Intelligent Time-Varying Metasurface Transceiver for Index Modulation in 6G Wireless Networks

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Abstract—Index modulation (IM) is one of the candidate technologies for the upcoming sixth generation (6G) wireless communications networks. In this paper, we propose a space-time-modulated reconfigurable intelligent metasurface (RI-MTS) that is configured to implement various frequency-domain IM techniques in a multiple-input multiple-output (MIMO) array configuration. Unlike prior works which mostly analyze signal-theory of general RI-MTS IM, we present novel electromagnetics-compliant designs of specific IMs such as sub-carrier index modulation (SIM) and MIMO orthogonal FD modulation IM (MIMO-OFDM-IM). Our full-wave electromagnetic simulations and analytical computations establish the programmable ability of these transceivers to vary the reflection phase and generate frequency harmonics for IM. We show that the bit error rates of our RI-MTS-based SIM and MIMO-OFDM-IM are within an order of conventional OFDM.

Index Terms—Index modulation, MIMO, OFDM-IM, reconfigurable intelligent surface, time-varying metasurface.

I. INTRODUCTION

TIME-modulated antenna arrays (TMAAs), whose radiated power pattern is steered by varying the width of the periodic pulses applied to each element, are long known to have applications in side-lobe reduction [1, 2], harmonic beamforming [3], and directional modulation in phased arrays [4]. Lately, TMAA based on metasurfaces (MTSs) have drawn significant interest in the engineering community [5] because of their ability to control and manipulate electromagnetic (EM) waves in a sub-wavelength thickness through modified boundary conditions [6, 7]. The MTS, viewed as a two-dimensional (2-D) equivalent of metamaterials (MTMs), is a synthetic electromagnetic (EM) surface composed of sub-wavelength patches, or meta-atoms, printed on one or more dielectric substrate layers [8]. Through careful engineering of each meta-atom, MTSs can transform an incident EM wave into an arbitrarily tailored transmitted or reflected waveform [9, 12].

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Recent developments in spatio-temporally (ST) modulated metasurfaces have unlocked a new class of nonlinear and nonreciprocal behaviors, including direct modulation of carrier waves [5], programmable frequency conversion [13, 14], controllable frequency harmonic generation [15], and cloaking [15, 17]. These properties are very attractive for designing future low-cost and light-weight wireless communications systems where control of beam-pattern is key to enable reliable and efficient information delivery through massive multiple-input multiple-output (MIMO) antenna arrays [18]. Notably, reconfigurable intelligent metasurfaces (RI-MTSs) are capable of applying dynamic transformations of EM waves and have been recently proposed as sensors in fifth and sixth-generation (5G and 6G) smart radio environments [19]. An RI-MTS employs an array of individually-controllable meta-atoms to scatter incident signals to maximize metrics such as receiver signal-to-noise ratio (SNR) [18]. While several theoretical studies analyze signal processing for 5G/6G RI-MTSs [19, 21] and large intelligent surfaces (LISs) [22, 23], their specific EM analyses remain unexamined.

Contrary to these previous works, in this paper, we focus on the EM analysis and implementation of RI-MTSs for wireless communications. In particular, we consider transceiver for index modulation (IM) which is identified as one of the preferred 5G/6G technologies [24] largely because of its improved energy and spectral efficiencies (EE and SE) over conventional modulations [25]. In IM, the information is transmitted through permutations of indices of spatial, frequency, or temporal media. Common IM techniques [26, 27] include spatial modulation (SM) [28], subcarrier index modulation (SIM) [29], and orthogonal frequency-division multiplexing (OFDM) [30].

