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Intelligent Time-Varying Meta surface 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 meta surface (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 frequency-domain 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. Our experiments for bit error rate show that RI-MTS- based SIM and MIMO-OFDM-IM are lower than conventional MIMO-OFDM.

Index Terms- OFDM-IM,Index modulation,MIMO-OFDM

I. INTRODUCTION

TIME-modulated antenna arrays, 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]. Such arrays 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, is a synthetic electromagnetic 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 wavefront [9–12]. Recent developments in spatio-temporally (ST) modulated MTSs 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, 16]. 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 [17]. Notably, reconfigurable intelligent MTSs (RI-MTSs) are capable of applying dynamic transformations of EM waves and have been recently proposed as sensors in fifth/sixth-generation (5G/6G) smart radio environments [18]. 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) [17]. While several theoretical studies analyze signal processing for 5G/6G RI-MTSs [18–20] and large intelligent surfaces (LISs) [21], their specific EM analyses remain unexamined. Contrary to these works, we focus on EM analysis and implementation of RI-MTSs for wireless communications. In particular, we consider transceiver for index modulation (IM) that is identified as one of the preferred 5G/6G technologies [22] largely because of better energy and spectral efficiencies than conventional modulations [23]. The information in IM is encoded through permutations of indices of spatial, frequency, or temporal media. Common IM techniques [24, 25] include spatial modulation [26] and subcarrier IM (SIM) [27]. Our prior work [28] introduced the concept of RIS-based spatial modulation. Motivated by recent research in ST- modulated MTSs, we hereby propose and demonstrate RIS-based designs for a variety of IM techniques such as frequency shift keying (FSK) [29], and orthogonal frequency-division multiplexing (OFDM) with IM (OFDM-IM) [22, 30], and MIMO-OFDM-IM [31]. We implement these frequency-domain IM

techniques using the concepts of ST-modulated metamaterials 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 lower than traditional OFDM. multiple flat-fading subchannels of equal bandwidth [32]. Unlike standard frequency domain modulation 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

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the peak of one coinciding with the nulls of the other, increases the spectral efficiency [33]. Each one of the Ns 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.

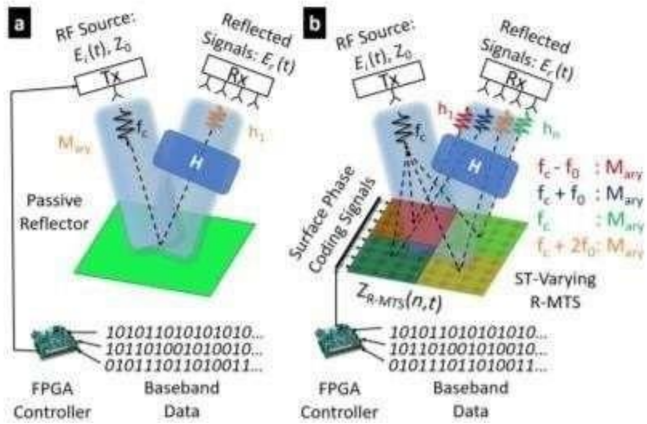

FIG 1.SIMPLIFIED ILLUSTRATION OF A CONVENTIONAL M-ARY PHASE SHIFT KEYING (PSK) SYSTEM

II. LITERATURE SURVEY

Beixiong Zheng et al."Multiple-Input Multiple-Output OFDM with Index Modulation: Low- Complexity Detector Design", in this paper proposed two low-complexity detectors derived from the SMC theory for the MIMO-OFDMIM system. The first proposed subblock-wise detector draws samples at the subblock level, exhibiting near-optimal performance for the MIMO- OFDMIM system. The second proposed subcarrier-wise detector draws samples at the subcarrier level, exhibiting substantially reduced complexity with a marginal performance loss. An effective legality examination method has been also developed to couple with the subcarrier wise detector. Computer simulation and numerical results have validated the outstanding performance and the low complexity of both proposed detectors.

