Guest Editorial
Spatial Modulation in Emerging Wireless Systems

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I. Introduction

THIS IEEE Journal on Selected Areas in Communications (JSAC) special issue (SI) aims to provide a comprehensive overview of the state-of-the-art advances and a view of emerging research challenges and opportunities for *Spatial Modulation in Emerging Wireless Systems*. This SI solicits high-quality original research papers regarding theoretical studies, and application-oriented contributions dealing with architectures, platforms, and multiple access schemes.

Due to the continuous growth of mobile devices and rapid development of the Internet of Things (IoT), the fifth generation (5G) wireless communication networks impose an explosive demand on both high spectral efficiency and high energy efficiency [1]. Specifically, it is expected that a further explosion of mobile data traffic will appear in the coming years, which may overwhelm the limited spectrum resource significantly and increase the power consumption dramatically. Therefore, the unprecedented surge of mobile data traffic has urged researchers to develop new transmission technologies for maximizing both the achievable throughput and the spectral efficiency [2]. By equipping with massive antennas, conventional multi-input multi-output (MIMO) may achieve high spectral efficiency, which, however, fails to meet the requirement of high energy efficiency due to the dynamic power consumption with a large amount of full-active antennas [1]. As a novel MIMO scheme, spatial modulation (SM) has emerged as an attractive candidate to achieve the spectral and energy efficiency fulfillment of the next generation wireless communications [3]. In SM, the information bits are conveyed by not only the modulation symbol but also the index of the active antenna. As only one antenna is activated to carry one modulation symbol at each time instant, only one radio frequency (RF) chain is required at the transmitter, significantly saving the system energy consumption in downlink communications, and significantly reducing the hardware cost at the user terminal in uplink communications when multiple RF chains are required. Compared with classical MIMO, SM enjoys a number of advantages, including reduced inter-channel interference, relaxed inter-antenna synchronization requirements, and reduced receiver complexity [2].

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II. Summary of the Papers in This SI

This SI starts with a guest editor-authored tutorial paper that summarizes research progresses, applications of SM, and future research area of SM. After all, we include 14 papers in the areas of transceiver design for SM, SM in mmWave band, SM in Terahertz band, SM in Optics and LiFi/visible light communications, SM with non-orthogonal multiple access (NOMA), machine learning for the MIMO-SM system, and modulation/coding/hardware issues of SM. These papers cover a feast of hot research topics as follows.

A. Transceiver Design for SM

The first paper, titled "Soft demodulators based on deterministic SMC for single-carrier GSM in broadband channels," by Shaoe Lin *et al.* designed a soft demodulator based on the technique of deterministic sequential Monte Carlo (SMC) for the single-carrier generalized spatial modulation (SC-GSM) system. The authors exploited the natural triangular structure of the multipath channel with zero-padding (ZP) and performed the SMC sampling procedure and successive interference cancellation (SIC) on a vector-by-vector basis. This demodulator obtains near-optimal performance with low and fixed computational complexity. However, it involves an exhaustive search over all possible realizations of GSM signal. To tackle this problem, the authors further proposed a symbol-level SMC demodulator, which dispenses with this search by constructing a sequential structure for each GSM vector and drawing samples in a symbol-based manner from the expanded constellation including origin. Furthermore, since both the proposed SMC demodulators produce soft outputs, they can improve the performance of the coded SC-GSM system by acting as a soft demodulator in the turbo receiver.

The second study, "Joint transmitter-receiver spatial modulation design via Euclidean distance maximization" by Junshan Luo *et al.* presented an advanced joint transmitter–receiver spatial modulation (JSM) paradigm to increase spectral efficiency compared to the conventional JSM. The enhancement in this scheme is gained by maximizing the minimum Euclidean distance (MED) between the received signals, coined as MED-JSM. Since the optimal MED-JSM implements an exhaustive search, the authors then proposed a suboptimal scheme with lower complexity. Simulation results manifest that MED-JSM outperforms conventional JSM in terms of system reliability.

