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Advances in Spacetime-Modulated Metasurfaces

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Abstract

Breaking the fundamental limitations of conventional time-invariant systems, spacetime-modulated metasurfaces have a transformative potential for modern electromagnetic technology. This paper reviews some of our recent research in this area, which includes the applications of spread-spectrum camouflaging, Direction-of-Arrival (DoA) estimation and wireless multiplexing or tunable refraction. Moreover, it discusses the challenges related to this emerging technology.

1 Introduction

Metasurfaces are the two-dimensional counterparts of voluminal metamaterials. They consist of two-dimensional lattices of subwavelength scattering particles supported by a deeply subwavelength substrate, and they represent a revolutionary concept in electromagnetic technology given their attractive features of low profile, low loss, easy fabrication and unprecedented flexibility in manipulating waves [1, 2].

The vast majority of the metasurfaces reported to date are modulated in space only, and not in time. As a result, they are limited by the fundamental bounds imposed by the laws of physics to linear time-invariant (LTI) systems. In contrast, time-variant, or spacetime-variant, metasurfaces, are not subjected to these bounds, and present therefore an interesting potential for novel electromagnetic systems with superior performance and extra functionalities [3–5].

Research on time-modulated and spacetime-modulated metasurfaces has been recently initiated and a few related applications have already been reported. These applications include magnetless nonreciprocal devices [6, 7], simplified wireless communication systems [8, 9] and serrodyne frequency translators [10].

This paper overviews some of our recent work in this area, presenting particularly the applications of spread-spectrum camouflaging, Direction-of-Arrival (DoA) estimation and wireless multiplexing or tunable refraction, and discussing the challenges of this technology [11–15].

2 Spread-Spectrum Camouflaging

Figure 1 depicts concepts of metasurface spread-spectrum camouflaging that we have been recently working on.

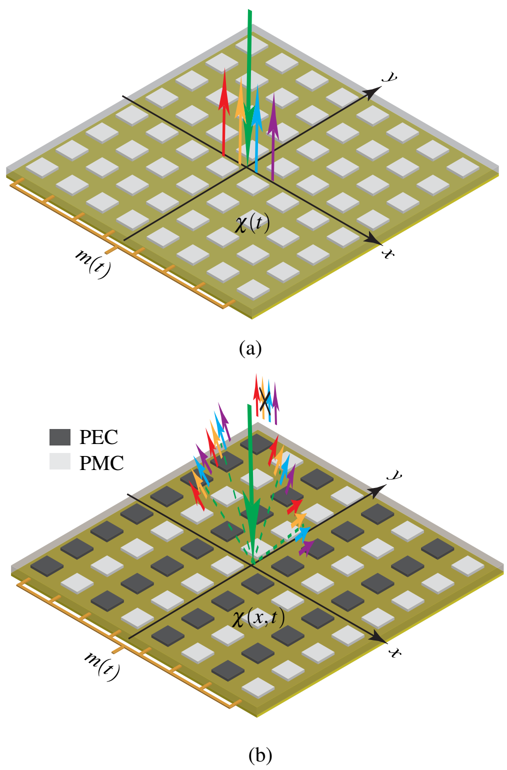

Figure 1. Camouflaging based on a spacetime-modulated metasurface [13]. (a) Time-only modulation, providing temporal spectrum spreading. (b) Spacetime modulation, providing simultaneously temporal and spatial spectrum spreading.

Figure 1(a) represents the pure-time modulated camouflaging metasurface system reported in [13]. In this system, time modulation is realized by alternating the metasurface between the states of a Perfect Electric Conducting (PEC) mirror and a Perfect Magnetic Conducting (PEC) mirror, using a periodically repeated random sequence that controls diodes connecting the patches to the ground plane of the structure. This modulation spreads out the temporal spectrum of the incoming wave and thereby reduces the power spectral density of the signal below the presumed detection level of the interrogator. As a result, objects placed below the metasurface are camouflaged, without requiring any size or shape alteration. Moreover, this system offers the extra features of selective camouflaging and interference immunity, provided by the favorable autocorrelation property of the selected pseudo-random noise modulation sequence [11].

Figure 1(b) shows an extension of the metasurface camouflaging system of Fig. 1(a). Now the metasurface is not only time-modulated, but also space-modulated insofar as the unit cell is formed by a PEC-PMC pair mirror at each instant of time, with both states being temporally modulated (as before) to their counterpart. As a result, this system adds spatial spectrum spreading to temporal spectrum spreading, which further reduces the power spectral density of a given observer and hence further enhances the camouflaging performance of the system.

3 Direction of Arrival (DoA) Estimation

Figure 2 describes the concept of Direction-of-Arrival (DoA) estimation based on a spacetime-modulated metasurface [14].

