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INVITED PAPER

Index Modulation Techniques for Next-Generation Wireless Networks

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ABSTRACT What is index modulation (IM)? This is an interesting question that we have started to hear more and more frequently over the past few years. The aim of this paper is to answer this question in a comprehensive manner by covering not only the basic principles and emerging variants of IM, but also reviewing the most recent as well as promising advances in this field toward the application scenarios foreseen in next-generation wireless networks. More specifically, we investigate three forms of IM: spatial modulation, channel modulation and orthogonal frequency division multiplexing (OFDM) with IM, which consider the transmit antennas of a multiple-input multiple-output system, the radio frequency mirrors (parasitic elements) mounted at a transmit antenna and the subcarriers of an OFDM system for IM techniques, respectively. We present the up-to-date advances in these three promising frontiers and discuss possible future research directions for IM-based schemes toward low-complexity, spectrum- and energy-efficient next-generation wireless networks.

INDEX TERMS 5G wireless networks, channel modulation, cognitive radio networks, cooperative networks, full-duplex networks, index modulation, MIMO systems, multi-carrier systems, multi-user systems, OFDM, OFDM with index modulation, practical implementations, reconfigurable antennas, spatial modulation, vehicular communications, visible light communications.

NOMENCLATURE

4G	4th generation	BPSK	Binary phase shift keying
5G	5th generation	BS	Base station
ABEP	Average bit error probability	CDMA	Code division multiple access
ACO-OFDM	Asymmetrically clipped optical OFDM	CFO	Carrier frequency offset
ADC	Analog-to-digital conversion	CI-DCSK	Carrier index differential chaos shift keying
AF	Amplify-and-forward	CIM-SS	Code index modulation-spread spectrum
APEP	Average pairwise error probability	CIOD	Coordinate interleaved orthogonal design
APSK	Amplitude phase shift keying	CI-OFDM-IM	Coordinate interleaved OFDM-IM
ASM	Adaptive spatial modulation	CP	Cyclic prefix
BER	Bit error rate	CR	Cognitive radio
		CRC	Cyclic redundancy check

CS	Compressed sensing	LP-OFDM-I/Q-IM	Linear constellation precoded OFDM-I/Q-IM
CS-DSM	Cyclic-signaling-based DSM	LTE-A	Long-Term Evolution Advanced
CSI	Channel state information	M2M	Machine-to-machine
D	Destination node	MA-SM	Multiple active spatial modulation
D2D	Device-to-device	MBM	Media-based modulation
DAC	Digital-to-analog conversion	MC-CDMA	Multi-carrier code division multiple access
DC	Direct current	MIMO	Multiple-input multiple-output
DCO-OFDM	DC biased optical OFDM	MIMO-OFDM-IM	Multiple-input multiple-output OFDM with IM
Dh-SM	Dual-hop spatial modulation	MIMO-eU-OFDM	Multiple-input multiple-output enhanced U-OFDM
Di-SM	Distributed spatial modulation	ML	Maximum likelihood
Di-SSK	Distributed space shift keying	MM-OFDM-IM	Multiple-mode OFDM with index modulation
DM	Dispersion matrix	MMSE	Minimum mean square error
DM-OFDM	Dual-mode OFDM	mmWave	Millimeter-wave
DF	Decode-and-forward	MS-STSK	Multi-set space-time shift keying
DSM	Differential spatial modulation	MU	Multi-user
DSTSK	Differential space-time shift keying	MU-MIMO	Multi-user MIMO
DP-SM	Dual-polarized spatial modulation	NDC-OFDM	Non-DC-biased OFDM
e-GLIM-OFDM	Enhanced generalized LED index modulation OFDM	NOMA	Non-orthogonal multiple access
ESM	Enhanced spatial modulation	OFDM	Orthogonal frequency division multiplexing
E-SMX	Enhanced spatial multiplexing	OFDMA	Orthogonal frequency division multiple access
eU-OFDM	Enhanced unipolar OFDM	OFDM-HIQ-IM	OFDM with hybrid in-phase/quadrature IM
FBMC	Filter-bank multi-carrier	OFDM-IM	OFDM with index modulation
FD	Full-duplex	OFDM-IM-TD	OFDM with index modulation transmit diversity
FE-DSM	Field-extension-based DSM	OFDM-I/Q-IM	OFDM with in-phase/quadrature index modulation
FFT	Fast Fourier transform	O-OFDM-IM	Optical OFDM with index modulation
FOV	Field of view	OOK	On-off keying
FQAM	Frequency and quadrature amplitude modulation	OSM	Optical spatial modulation
FSK	Frequency shift keying	OW	Optical wireless
FSO	Free space optics	PAM	Pulse amplitude modulation
GCIM-SS	Generalized code index modulation-spread spectrum	PAPR	Peak-to-average power ratio
GFDM	Generalized frequency division multiplexing	PD	Photo-detector
GFDM-IM	Generalized frequency division multiplexing with IM	P-DSM	Permutation-based DSM
GLIM-OFDM	Generalized LED index modulation OFDM	PEP	Pairwise error probability
GSM	Generalized spatial modulation	PHY	Physical layer
GSSK	Generalized space shift keying	PIM	Precoder index modulation
G-STSK	Generalized space-time shift keying	PIM-SM	Precoder index modulation spatial modulation
HD	Half-duplex	PLC	Power line communications
ICI	Inter-carrier interference	PLNC	Physical-layer network coding
IFFT	Inverse fast Fourier transform	PPM	Pulse position modulation
IQ	In-phase and quadrature	PR	Primary receiver
IM	Index modulation	PT	Primary transmitter
IM/DD	Intensity modulation with direct detection	PU	Primary user
IoT	Internet of Things	PSK	Phase shift keying
ISI	Inter-symbol interference		
LD	Laser diode		
LDPC	Low density parity check		
LED	Light emitting diode		
LLR	Log-likelihood ratio		