ErtugrulBasaret al."Multiple-Input Multiple-Output OFDM with Index Modulation", A novel scheme called MIMOOFDM with index modulation has been proposed as an alternative multicarrier transmission technique for 5G networks. It has been shown via extensive computer simulations that the proposed scheme can provide significant BER performance improvements over classical MIMO-OFDM for several different configurations. The following points remain unsolved in this study:

i) performance analysis,

ii) the selection of optimal N and K values,

iii) diversity techniques for MIMO-OFDM-IM, and

iv) Implementation scenarios for high mobility. ErtugrulBasar et al. "On Multiple-Input Multiple-Output OFDM with Index Modulation for Next Generation Wireless Networks", In this study, the recently proposed MIMO-OFDM-IM scheme has been investigated for next generation 5G wireless networks. For the MIMO-OFDM-IM scheme, new detector types such as ML, near-ML, simple MMSE, MMSE-LLR-OSIC detectors have been proposed and their ABEP have been theoretically examined. It has been shown via extensive computer simulations that MIMO-OFDM-IM scheme provides an interesting trade-off between complexity, spectral efficiency and error performance compared to classical MIMO-OFDMscheme and it can be considered as a possible candidate for 5G wireless networks.

The main features of MIMO-OFDM-IM can be summarized as follows:

i) better BER performance,

ii) flexible system design with variable number of active OFDM subcarriers and

iii) better compatibility to higher MIMO setups. However, interesting topics such as diversity methods, generalized OFDM-IM cases, high mobility implementation and transmit antenna indices selection still remain to be investigated for the MIMO- OFDM-IM scheme.

Ertugrul Bas¸ et al. "Performance of Multiple-Input Multiple-Output OFDM with Index Modulation", In this paper, proposed ML and near-ML detectors for the recently introduced MIMO-OFDM-IM scheme to improve its error performance compared to MMSE based detection. The ABEP upper bound of the MIMO-OFDM-IM scheme with ML detection has been derived and it has been shown that the derived theoretical upper bound can be used as an efficient tool to predict the BER performance of the MIMO-OFDMIM scheme. It has been shown via computer simulations that MIMO- FDM-IM scheme can provide significant improvements in BER performance over classical MIMO-OFDM using different type of detectors and MIMO configurations.

Beixiong Zheng et al. "Low-Complexity ML Detector and Performance Analysis for OFDM With In-Phase/Quadrature Index Modulation", In this letter, we've planned a low-complexity detector supported the milliliter criterion, that dispenses with a priori data of the noise variance and also the potential realizations of the active subcarrier indices. supported the framework of OFDM-I/Q-IM using the planned milliliter detector, the straight line ABEP and also the actual coding gain achieved by OFDMI/Q-IM are derived, that absolutely matches the simulation results. Moreover, the exact coding gain including the spectral efficiency price has provided a clear plan of a basic trade-off between the system performance and also the spectral efficiency of OFDM-I/Q-IM by the adjustment of the quantity of active subcarriers.

Sheng Wu et al."Low-Complexity Iterative Detection for Large-Scale Multiuser MIMO- OFDM Systems Using Approximate Message Passing", For the detection of large-scalemultiuser MIMO-OFDM systems, we have proposed a range of low-complexity approximate message passing algorithms that can offer desirable tradeoff between performance and complexity. It is verified through extensive simulations that our proposed approximate message passing algorithms can achieve near optimal performance with low complexity. Compared with existing turbo detection algorithms, the proposed schemes can achieve or even outperform the performance of some complex algorithms, such as the iterative decoding based on STS-SD and MMSESIC. In addition, the number of iterations required to achieve near-optimal performance is small and does not increase with the system dimension.