The third contribution, which is titled "Optimum low-complexity decoder for spatial modulation," by Ibrahim Alnahhal *et al.* proposed the m-M algorithm to reduce the detection complexity. The authors took into account of perfect and imperfect channel state information (CSI) at the receiver. The authors also analyzed the computational complexity comparing with the state art sphere detector (SD) of the SM system, and then showed that the proposed SD can achieve the near optimal detection performance with a reduced computational complexity.

B. SM in mmWave Band

The fourth paper, which is titled as "Generalized beamspace modulation using multiplexing: A breakthrough in mmWave MIMO," by Shuaishuai Guo *et al.* investigated multiple-data-stream beamspace set index modulation for mmWave MIMO communications from a spectral efficiency maximization perspective. They showed that by making use of beamspace set index to carry information and optimizing the activation probability of different beamspace sets, one can achieve higher spectral efficiency than the transmission solely relying on the best beamspace set.

The fifth treatise, namely "Spatial multiplexing with limited RF chains: Generalized beamspace modulation (GBM) for mmWave Massive MIMO," by Shijian Gao *et al.* proposed a novel spatial modulation for hybrid mmWave massive MIMO systems, which facilitates full multiplexing and array gain with fewer RF chains. The specific design is based on natural exploitation of the beamspace channel properties and the hybrid transceiver structure, with minor modification of existing systems. Extensive simulations and analyses validated the remarkable superiority of GBM in terms of both the energy efficiency and spectrum efficiency, in comparison with non-GBM alternatives. This makes GBM particularly feasible for uplink scenarios with mobile stations (MS) being significantly restricted by cost and complexity.

C. SM in Terahertz Band

The sixth contribution advocates "Terahertz-band ultra-massive MIMO spatial modulation" by Hadi Sarieddeen *et al.* which revealed the existing problems in future ultra-massive MIMO systems operated in the Terahertz (THz)-band with graphene-based plasmonic nano-antenna arrays employed. Lack of spatial degrees of freedom is one of the emerging challenges in THz-band ultra-massive MIMO systems with spatial multiplexing mode. To tackle this problem, a specific SM can serve as a new paradigm that can obtain spectral efficiency and keep beamforming performance acceptable. The proposed scheme demonstrated a 5 dB gain compared to conventional SM in terms of symbol and bit error rates, indicating the feasibility of THz-band SM.

D. SM in Optics

The seventh paper is titled "Optical spatial modulation for FSO IM/DD communications with photon-counting receivers: Performance analysis, transmit diversity order and aperture selection" by Chadi Abou-Rjeily *et al.* studied the performance analysis of multiple-input single-output (MISO) free-space optical (FSO) communication with intensity-modulation/direct-detection (IM/DD) of two variants of optical spatial modulation (OSM): a) optical space shift keying (OSSK) and b) spatial pulse position modulation (SPPM) over gamma-gamma atmospheric turbulence channels in the open-loop and closed-loop scenarios. What differentiates this work is the adoption of the exact Poisson photon-counting detection model in contrary to the AWGN used in all previously published works. Moreover, exact and simple approximate symbol error probability (SEP) expressions and transmit diversity orders achieved by OSSK and SPPM were extracted. Additionally, a novel diversity-maximizing transmit aperture selection scheme for the closed-loop scenario was proposed showing that a tradeoff exists between the achievable multiplexing gains and diversity gains offering a leeway in the design of practical multi-aperture FSO systems.

E. SM in LiFi/Visible Light Communications

The eighth treatise, which is titled as "Bidirectional optical spatial modulation for mobile users: Towards a practical design for LiFi systems" by Mohammad Dehghani Soltani *et al.* compared the proposed adaptive SM with the conventional SM for optical wireless communications. Two transmitters and receivers were considered as the system system configuration. The authors conducted real measurements, and then investigated the channel model incorporating the line-of-sight and non-line-of-sight channel gain components, user mobility, and random orientation of user equipment. Their impacts on the performance of the proposed SM were investigated. Performance improvement was verified in a typical indoor environment with walking and sitting activities.

