IEEE Access Special Section Editorial:

Index Modulation Techniques for Next-Generation Wireless Networks

Index modulation (IM) techniques appear as competitive candidates for next-generation (5G and beyond) wireless networks due to the attractive advantages they offer in terms of spectral and energy efficiency as well as hardware simplicity. IM is a highly spectrum- and energy-efficient yet simple digital modulation technique, which utilizes the indices of the building blocks of the corresponding communication systems to convey additional information bits. IM systems provide alternative ways to transmit information in contrast to traditional digital modulation schemes that rely on the modulation of the amplitude/phase/frequency of a sinusoidal carrier signal for transmission, as widely considered in the field of communications over the past 50 years. Radically, IM schemes have the ability to map information bits by altering the on/off status of their transmission entities such as transmit antennas, subcarriers, radio frequency (RF) mirrors, transmit light emitting diodes, relays, modulation types, time slots, precoder matrices, dispersion matrices, spreading codes, signal powers, loads and so on. In other words, IM creates completely new dimensions for data transmission. Since the initial skepticism of both academia and industry on the potential and applicability of IM technologies has now gone away, we strongly believe that IM is not another simple digital modulation alternative, but rather can be a game-changing communication paradigm whose time has come!

There has been a tremendous interest in IM schemes over the past few years. Therefore, we decided to organize this IEEE Access Special Section, which has been the first in the literature in this frontier, at the end of 2016. The aim of this IEEE Access Special Section has been to provide a forum for the latest research and advances in the field of emerging IM techniques. With this purpose, we have accepted 23 high-quality papers from leading research groups worldwide during the period of June 2017-January 2018.

IEEE Access's multidisciplinary, application-oriented, and all-electronic concept has provided a great opportunity for the dissemination of the most recent and interesting results in the field of IM technologies. Because of its open access nature, this Special Section is freely accessible to all readers around the world.

The 23 papers published in this Special Section can be categorized under four major groups. We have received i) 3 tutorial type articles (one of them has been submitted by our Guest Editorial Team itself upon the invitation of the Editor-in-Chief of IEEE Access), ii) 10 papers covering the most recent advances in the field of orthogonal frequency division multiplexing with index modulation (OFDM-IM), iii) 6 papers on the recent developments in the field of spatial modulation (SM) techniques, and iv) 4 papers in other relevant areas in which IM technologies were applied.

In the opening article of this Special Section (Index Modulation Techniques for Next-Generation Wireless Networks), which carries the same title as our Special Section, we have provided a comprehensive overview of the most recent developments in the field of IM technologies and focused on the three popular forms of IM: SM, channel modulation (media based modulation) and OFDM that consider the transmit antennas of a multiple-input multiple-output (MIMO) system, the RF mirrors (parasitic elements) mounted at a transmit antenna, and the subcarriers of an OFDM system for IM techniques, respectively. We strongly believe that this 54-page masterpiece will be a classic reference for the researchers working in this frontier

for many years to come. In the invited tutorial article of Sugiura et al. (State-of-the-Art Design of Index Modulation in the Space, Time, and Frequency Domains: Benefits and Fundamental Limitations), the authors presented a comprehensive review of IM architectures that operate in the space, time, and frequency domains and clarified the advantages of IM-based systems over the conventional schemes in wireless standards, such as spatial multiplexing, OFDM, and single-carrier frequency division multiple access. Our Special Section closes with the tutorial article of Hamadeh et al. (Hierarchical Multi-Functional Layered Spatial Modulation), which presents the novel multi-functional architecture of layered multi-set modulation. In this study, a generalized framework that subsumes various MIMO techniques exhibiting different multiplexing and diversity functionalities, has been proposed by the authors.

Our Special Section has attracted the attention of the researchers working on OFDM-IM, which is a promising alternative to the classical OFDM, and we have accepted 10 papers in this frontier. Considering the adoption of OFDM for both uplink and downlink of the 5G New Radio in 2017, research studies in the field of OFDM-IM have gained a remarkable momentum in the past year. Li et al. (Information Guided Precoding for OFDM) proposed a novel information guided precoding technique, called precoding aided OFDM-IM, to improve the spectral efficiency of OFDM-IM. Hu et al. (Low-Complexity Subcarrier-Wise Detection for MIMO-OFDM with Index Modulation) considered MIMO implementation of OFDM-IM and developed an optimal detection algorithm with reduced complexity for MIMO-OFDM-IM along with a low-complexity near-optimal detector based on sequential Monte Carlo technique. Mao et al. (Zero-Padded Orthogonal Frequency Division Multiplexing with Index Modulation Using Multiple Constellation Alphabets) proposed the scheme of zero-padded tri-mode OFDM-IM to achieve higher spectral and energy efficiency. In this scheme, only a fraction of the available subcarriers is modulated by two distinguishable constellation alphabets, while the other subcarriers remain empty to reduce the energy consumption. Inspired by the advantages of vector OFDM, Liu et al. (Vector OFDM with Index Modulation) introduced an enhanced OFDM-IM scheme termed vector OFDM with IM not only to improve the BER performance of OFDM-IM but also to reduce the PAPR of the transmit signals. Zhang et al. (Dual-Mode Index Modulation Aided OFDM with Constellation Power Allocation and Low-Complexity Detector Design) proposed a new dual-mode IM-aided OFDM-IM scheme by considering constellation power allocation and focused on the transceiver design and the performance optimization of dual-mode OFDM. Based on the concept of multiple-mode OFDM-IM, Li et al. (Space-Time Multiple-Mode Orthogonal Frequency Division Multiplexing with Index Modulation) proposed the scheme of space-time multiple-mode OFDM-IM to further obtain a transmit diversity gain. Lee et al. (Secure Index and Data Symbol Modulation for OFDM-IM) proposed a secure index and data symbol modulation scheme for OFDM-IM systems by exploiting randomized mapping rules for IM as well as data symbol modulation to degrade the error performance of the eavesdropper. Bouhlel et al. (Performance of OFDM-IM Under Joint Hardware Impairments and Channel Estimation Errors Over Correlated Fading Channels) investigated the theoretical error performance of OFDM-IM in the presence of imperfect channel estimation and hardware impairments over correlated Rayleigh and Rician fading channels. Using software defined radio technology, practical implementation of OFDM-IM along with other IM-based waveforms has been investigated for the first time in the literature by Gokceli et al. (Practical Implementation of Index Modulation-Based Waveforms) and promising results are reported regarding the real-time potential of IM-based waveforms. Finally, Liu et al. (Enhanced Coordinate Interleaved OFDM with Index Modulation) proposed