III. PROPOSED WORK

The block diagram of the MIMO-OFDM-IM transceiver is shown. We consider a MIMO system employing transmit and receive antennas. As seen from, for the transmission of each frame, a total of information bits enter the MIMO-OFDM-IM transmitter. These bits are first split into groups and the corresponding bits are processed in each branch of the transmitter by the OFDM index modulators. The incoming information bits are used to form the OFDM-IM block , in each branch of the transmitter, where is the size of the fast Fourier transform (FFT) and . According to the OFDM-IM principle, these bits are split into groups each containing bits, which are used to form OFDM-IM sub blocks, of length N.

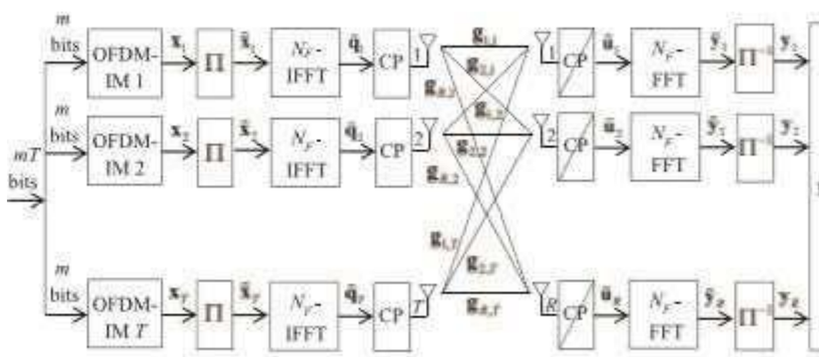

Fig. 1. Transceiver Structure of the MIMO-OFDM-IM Scheme for a $T \times R$ MIM

To the corresponding bits, only out of available subcarriers are selected as active by the index selector at each sub block ,while the remaining subcarriers are inactive and set to zero. On the other hand, the remaining bits are mapped onto the considered M-ary signal constellation. Therefore, unlike classical MIMO-OFDM, contains some zero terms whose positions carry information for MIMO-OFDM-IM. In this study, active subcarrier index selection is performed by the reference look-up tables at OFDM index modulators of the transmitter. The considered reference look-up tables for and are given in Tables I and II, respectively, where for. As seen from Table I, for and , the incoming bits can be used to select the indices of the two active subcarriers out of four available sub carriers according to the reference look-up table of size . The OFDM index modulators in each branch of the transmitter obtain the OFDM-IM sub blocks

first and then concatenate these sub blocks to form the main OFDM blocks . In order to transmit the elements of the sub blocks from uncorrelated channels, block inter leavers are employed at the transmitter. The block interleaved OFDM-IM frames are processed by the inverse FFT (IFFT) operators to obtain. We assume that the time-domain OFDM symbols are normalized to have unit energy, i.e., for all. After the addition of cyclic prefix of samples, parallel-to-serial and digital-to analog conversions, the resulting signals sent