Our prior work [31] introduced the concept of RIS-based spatial modulation (SM). Motivated by recent research in ST-MTSs, we hereby propose and demonstrate RIS-based designs for a variety of IM techniques such as frequency shift keying (FSK) [32], OFDM-IM [24], and MIMO-OFDM-IM [33]. We implement these FD-IM techniques using the concepts of ST-metamaterials, TMAAs, and reflect-array antennas. Our full-wave EM simulations for meta-atom design validate the scattering radiation pattern of our finite RI-MTS array. Finally, we validate the RIS performance using wireless communications model and establish that, despite occupying less spectrum, our proposed designs result in bit error rates (BERs) that are very close to traditional OFDM.
II. SYSTEM MODEL

Consider a MIMO-OFDM wireless system with \( N_t \) transmit and \( N_r \) receive antennas. In OFDM, a frequency-selective fading channel is handled by dividing the spectrum into multiple flat-fading subchannels of equal bandwidth \([30]\). Unlike standard FDM where the carriers are non-overlapping and separated by additional guard bands, the gap between OFDM subcarriers is equal to the inverse of the symbol duration. The resulting overlap of subcarriers, with the peak of one coinciding with the nulls of the other, increases the spectral efficiency \([34]\). Each one of the \( N_r \) symbols independently modulates one of the equi-bandwidth OFDM subcarriers that are transmitted simultaneously. The sum of the modulated signals is the complex baseband OFDM signal

\[
x(t) = \frac{1}{\sqrt{N_t}} \sum_{n=0}^{N_t-1} X_n e^{j2\pi n/\tau}, 0 \leq t \leq \tau,
\]

where \( X_n \) are data symbols and \( \tau \) is symbol duration. The length of the entire message bit sequence is \( N_t = M N_r \), where each message sequence vector is a \( M \)-bit codeword. The transmit signal at the RF stage is \( x = C_{\text{OFDM}} \).

For line-of-site (LoS) communications, the standard statistical model for a multipath fading channel follows a Rician distribution \([35]\). Here, the \( N_r \times N_r \) complex channel impulse response (CIR) \( H \) is modeled as the sum of the fixed LOS component and a random multipath non-LoS (nLoS) channel component as

\[
H = \sqrt{\frac{K}{K+1}} H_{\text{LOS}} + \sqrt{\frac{1}{K+1}} H_{\text{nLOS}},
\]

where \( K \) is the Rician \( K \)-factor of the channel, \( H_{\text{LOS}} \in \mathbb{C}^{N_r \times N_t} \) is the LoS channel component that is unchanged during the channel coherence time, and \( H_{\text{nLOS}} \in \mathbb{C}^{N_r \times N_t} \) is the nLoS fading component representing random multipath fading. The Rician \( K \)-factor is the ratio between the power in the direct path (LoS) and the power in the other scattered nLoS paths. Assuming a narrowband block-fading channel, the received signal is

\[
y = H x + n,
\]

where \( y \in \mathbb{C}^{N_r \times 1} \) is the output of \( N_r \) receive antennas and \( n \in \mathbb{C}^{N_r \times 1} \) is the circularly symmetric white Gaussian noise. The BER is computed after decoding the received symbols usually via maximum likelihood (ML) detector \([28]\).

Current MIMO-OFDM techniques suffer from limited EE caused by power consumption that increases linearly with the number of radio-frequency (RF) chains \([37]\). This is overcome in SIM-OFDM or OFDM-IM \([29]\), where a new dimension of subcarrier index is employed for modulating additional bits in addition to the usual phase and amplitude indices of the signal constellation. In OFDM-IM, \( K_r \) of \( N_r \) subcarrier are activated per symbol leaving \( p_1 = N_r - K_r \) index bits for signaling. More recently, OFDM-IM has been combined with a MIMO configuration to yield MIMO-OFDM-IM which achieves significantly lower BER than the traditional MIMO-OFDM \([33]\). The number of bits per channel use (bpcu) for MIMO-OFDM-IM is \( N_r (p_1 + \log(M)) K_r \). Note that when \( M = 1 \) in OFDM-IM, the system is equivalent to FSK \([26]\).