QAM	Quadrature amplitude modulation
QPSK	Quadrature phase shift keying
QSM	Quadrature spatial modulation
QSSK	Quadrature space shift keying
R	Relay node
RA	Reconfigurable antenna
RC	Repetition code/coding
RF	Radio frequency
S	Source node
SAGE	Space-alternating generalized expectation max.
SAP	Subcarrier activation pattern
SC-FDMA	Single-carrier frequency-division multiple-access
SC-IFDMA	Single-carrier interleaved FDMA
SC-SM	Single-carrier spatial modulation
SFC-IM	Space-frequency coded index modulation
SIMO	Single-input multiple-output
SIPM-O-OFDM	Subcarrier index-power modulated optical OFDM
SISO	Single-input single-output
SM	Spatial modulation
SMFD	Spatial modulated full-duplex
SM-MBM	Spatial modulation media-based modulation
SMX	Spatial multiplexing
SPPAM	Spatial pulse position amplitude modulation
SR	Secondary receiver
SSK	Space shift keying
ST	Secondary transmitter
STBC	Space-time block code/coding
STBC-SM	Space-time block coded spatial modulation
STC	Space-time code/coding
STCM	Space-time channel modulation
STIM	Space-time index modulation
STSK	Space-time shift keying
SU	Secondary user
TC-SM	Trellis coded spatial modulation
TI-MBM	Time-indexed media-based modulation
TI-SM	Time-indexed spatial modulation
TI-SM-MBM	Time-indexed SM-media-based modulation
U-DSM	Unified differential spatial modulation
UFMC	Universal filtered multi-carrier
U-OFDM	Unipolar OFDM
UV	Ultraviolet
UWA	Underwater acoustic
V2X	Vehicle-to-vehicle and vehicle-to-infrastructure
V2V	Vehicle-to-vehicle
V-BLAST	Vertical Bell Laboratories layered space-time
VLC	Visible light communications

