Editorial: Introduction to the Issue Index Modulation for Future Wireless Networks: A Signal Processing Perspective

THE last few years have witnessed a tremendous growth of the demand for wireless services and a significant increase of the number of mobile subscribers. A recent data traffic forecast from Cisco reported that the global mobile data traffic reached 1.2 zettabytes per year in 2016, and the global IP traffic will increase nearly threefold over the next 5 years. Based on these predictions, a 127-fold increase of the IP traffic is expected from 2005 to 2021. It is also anticipated that the mobile data traffic will reach 3.3 zettabytes per year by 2021, and that the number of mobile-connected devices will reach 3.5 per capita.

With such demands for higher data rates and for better quality of service (QoS), fifth generation (5G) standardization initiatives, whose initial phase was specified in June 2018 under the umbrella of Long Term Evolution (LTE) Release 15, have been under vibrant investigation. In particular, the International Telecommunication Union (ITU) has identified three usage scenarios (service categories) for 5G wireless networks: (i) enhanced mobile broadband (eMBB), (ii) ultra-reliable and low latency communications (uRLLC), and (iii) massive machine type communications (mMTC). The vast variety of applications for beyond 5G wireless networks has motivated the necessity of novel and more flexible physical layer (PHY) technologies, which are capable of providing higher spectral and energy efficiencies, as well as reduced transceiver implementations.

During the last decades, wireless researchers and engineers have introduced effective PHY technologies, such as massive multiple-input multiple-output (MIMO) systems, millimeter-wave communications, and new waveform designs. However, the wireless communication and signal processing research communities are still actively working on identifying new and more flexible PHY solutions that can be meet the diverse capacity and QoS requirements of future wireless networks. In this context, transmission methods based on the concept of index modulation (IM) are expected to play an important role on shaping 5G and beyond radio access technologies (RATs) due to their advantages over conventional modulation schemes.

IM-based transmission methods have received growing interest over the past few years. Traditional digital transmission schemes modulate the amplitude, the phase, or the frequency of sinusoidal carriers for transmitting data. IM-based systems, on the other hand, map information bits onto the on/off status of, e.g., transmit antennas, subcarriers, antennas, radiation patterns, radio frequency (RF) mirrors, transmit light emitting diodes (LEDs), relays, modulation types, time slots, precoding matrices, dispersion matrices, spreading codes, signal powers, loads, etc. Therefore, the concept of IM introduces new dimensions for data transmission and for increasing the data rate at low complexity. Since the on/off status of a variety of information-carrying elements is employed to modulate data, the total transmit power can be used more efficiently, which results in better error performance. Furthermore, IM-based modulation schemes help reducing the inter-channel interference, the complexity, the cost, and the power consumption of communication systems. The opportunities of applying IM to wireless communications is broad and diverse, and encompasses RF communication systems, optical wireless communication systems, and reconfigurable antenna-based systems. The potential advantages of IM-based systems, however, can be obtained only through specified and advanced signal processing methods. These considerations motivate the present special issue.

Since the turn of the century, IM has received tremendous academic interest, and its development and research impact have been determined by a few key remarkable experimental activities. In 2013, the performance of spatial modulation (SM), which is the most popular form of IM, was substantiated through a measurement campaign and through the realization of the first fully-functional prototype by a team of researchers from the UK and France. In 2016, Samsung Electronics realized a 5G prototype for field trials and further validated the performance of SM. During the 3rd Generation Partnership Project (3GPP) RAN1#87 meeting in November 2016 and the 3GPP TSG RAN WG1 NR Ad-Hoc Meeting in January 2017, InterDigital Communications proposed SM for further evaluation in the context of the 5G new radio (NR) standard. At the IEEE 5G Roadmap Workshop, which was co-located with IEEE ICC 2017 and was organized by the IEEE 5G Initiative in May 2017, SM was regarded as one of emerging wireless paradigms along with millimeter-wave, full-duplex, and massive MIMO systems. At IEEE ICC 2017, a team of French researchers coordinated by Orange Labs showcased the first fully-functional prototype of SM based on small, compact, and reconfigurable antennas. The testbed operated in real time and gave wide visibility and credibility to the SM technology. In 2017, a team of researchers from

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Turkey and China evaluated the performance of orthogonal frequency division multiplexing with IM (OFDM-IM) schemes in real-time to assess their potential for next-generation networks. Finally, in 2018, a team of researchers from Austria and France substantiated the feasibility and unveiled the performance of SM for operation at millimeter-wave frequency bands (60 GHz)

In practice, every communication system can be regarded as a special form of IM. The term IM is, however, de facto referred to the family of communication systems that employ other than the amplitude, the frequency, or the phase of the transmit signals to convey information. In addition, IM can be combined with conventional modulation schemes for further improving the system performance. Due to its peculiar properties and promising performance, IM is receiving increased interest from both academia and industry.

Motivated by these observations, this special issue of the IEEE JOURNAL OF SELECTED TOPICS IN SIGNAL PROCESSING (IEEE J-STSP) puts together the most recent innovations in the realm of IM research, and elaborates on future research directions from the perspective of signal processing for communications. The special issue features 17 original articles, which encompass the application of IM to MIMO systems, multi-carrier communications, millimeter-wave systems, chaos shift keying, non-orthogonal multiple access systems, and optical wireless communications. In the rest of this Editorial, we briefly outline the contribution of each paper of the special issue.

In Joint Code-Frequency Index Modulation for IoT and Multi-User Communications, Au *et al.* propose a specific family of IM systems for multi-user communication, which can operate at low-power consumption and low operational complexity. In their proposed scheme, the authors implement joint code frequency-IM by considering code and frequency domains for applying IM and for obtaining a new multi-carrier waveform for future IoT applications.