In a conventional wireless communication transceiver with a passive reflector (Fig. 1h), modulation is performed using complex RF circuitry in the feed usually only in a single input/output (SI/SO) configuration. For MIMO-based IM, we consider ST-coded RI-MTS (Fig. 1f) comprising an array of \( N_1 \times N_2 \) meta-atoms, each of which is embedded with a varactor diode and variable resistor to control the time-varying reflection amplitude and phase of each meta-atom. A field programmable gate array (FPGA) controller and multiplexer translates information bits to a ST coding matrix (STCM) \([31]\).

To formulate the response of each meta-atom, consider \( E \) (V/m) as the electric field excitation for the surfaces and media that form the MTS. Assuming linear and time-varying medium, the electric flux density \( D \) (Am\(^{-2}\)) at Cartesian position vector \( r = [x \ y \ z]^T \) and time \( t \) is

\[
D(r, t) = \frac{1}{2\pi} \int \epsilon(t, \omega) E(r, t) e^{j\omega t} d\omega, \tag{4}
\]

where \( \epsilon(t, \omega) \) is the time-varying permittivity and \( \omega \) is the angular frequency. We consider an RI-MTS with an active tuning element embedded in each meta-atom capable of modulating \( \epsilon(t, \omega) \) using a time-varying voltage signal from a digital controller as stimulus. Through this ST-modulation of \( \epsilon(t, \omega) \), we directly modulate communication signal bits onto the resulting wave (Fig. 1b).

Our reflect-array MTS is fully reflective with no transmitted fields. At the surface of the RI-MTS (\( z = 0 \)), the reflected electric field \( E_r \) is

\[
E_r(z = 0, t) = \Gamma(t) E_i(z = 0, t), \tag{5}
\]

where \( E_i \) is incident field and \( \Gamma(t) \) is time-varying complex reflection coefficient. The \( \Gamma(t) \) is related to the complex surface impedance \( Z_s \) which characterises the behavior of each meta-atom by \( \Gamma(t) = Z_s(t)/Z_0 \), where \( Z_0 = 377 \Omega \) is the free-space impedance.

To perform OFDM-IM, Fourier transform of (5) yields the angular frequency response

\[
E_r(\omega) = \Gamma(\omega) * E_i(\omega) = \int \Gamma(\omega - \omega') E_i(\omega') d\omega', \tag{6}
\]
where * denotes convolution. Given an incident wave of $E_i(\omega)$, the spectrum of the scattered wave $E_s(\omega)$ is controlled by varying $\Gamma(\omega)$ of each meta-atom. If $\Gamma(t)$ is a periodic signal, then it is a linear combination of complex exponentials [40], i.e., 

$$\Gamma(t) = \sum_{m=-\infty}^{\infty} a_m e^{j2\pi m f c t / T_0},$$

where $T_0$ is the modulation period, $\omega_0 = \frac{2\pi}{T_0}$, and $a_m$ is the Fourier series (FS) coefficient of the $m$-th harmonic. The corresponding reflected wave in the spectral-domain is

$$E_s(\omega) = 2\pi \sum_{m=-\infty}^{\infty} a_m E_i(\omega - m\omega_0).$$  (7)

We ST-modulate $\Gamma$ for each meta-atom to radiate the $m$th harmonic frequency or a combination of harmonic frequencies to the desired steer angle. We now propose our meta-atom design and determine its steady-state $\Gamma(\omega)$ at each coding state.

III. META-ATOM DESIGN FOR IM TRANSCEIVERS

Consider a metasurface whose $N_1 \times N_2$ meta-atoms are indexed by integers $p$ and $q$ along the $x$- and $y$-axis, respectively. The inter-element spacing in the $x$ ($y$) dimension is $d_x$ ($d_y$). Given time-varying complex reflection coefficient $\Gamma_{pq}$ of the $pq$-th meta-atom, the approximate far-field pattern reflected by a ST-modulated metasurface that is illuminated by a plane wave at time $t$ is $f(\theta, \phi, t) = \sum_{p=1}^{N_1} \sum_{q=1}^{N_2} E_{pq}(\theta, \phi) \Gamma_{pq} e^{j(k_0 d_x \cos \theta \sin \phi + q d_y \sin \theta \sin \phi)},$  (8)

where $\theta$ and $\phi$ denote angles in spherical coordinates, $E_{pq}(\theta, \phi)$ is the pattern response, and $k_0 = \frac{2\pi}{\lambda}$ is the wavenumber.