The ninth treatise is related to the subject of "On the secrecy rate of spatial modulation based indoor visible light communications" by Jin-Yuan Wang *et al.* investigated the physical-layer security for a spatial modulation (SM) based indoor visible light communication (VLC) system with multiple VLC transmitters. The active transmitter is selected via a uniform selection (US) scheme; lower and upper bounds of secrecy rate with non-negativity, average optical intensity, and peak optical intensity constraints were extracted in closed-form. Moreover, a channel adaptive selection (CAS) scheme and a greedy selection (GS) scheme were proposed to select the active transmitter and further improve the secrecy performance.

F. SM With Non-Orthogonal Multiple Access

The tenth paper, namely "QoE-driven multi-user video transmission over SM-NOMA integrated systems" by Hancheng Lu *et al.* proposed the SM that integrates NOMA for multi-user video transmission. This integration jointly exploits the benefits from two transmission schemes to achieve a higher energy efficiency and throughput. To avoid inter-antenna interference, the authors utilized base layer (BL) and enhance layer (EL) transmissions. In the BL transmission, only one antenna is applied in the spatial domain. The ELs of multiple users are superposed and then transmitted in the signal domain with the use of NOMA. This joint method can provide a near-optimal quality of experience (QoE) for multi-user video transmission. The authors also provided convergence, optimality, and complexity of the developed method.

G. Machine Learning for the MIMO-SM System

The eleventh contribution addresses the issues of “Adaptive spatial modulation MIMO based on machine learning” by Ping Yang *et al.* proposed a novel link adaptation framework based on machine learning techniques for MIMO-SM systems, where the conventional optimization-driven link adaptation problems can be solved by low-complexity data driven predictions instead of tedious calculations. Specifically, two types of intelligent algorithms were proposed based on the supervised-learning classifiers and deep neural networks for the problems of transmit antenna selection (TAS) and power allocation (PA) in SM-MIMO, where impact of the utilization of different feature vectors was investigated. Moreover, it is shown that the proposed algorithms can be further extended to other adaptive index modulation (IM) schemes. Through the computational complexity and BER comparisons among the proposed and past known schemes, this paper provided an insight into the potential benefits of integrating machine learning with index modulation.

H. Modulation/Coding/Hardware Issues of SM

The twelfth paper, namely “On the capacity of MISO channels with one-bit ADCs and DACs” by Yunseo Nam *et al.* derived the channel capacity of single-input single-output and multiple-input single-output fading channel with one-bit analog-to-digital converters (ADCs) at the receiver and one-bit digital-to-analog converters (DACs) at the transmitter with perfect CSI. When perfect CSI is not available, the authors showed performance loss and proposed channel-training channel-training to find the quasi-optimal channel input distribution.

The thirteenth treatise, namely “Near-Perfect” finite-cardinality generalized space-time shift keying” by Chao Xu *et al.* proposed a finite-cardinality generalized space time shift keying (FC-GSTSK) scheme, which can overcome the limitation of conventional space-time block coding (STBC) scheme. Keeping the same level of peak-to-average power ratio (PAPR) and inter-antenna interference (IAI) as those of vertical Bell Laboratories layered space-time (V-BLAST), FC-GSTSK can work better than V-BLAST and STBC. A reduced RF-version of FC-GSTSK, inspired by index modulation, was also proposed. It was shown to achieve better performance than GSM and STBC-SM without increasing PAPR and IAI. The authors also verified that FC-GSTSK can enhance energy, bandwidth, and power-efficiency.

The final contribution reports on advances in “Fundamental applicability of spatial modulation: High-SNR limitation and low-SNR advantage” by Yan-Yu Zhang *et al.* investigated two distinctive operating regions, namely, high-signal-to-noise ratio (SNR) region and low-SNR region. In the low-SNR region, a non-coherent SM is employed in a massive MIMO setup. In addition, it was verified that SM can provide the optimal solution for transmissions to meet the desired error performance. In contrast, in the high-SNR region, the authors showed the limitations of SM-MISO and SM-MIMO, which was outperformed by a single RF transmission. For various schemes, the authors verified the bounds on Euclidean distance and discussed energy detection for SM systems. User index is also used to carry additional information.

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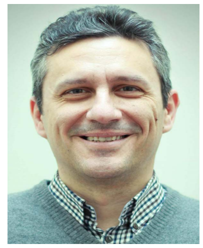

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