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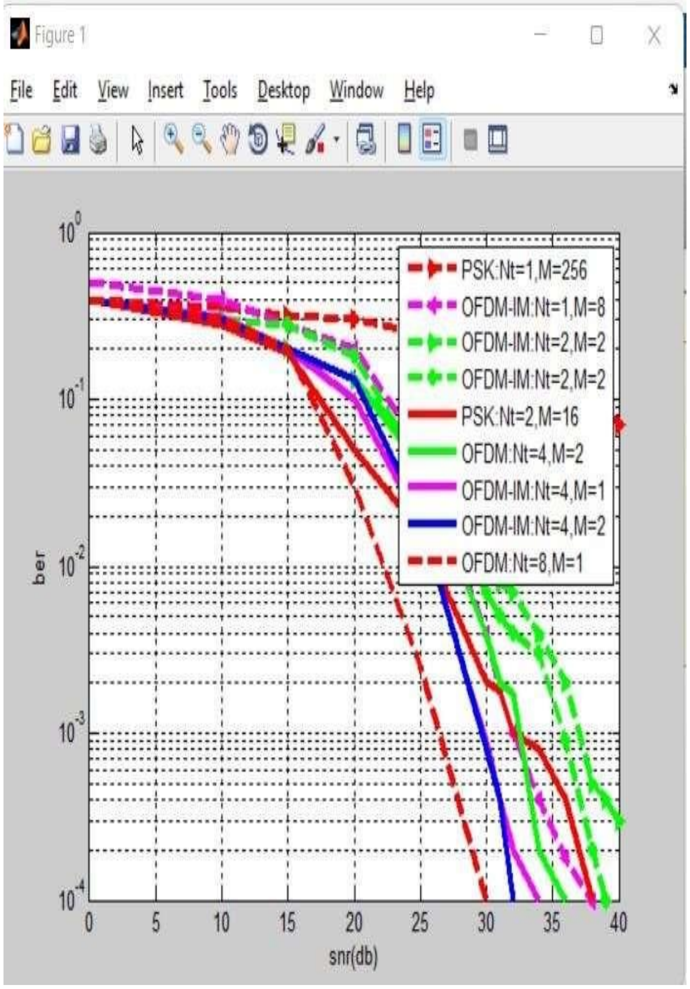
simultaneously from transmit antennas over a frequency selective Rayleigh fading MIMO channel, where represents the -tap wireless channel between the transmit antenna and the receive antenna ,whose elements are independent and identically distributed with. Assuming the wireless channels remain constant during the transmission of a MIMO-OFDM-IM frame and , after removal of the cyclic prefix and performing FFT operations in each branch of the receiver, the input-output relationship of the MIMO-OFDM-IM scheme in the frequency domain is obtained as (1) for , where is the vector of the received signals for receive antenna , represents the frequency response of the wireless channel between the transmit antenna and receive antenna , and is the vector of noise samples. The elements of and follow and distributions, respectively, where denotes the variance of the noise samples in the frequency domain, which is related to the variance of the noise samples in the time domain as. We define the signal-to-noise ratio (SNR) as where [joules/bit] is the average transmitted energy per bit. The spectral efficiency of the MIMO-OFDM-IM scheme is [bits/s/Hz], which is equal to times that of the OFDM-IM scheme.

As seen from (4), the ML detector has to make a joint search overall transmit antennas due the interference between the sub blocks of different transmit antennas. Since has different realizations, the total decoding complexity of the ML detector in (4), in terms of complex multiplications (CMs), is per sub block, which becomes impractical for higher order modulations and MIMO systems. Instead of the exponentially increasing decoding complexity of the ML detector, we propose a novel MMSE detection and LLR calculation based detector, which has a linear decoding complexity as that of classical MIMO-OFDM with MMSE detection. For the detection of the corresponding OFDM-IM sub blocks of different transmit antennas, the following MIMO signal model is obtained from(3) for subcarrier of sub block :

where is the received signal vector, is the corresponding channel matrix which contains the channel coefficients between transmit and receive antennas and assumed to be perfectly known at the receiver, is the data vector which contains the simultaneously transmitted symbols from all transmit antennas and can have zero terms due to index selection in each branch of the transmitter and is the noise vector. For classical MIMO-OFDM, the data symbols can be simply recovered after processing the received signal vector with the MMSE detector. On the other hand, due to the index information carried by the sub blocks of the proposed scheme, it is not possible to detect the transmitted symbols by only processing for a given subcarrier in the MIMO-OFDM-IM scheme. Therefore, successive MMSE detections are performed for the proposed scheme using the MMSE filtering matrix.

IV. RESULTS AND DISCUSSION



V. CONCLUSION

We modeled and demonstrated an ST-modulated RI-MTS to perform key IM schemes for 5G/6G wireless networks. Our RIS-based implementations do not require conventional phase shifters, mixers, or a lossy RF manifold network, but need a control network to individually address the antenna elements. Consequently, these RI-MTS architectures hold the promise to achieve direct frequency modulation and beam scanning in significantly less size, weight, and power consumption compared to conventional phased arrays.

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