We can observe that the reflected beam by coding the RI-MTS with a progressively varying phase shift. The phase of each meta-atom $\Gamma_s(p, q)$ is $\Gamma_s(p, q) = e^{-j\theta(p-1) d_x \sin \theta \sin \phi + (q-1) d_y \sin \theta \sin \phi)},$  (9)

where $\theta_s$, $\phi_s$ is the desired steering direction of the radiation pattern. From FS, the $m$-th harmonic amplitude $a_m^{pq}$ of $\Gamma_{pq}(t)$ is $a_m^{pq} = \sum_{n=1}^{L} \frac{L}{L} \sin \left(\frac{\pi m}{L}\right) e^{-j\frac{\pi n}{L} \theta s},$  (10)

where $L$ is the number of time-steps in the coding sequence per modulation period $T_0$. This provides the amplitude and phase of the $m$th harmonic frequency reflected from the RI-MTS as a function of $\Gamma_{pq}$. By varying the slope of the phase coding sequence according to $m$, we shift $f_s$ to $f_m$ [43, 44]. To implement OFDM or OFDM-IM, multiple simultaneous sub-carriers are superimposed to produce

$$\Gamma_{pq} = \sum_{m} X_m e^{j2\pi m f s t / T_0},$$  (11)

where $X_m$ encapsulates the modulated amplitude and phase of each sub-carrier $m$.

A time shift $t_q$ in the periodic time-varying coding sequence is equivalent to spatial phase shift $\Gamma_{pq} = e^{j2\pi p q t / T_0},$  (12)

where $T_0$ is the modulation period, $\omega_0 = \frac{2\pi}{T_0}$, and $a_m$ is the Fourier series (FS) coefficient of the $m$-th harmonic frequency $f_m$. We now propose our meta-atom design and determine its steady-state $\Gamma(\omega)$ at each coding state.

Fig. 2. Illustration of our proposed time-varying RI-MTS meta-atom. (a) Isometric and (b) Top-down view of the unit cell. Here, $H = 0.2 \text{ mm}$, $L_1 = 2.8 \text{ mm}$ ($h/3.83$), $L_2 = 2.8 \text{ mm}$ ($h/3.83$), $L_3 = 0.1 \text{ mm}$, $L_4 = 0.1 \text{ mm}$, $L_5 = 2.0 \text{ mm}$, $L_6 = 1.3 \text{ mm}$, $L_7 = 0.1 \text{ mm}$, and $L_8 = 0.1 \text{ mm}$. The metal traces (top layer) and ground-plane (bottom layer) are copper. The dielectric layer of thickness $H$ is a RT/Duroid® 5880 ($\varepsilon_r = 2.2$, tan $\delta = 0.0009$) substrate. (c) Equivalent circuit model representation of the meta-atom. The complex impedance of the MTS is $Z_{pq}(p, q, t) = R(t) + jX(t)$. (d) Circuit model of our tunable diode comprises a tunable series resistance ($R$) and capacitance ($C$).

Fig. 3. Simulated tunable reflection (a) phase and (b) amplitude of the RI-MTS meta-atom in Fig. 2 with tunable diode resistance $R = 0.5 \Omega$ and varying capacitance $C$ in the range 0.01-1.50 pF.

We use this relation to generate and spatially steer frequency harmonics in a controllable manner for advanced RIS-based modulation, multiplexing, and beamforming.

We designed a reflective time-varying R-MTS (Fig. 2) where each meta-atom unit cell is embedded with two varactor diodes. Figure 2 shows an isometric view of the meta-atom unit cell. To reduce fabrication cost and complexity of this design, we chose a meta-atom architecture that does not require vertical interconnect access (vias). Among prior works, the closest to our proposed meta-atom is [44]. However, our design is modified for reflective R-MTS rather than transmit MTS-based phase shifters of [44].