the scheme of enhanced coordinate interleaved OFDM-IM to improve the error performance of the plain coordinate interleaved OFDM-IM scheme through an additional diversity gain.

Our Special Section also published 6 papers on most recent SM technologies. Cheng et al. (On Simultaneous Wireless Information and Power Transfer for Receive Spatial Modulation) studied the performance of receive spatial modulation combined with simultaneous wireless information and power transfer. Rajashekar et al. (Transmit Antenna Subset Selection in Spatial Modulation Relying on a Realistic Error-Infested Feedback Channel) shed light on the performance of SM employing Euclidean distance-based antenna selection in the presence of a realistic error-infested feedback channel. Hai et al. (Complex Hadamard Matrix-Aided Generalized Space Shift Keying Modulation) presented a complex Hadamard matrix-aided generalized space shift keying modulation scheme by introducing complex-Hadamard-based signal vectors at the transmitter to improve the spectrum efficiency of generalized space shift keying. Zheng (Hybrid Spatial Modulation Aided Distributed Relays: Threshold Detection and Constellation Rotation) studied hybrid SM-aided virtual MIMO one-way and two-way relaying architectures with multiple distributed single-antenna relay nodes and proposed a two-stage relay detector for one-way relaying. Hiari et al. (A Reconfigurable SDR Transmitter Platform Architecture for Space Modulation MIMO Techniques) proposed a single software defined radio platform architecture that implements different space modulation techniques using currently available off-the-shelf components and studied the impact of different hardware components. Finally, Qu et al. (Generalized Spatial Modulation with Transmit Antenna Grouping for Massive MIMO) proposed a new generalized spatial modulation scheme called grouping GSM to improve the system performance in the presence of high channel correlation for massive MIMO systems.

As mentioned in the opening article of this Special Section, IM-based solutions have spread into totally new communication systems in the past 1-2 years. Within this perspective, 4 papers that deal with interesting IM-aided solutions, are accepted. Nakao et al. (Dual-Mode Time-Domain Index Modulation for Nyquist-Criterion and Faster-Than-Nyquist Single-Carrier Transmissions) proposed the scheme of dual-mode time-domain single-carrier IM in which the combination of two constellation modes carries information bits in addition to ordinary modulation symbols. The authors also extended this scheme for the scenario of faster-than-Nyquist signaling to further increase bandwidth efficiency. Ozturk et al. (Generalized Frequency Division Multiplexing with Flexible Index Modulation) presented a framework, which integrates GFDM with space and frequency IM schemes to provide flexible and advanced novel radio access technologies for future wireless networks, considering the advantages of alternative waveforms and the IM concept. In this study, several generalized frequency division multiplexing-based waveforms are presented and their bit error ratio performances, computational complexities, and spectral efficiencies are analyzed. In their invited paper, Shamasundar et al. (Multidimensional Index Modulation in Wireless Communications) proposed the promising concept of multidimensional IM in which multiple transmission entities, such as antennas, time slots, and RF mirrors, are indexed simultaneously. Considering the inherent sparsity of multidimensional IM-based systems, signal detection schemes that use compressive sensing-based reconstruction algorithms were proposed by the authors. Finally, inspired by OFDM-IM, Hamamreh et al. (OFDM-Subcarrier Index Selection for Enhancing Security and Reliability of 5G URLLC Services) proposed an efficient physical layer security technique, called OFDM with subcarrier index selection, to secure the transmission of OFDM-based waveforms against eavesdropping in 5G and beyond wireless

networks. In this technique, one and two security levels are provided in frequency division duplexing and time division duplexing modes, respectively.

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Recent recognition of his research includes the Turkish Academy of Sciences Outstanding Young Scientist Award in 2017, the first-ever IEEE Turkey Research Encouragement Award in 2017, and the Istanbul Technical University Best Ph.D. Thesis Award in 2014. He is also the recipient of four Best Paper Awards including one from the IEEE International Conference on Communications 2016. He has served as a TPC member for several IEEE conferences and is a regular reviewer for various IEEE journals. Dr. Basar currently serves as an Associate Editor of the IEEE COMMUNICATIONS LETTERS and the IEEE ACCESS, and as an Editor of *Physical Communication* (Elsevier).

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