WiMAX	Worldwide Interoperability for Microwave Access
ZF	Zero forcing

I. INTRODUCTION

5th generation (5G) of wireless networks, which is expected to be introduced around 2020, has been one of the hottest topics in the wireless communications community over the past few years [1], [2]. Although there is an ongoing debate on 5G wireless technology whether it will be a simple evolution compared to its fourth generation (4G) counterpart, or a radically new communication network, 5G wireless networks are expected to not only provide immense bandwidth and much higher data rates with considerably lower latency, but also enable a variety of new applications such as connected autonomous cars, smart appliances and the Internet of Things (IoT) [3]. The February 2017 announcement [4] and the draft report of the International Telecommunications Union (ITU) on the key performance requirements of IMT-2020 [5], which specifies a downlink peak data rate of 20 Gbps and a peak spectral efficiency of 30 bits/sec/Hz with a multiple-input multiple-output (MIMO) system configuration up to eight transmit and receive antennas, have proven the necessity of new spectrum- and energy-efficient physical layer (PHY) techniques for 5G and beyond wireless networks. Researchers have already put forward effective PHY solutions such as massive MIMO systems, millimeter-wave (mmWave) communications and flexible waveform designs; however, the wireless community is still working in a relentless manner to come up with new and more effective PHY solutions towards 5G and beyond wireless networks. Index modulation (IM) techniques, which consider innovative ways to convey information compared to traditional communication systems, appear as competitive candidates for next-generation wireless networks due to the attractive advantages they offer in terms of spectral and energy efficiency as well as hardware simplicity.

There has been a tremendous interest in IM schemes over the past few years. 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 [6]. 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 (LEDs), 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 indices of these building blocks can be used to transmit information through

TABLE 1. Prominent members of the index modulation family.

Index Modulation									
Antennas	Subcarriers	RF Mirrors	LEDs	Relays	Modulation types	Time slots/samples	Precoding matrices	Dispersion matrices	Spreading codes
SM[7]	OFDM-IM[8]	CM (MBM/RA)[11]	OSM[12]	Di-SSK[13]	ESM[14]*	U-OFDM[15]	PIM[16]	STSK[17]	CIM-SS[18]
SSK[19]	OFDM-I/Q-IM[20]	MIMO-MBM[21]	NDC-OFDM[22]	Di-SM[23]	E-SMX[24]	eU-OFDM[25]	PIM-SM[16]*	DSTSK[17]	GCIM-SS[26]
GSM[27]	OFDM-GIM[28]	RA-SSK[29]*	GLIM-OFDM[30]		DM-OFDM[31]§	TI-SM[32]*		G-STSK[33]	
GSSK[34]	CI-OFDM-IM[35]	SM-MBM[32]*	e-GLIM-OFDM[36]		GDM-OFDM[37]§	TI-MBM[32]†		MS-STSK[38]*	
MA-SM[39]	OFDM-HIQ-IM[40]	GSM-MBM[41]			MM-OFDM-IM[42]§	TI-SM-MBM[32]*†		MSF-STSK[43]*§	
STBC-SM[44]	LP-OFDM-I/Q-IM[40]	STCM[11]			GFDM-SFIM[45]*§	STIM[46]*			
TC-SM[47]	MIMO-OFDM-IM[48]	DP-SM[49]*				SC-IM[50]			
QSM[51]	GSFIM[52]*								
FBE-SM[53]	GFDM-IM[54]								
ASM[55]	O-OFDM-IM[56]								
DSM[57]	SIPM-O-OFDM[58]								
ST-QSM[59]	FBMC-IM[60]								
SC-SM[61]	DCT-OFDM-IM[62]								
Dh-SM[63]	CI-DCSK[64]								

* also employs IM for antennas

† also employs IM for RF mirrors

§ also employs IM for subcarriers

an on/off keying mechanism, IM schemes have the ability to transfer the saved transmission energy from the inactive transmit entities to the active ones, and this results in an improved error performance compared to the traditional schemes that use the same total transmission energy. From another perspective, IM schemes have the ability to convey information in a more energy-efficient way by deactivating some of the main elements of the system, while still exploiting them for data transferring purposes. Finally, since IM comes up with new dimensions for conveying digital information, the spectral efficiency of the considered communication system can be increased effectively without increasing the hardware complexity.