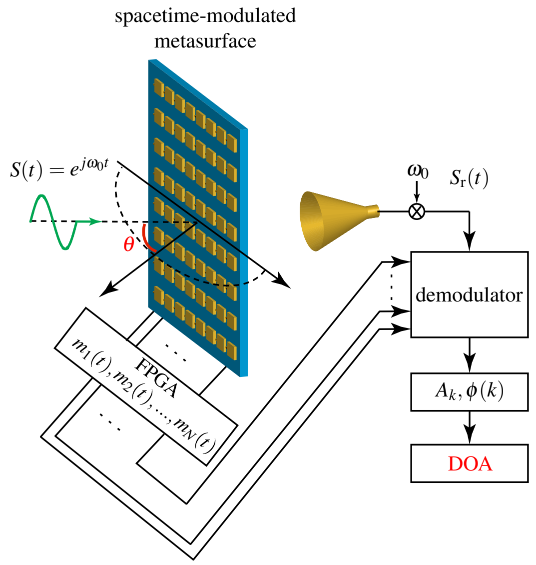

Figure 2. Direction-of-Arrival (DoA) estimation based on a spacetime-modulated metasurface [13].

Each column of the metasurface is modulated by a time sequence selected from a set of orthogonal sequences. When a wave impinges on the metasurface, under a given angle, it first interacts with the spacetime-modulated metasurface, and passes through it to reach a pick-up antenna. Due to the orthogonality of the modulation, the phase information of each the column, namely the array factor vector of that column, can be retrieved, and the direction of arrival of the wave is hence estimated. Compared to conventional DoA estimators, this system offers the benefit of using a single antenna instead of an antenna array.

4 Spatial Multiplexing and Tunable Refraction

Finally, Fig. 3 presents the concept of spatial multiplexing based on a space-time modulated metasurface [15].

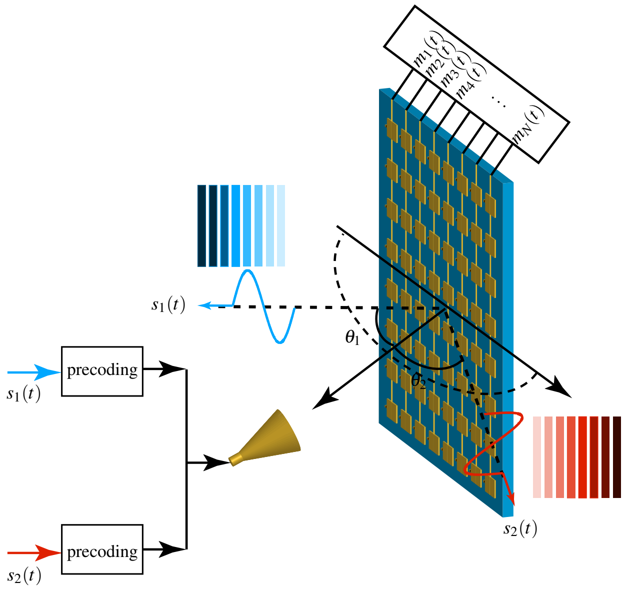

Figure 3. Spatial multiplexing based on a spacetime-modulated metasurface [15].

As in the DoA system, each column of the metasurface is modulated by a time-sequence selected from an orthogonal set. For simplicity, the figure shows the case of just two users. First, the user signals are encoded so as to carry the information of the direction of the intended receivers. Next, these signals are combined together and radiated by a base-station antenna towards the metasurface, which is placed in the area intended for communication. The mixed signal received by the metasurface is then spacetime-demodulated by a processor that imparts to the structure the required phase gradients to radiate the different signals to their final destination.

This metasurface may also be used for tunable generalized scattering, whereby the information on the desired reflection or/and refraction angles is encoded in the incident wave so that this wave is then routed to the corresponding direction(s). In contrast to conventional technology, where different reflection-refraction angles require different metasurface structures, this technology achieves arbitrary reflection-refraction directions from a unique metasurface structure via proper encoding.

5 Discussion

Spacetime-modulated metasurfaces, remarkably, can simultaneously manipulate the temporal and spatial spectra of electromagnetic waves [3], and realize operations that break the fundamental bounds imposed on conventional

LTI systems [4, 5]. However, they will need to meet a number of technical challenges to really become a transformative technology. Some of these challenges are the following:

1) Although all the spacetime-modulated metasurfaces described in this paper have only two states (PEC and PMC), more general amplitude and phase states are required for more sophisticated applications. The engineering of metasurfaces offering such response diversity is of great complexity.

2) Most of the designs of spacetime-modulated metasurfaces require lumped elements, such as diodes and varactors. These elements typically include parasitic resistances which leads to non-negligible loss, whose mitigation is not trivial.

3) Time-modulated metasurfaces induce temporal frequency transitions, i.e. the generation of new temporal frequencies, as nonlinear systems. In some applications, such as that of camouflaging, such temporal frequency generation is naturally desired. However, it may be undesired in other applications, such as for instance refraction and multiplexing. The termination of undesired frequencies is an area that still needs to be explored.

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