, and digital signal processing units. However, they are realized based on a parsimonious utilization of RF chains and power amplifiers, as compared with the number of scattering elements. This application is illustrated in Fig. 2. More precisely, two electrically-large surfaces operating in the Fresnel region under paraxial conditions create a wireless channel whose number of degrees of freedom (DoF) is

$$\mathrm{DoF} \approx \max\left\{1, \frac{A_T A_R}{(\lambda d)^2}\right\} \tag{1}$$

where A_T and A_R are the apertures of the transmit and receive surface, respectively, λ is the wavelength, and d is the transmission distance between the two surfaces.

The DoF in (1) represents the number of symbols that can be spatially multiplexed in an interference-free manner provided that appropriate basis functions are utilized for encoding and decoding them [7], [8]. This implies that it is possible to realize a hybrid architecture, as illustrated in Fig. 2, in which the number of RF chains and associated digital-to-analog and analog-to-digital converters are equal to the number of DoF and are independent of the number of reconfigurable elements of the surface. This approach is reminiscent of the concept of continuous aperture phased MIMO [9].

IV. Information Surfaces

A. Backscattering

A third emerging application of dynamic surfaces in wireless communications is the design of efficient backscatter communications. This is illustrated in Fig. 3 and was originally introduced in [10]. Consider a dynamic metasurface equipped with sensors for environmental monitoring. The data measured by the sensors may be encoded "for free" in the reflected electromagnetic wave by modifying any reconfigurable feature of the surface, such as the waveform of the reflected wave.

B. Index Modulation

Another possible application of dynamic metasurfaces in wireless communications is the implementation of single-RF multi-stream modulation schemes. A simple example for single-stream transmission is illustrated in Fig. 4. In this case, the symbol to be transmitted is encoded, through reflections, onto specified activation patterns of the surface. Multiple streams can be encoded by mapping tuples of symbols onto appropriately optimized activation patterns, or, more in general, reconfigurable features of the surface. This approach is referred to as metasurface-based modulation [11].

V. Conclusion

In this paper, we have overviewed the potential applications of reconfigurable surfaces for wireless applications, and have elaborated on the specific features and functionalities of three types of surfaces, namely relay-type surfaces, MIMO-type surfaces, and information surfaces.

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