In Single-Carrier Index Modulation for IoT Uplink, Choi studies a single-carrier IM based scheme for the uplink of the IoT, which, in contrast to OFDM-IM, has a low peak-to-average power ratio (PAPR) and does not require the computation of an inverse fast Fourier transform at the devices. The author also considers precoding in order to generalize the proposed scheme for application to multiple access channels with multiple IoT devices.

In NOMA with Index Modulation for Uplink URLLC through Grant-Free Access, Dogan *et al.* propose a novel non-orthogonal multiple access scheme based on OFDM and OFDM-IM in order to reduce the impact of collisions for ultra-reliable and low latency communications URLLC. In this work, the available resources are shared between URLLC and latency-tolerant communication systems, in order to provide ultra-reliable transmission with low latency and to avoid the inefficient utilization of the spectrum.

In Dual-Polarized Spatial Media-Based Modulation, Chen *et al.* propose a novel scheme called dual-polarized spatial media-based modulation (MBM), which combines MBM, SM, and dual-polarized antennas in order to convey additional information. The authors show that the proposed scheme provides a smaller bit error rate and a higher data rate compared with existing techniques.

In Binary-Tree Encoding for Uniform Binary Sources in Index Modulation Systems, Coon *et al.* investigate the problem of designing bit-to-pattern mappings and power allocation schemes for OFDM systems that employ subcarrier IM. The authors optimize the bit-to-pattern mapping and transmit power to maximize the rate when channel state information is available at the transmitter.

In Modified CI and Modulation Order Replacement for Enhancing OFDM-IM Performance, Nambi and Giridhar introduce a novel coordinate interleaving scheme, which works on the entire sub-block and disregards the existence of inactive subcarriers. It is shown that the proposed approach achieves a higher SNR gain over existing OFDM-IM schemes.

In Euclidean Geometries based Space-Time Block Coded Spatial Modulation, Jiang *et al.* propose an approach to construct the codebooks of space-time block coded SM. The proposed codebook is based on Euclidean geometries and is shown to be more efficient than exhaustive searching schemes.

In Enhanced Receive Spatial Modulation Based on Power Allocation, Yang *et al.* investigate the benefits of power allocation for MIMO receive SM. The case studies with total transmit power constraint and a per-antenna power constraint are analyzed, and an enhanced receive SM scheme is introduced. Optimal power allocation policies are presented for some specific scenarios.

In Bridging Spatial Modulation with Spatial Multiplexing: Frequency-Domain ESM, Wei *et al.* introduce a frequency-domain enhanced SM scheme, which alleviates the spectral efficiency limitations and the antenna switching issues of SM. To this end, the authors exploit the property that switching occurs at the baseband and that the number of RF chains cannot be reduced in frequency-domain implementations. Therefore, they design schemes in which the transmitted codewords do not include any zeros.

In Super-Resolution mmWave Channel Estimation for Generalized Spatial Modulation Systems, Chu *et al.* propose super-resolution MIMO channel estimators for generalized SM-based millimeter-wave systems. By capitalizing on the inherent spatial sparsity of millimeter-wave channels, channel estimation is formulated using atomic norm minimization.

In Towards Higher Spectral Efficiency: Spatial Path Index Modulation Improves Millimeter-Wave Hybrid Beamforming, Wang *et al.* compare the spectral efficiency of millimeter-wave hybrid beamforming with a spatial path index modulation aided millimeter-wave system, which is a generalized IM-assisted system that subsumes IM-assisted and conventional millimeter-wave MIMO systems.

In Differential-Detection Aided Large-Scale Generalized Spatial Modulation Is Capable of Operating in High-Mobility Millimeter-Wave Channels, Ishikawa *et al.* propose a large-scale differential detection aided generalized SM system, which relies on a novel Gram-Schmidt basis set and an adaptive low-complexity detector. Simulation results compliant with IEEE 802.11ad specifications show that the performance of the considered differential scheme improves upon increasing the number of subarrays.

In Multi-Carrier M-ary DCSK System with Code Index Modulation: An Efficient Solution for Chaotic Communications, Cai *et al.* introduce an IM-based multi-carrier differential chaos shift keying system in which the reference and information-bearing signals for each subcarrier are transmitted simultaneously by using orthogonal sinusoidal carriers.

In Constant-Envelope Space-Time Shift Keying, Xu *et al.* propose a holistic signal construction approach for single-RF, reduced-RF, and full-RF MIMO setups, where a 0 dB peak-to-average power ratio (PAPR) transmission and no inter-channel interference are obtained. The authors conceive a new single-RF constant-envelope space-time shift keying modulations, which outperform conventional SM in Ricean fading channels.

In Design and Performance Analysis of an Index Time Frequency Modulation Scheme for Optical Communications, Escribano *et al.* propose an IM system suitable for optical communications, which is based on jointly exploiting time and frequency domains. The performance of the system is analyzed from the point of view of the power and spectrum efficiency, and the error probability in computed over non-turbulent free-space optical channels.

In Differential Optical Spatial Modulation Over Atmospheric Turbulence, Jaiswal *et al.* introduce a new scheme named differential optical SM in order to avoid the requirement of channel state information at the receiver. The average symbol error rate of this scheme is investigated over negative exponential and Gamma-Gamma channels.

In OFDM-Based Optical Spatial Modulation, Yesilkaya *et al.* investigate frequency-domain and time-domain SM OFDM-based schemes for application to optical wireless communications. Proof-of-concept experimental results are presented in order to showcase the practical feasibility of the considered schemes.

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