Every communication system can be theoretically considered as a special case of IM; however, the term of IM is explicitly used to cover the family of communication systems that consider other transmit entities than amplitudes/frequency/phases to convey information. Although early attempts have been made to explore the potential of IM-based schemes during the beginning of this century, after the introduction of *spatial modulation (SM)* and *orthogonal frequency division multiplexing with index modulation (OFDM-IM)* concepts by the inspiring works of [7] and [8] in 2008 and 2013, respectively, a new wave of alternative digital modulation schemes has started. As of today, this wave is increasingly spreading and speeding up. Even during the preparation of this article, several new studies on IM technologies have appeared in the literature and the text has been modified continuously to present the most recent interesting results to the readers.

SM, which considers IM for the transmit antennas of a MIMO system, has attracted tremendous attention over the past few years and introduced new directions for the implementation of MIMO systems. Although having very strong and well-established opponents such as vertical Bell Laboratories layered space-time (V-BLAST) [9] and space-time coding (STC) systems [10], SM schemes have quickly shown their true potential in terms of spectral and energy efficiency

and, consequently, have been regarded as possible candidates for next-generation small/large-scale and single/multi-user MIMO, full-duplex (FD), cooperative and cognitive radio (CR) systems. SM has been the front-runner of IM techniques and has also triggered the spread of IM to orthogonal frequency division multiplexing (OFDM) first, and then to other systems. The scheme of OFDM-IM [8] has shown that IM is not unique to the transmit antennas of MIMO systems and it has opened the door for the introduction of many other IM-based schemes in the recent 1-2 years. More importantly, recent studies have shown that OFDM-IM can offer appealing advantages over classical OFDM, which is an integral part of today's many wireless communication standards and also being considered as a strong waveform candidate for 5G wireless networks. Fortunately, IM has found new application areas by considering other transmit entities of communication systems such as time slots, precoding matrices, modulation types and so on. The third notable application of IM is media-based modulation (MBM) (or reconfigurable antenna (RA)-based) systems, which consider the indices of the RF mirrors (parasitic elements) mounted at a transmit antenna to convey information by altering the characteristics of the transmit antennas according to the information bits while employing a carrier signal with constant parameters. Since these type of systems literally carry information with the realizations of the wireless channel itself, they can be also termed as channel modulation (CM) schemes [11].

In Table 1, we categorize the prominent members of the vast IM family according to their specific type of IM implementation methods, i.e., system building blocks used in data transmission through IM. As seen from Table 1, IM techniques can be implemented for several different types of communication systems (single-input single-output (SISO)/MIMO, single/multi-carrier, optical wireless (OW), cooperative, orthogonal/non-orthogonal signaling, single/multi-transmission phase and spread spectrum systems) that have the ability to adjust the on/off status of their different transmit entities. It is interesting to note that

while some schemes consider a single transmission entity (building block of the communication system) for IM such as antennas (for SM) or subcarriers (for OFDM-IM), some schemes exploit more than a single entity for IM purposes to further increase the spectral efficiency of the system. As seen from Table 1, it is theoretically possible to construct a super IM scheme by exploiting several building blocks of a communication system for IM. It should be noted that most of these schemes, which have been proposed in the past few years, will be reviewed in the upcoming sections of this article, while we mainly focus on the IM of the following three important transmit entities: antennas, RF mirrors and subcarriers.

In this article, our main objective is to answer the question of what IM is in a comprehensive manner by covering not only the basic principles and variants of IM but also reviewing the most recent as well as promising advances in this field. More specifically, we put the emphasis on three emerging forms of IM in this article: SM, CM and OFDM-IM. The organization of the article is shown in Fig. 1.

Our survey article also differs from the existing magazines/survey articles/books in the literature [6], [65]–[69] by several aspects. First, it is the first article that overviews the concept of IM as a whole by covering not only SM and OFDM-IM schemes, but also CM as well as other relevant applications of IM. As a result, this article is by far the most comprehensive one in the broad area of IM. Second, we put our emphasis on the most recent developments in the past three years. Therefore, this article covers numerous up-to-date studies for the first time to enlighten the interested readers.