We selected the dimensions of the meta-atom (Fig. 2b) to provide an operational reflection phase tuning range of $>310^\circ$ at $f_c = 28 \text{ GHz}$, where the meta-atoms are relatively low-loss with a reflection amplitude of $<2.2 \text{ dB}$ for all simulated tuning states. We synthesized the dimensions of the meta-atom unit cell through parametric tuning and trial-and-error iteration in ANSYS HFSS full-wave EM simulations. The circuit model for our tunable varactor diode chip consists of tunable capacitance and resistance (Fig. 2c).

This tunable diode representation allows each column to have a tunable and programmable reflection phase and amplitude. The time-varying reflection phase is primarily controlled by
The number of transmit antennas were same as the number conventional OFDM and QAM systems in terms of their bpcu. In the signal model of (3) for OFDM-IM, we set 2 out of single-output (SISO) and MIMO-OFDM-IM. In the signal through BER performance for RI-MTS-based single-input RI-MTS array scattered radiation pattern is plotted in Fig. 5d. This generates the transceiver radiation pattern.

The resulting spectrum of \( a_{pq}^{m} \) for \( {\Gamma}_{np}^{m} \) for \( n = 1 \) to 16. (c) Normalized radiation pattern (\( \phi = 0 \) cut) for \( m = -2 \) to 2. Only the activated \( m = +1 \) and \( m = -1 \) harmonics are at the peak magnitude. (d) Full-wave finite RI-MTS array scattering simulation of the scanned (\( \theta_{s} = -45^\circ \)) reflected beam. The excitation is a plane wave traveling in the \( k = -z \) direction with E-field polarized in the \( x \) direction.

Fig. 6. BER versus SNR performance of various SISO/MIMO-OFDM-IM, a classical MIMO-OFDM (green diamonds), and classical SISO/MIMO-QAM (square/triangle). When \( M = 1 \) (red diamond), the system is equivalent to FSK.

We modeled and demonstrated an ST-modulated RI-MTS to perform key IM schemes for 5G/6G wireless networks. In particular, our RIS-based implementation of OFDM-IM and MIMO-OFDM-IM does not require complex RF components such as mixers and phase-shifters. This results in significantly less size, weight, and power consumption compared to conventional phased arrays. The RI-MTS transceiver for IM introduced in this paper helps pave the way for adoption of RIS-based transceivers in future smart-radio environments.

IV. Numerical Experiments

We verified the communications performance of our design through BER performance for RI-MTS-based single-input single-output (SISO) and MIMO-OFDM-IM. In the signal model of (3) for OFDM-IM, we set 2 out of \( N_{t} = 4 \) subcarriers and \( p_{1} = 2 \) index bits. We benchmark our design against conventional OFDM and QAM systems in terms of their bpcu. The number of transmit antennas were same as the number of receive antennas for each case (\( N_{t} = N_{r} \)). We divided the R-MTS into 2 and 4 sub-apertures for MIMO operation. We set \( K = 10 \) dB to be consistent with the experimental characterization at \( f_{c} = 28 \) GHz [45] and previous analyses of other LIS-based wireless systems [22]. Our simulation results (Fig. 6) with ML symbol detector shows that the BER achieved by MIMO-OFDM-IM is comparable, within an order, to the conventional MIMO-OFDM for the same number of bits per channel use (bpcu). Note that MIMO-OFDM-IM achieves this BER with less spectrum usage.

V. Summary

We modeled and demonstrated an ST-modulated RI-MTS to perform key IM schemes for 5G/6G wireless networks. In particular, our RIS-based implementation of OFDM-IM and MIMO-OFDM-IM does not require complex RF components such as mixers and phase-shifters. This results in significantly less size, weight, and power consumption compared to conventional phased arrays. The RI-MTS transceiver for IM introduced in this paper helps pave the way for adoption of RIS-based transceivers in future smart-radio environments.