II. THE CONCEPT OF SPATIAL MODULATION

SM, which considers the indices of the transmit antennas of a MIMO system for conveying additional information, is by far the most well-known application of IM. Although the roots of SM date back to the beginning of this century, in which the authors considered SM-like transmission schemes in [70]–[73] by using different terminologies, the term of *spatial modulation* is first coined in the studies of [74]–[76] during 2006. In the following years, the SM concept has started a new wave of alternative digital modulation schemes and numerous papers have been published in the literature. For a comprehensive historical overview of the SM concept, interested readers are referred to [65]–[68] and the references therein.

SM considers an innovative approach to transmit information by means of the indices of the transmit antennas of a MIMO system in addition to the conventional M -ary signal constellations [7]. The conventional MIMO schemes rely on either spatial multiplexing (SMX) to boost the data rate by the transmission of different data symbols from different transmit antennas [9], or spatial diversity to improve the error performance by the reception of multiple copies of the data symbols from different transmit/receive antennas at different time slots [77], [78]. In other words, the multiple transmit

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FIGURE 1. Organization of this article.

antennas of a MIMO system are used for a different purpose in these scenarios compared to SM. More specifically, two information carrying units exist in SM: the indices of the available transmit antennas and the M -ary constellation symbols. For each transmission interval, a total of

$$\log_2(n_T) + \log_2(M) \quad (1)$$

bits enter the transmitter of an SM system as depicted in Fig. 2, where n_T and n_R denote the number of transmit and receive antennas, respectively, and M is the size of the considered signal constellation diagram such as M -ary phase shift keying (M -PSK) or M -ary quadrature amplitude modulation (M -QAM). In a traditional fashion, the first $\log_2(M)$ bits of

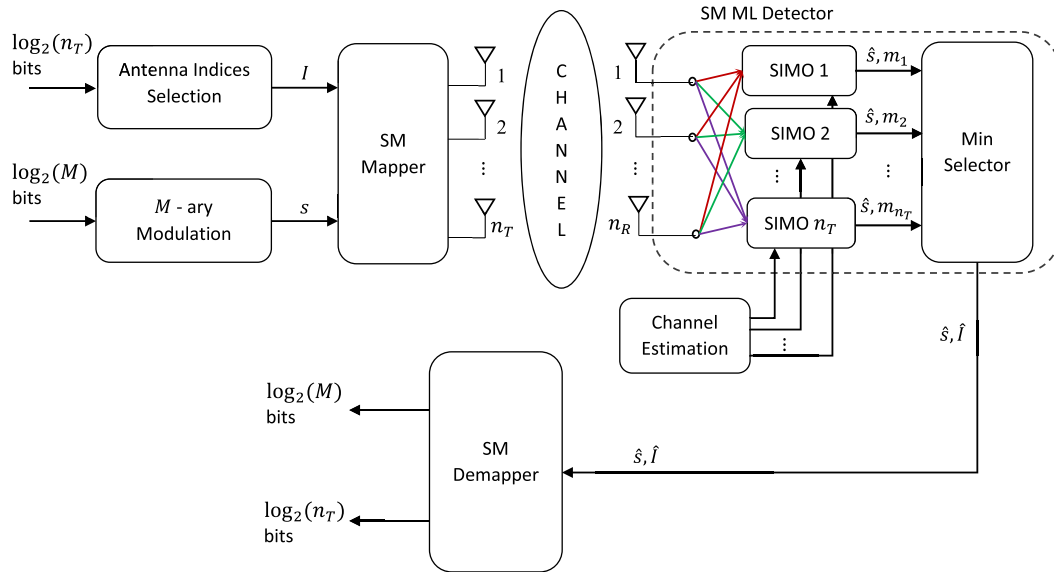


FIGURE 2. SM system model with n_T transmit and n_R receive antennas.

the incoming bit sequence are used to modulate the phase and/or amplitude of a carrier signal. On the other hand, the remaining $\log_2(n_T)$ bits of the incoming bit sequence are considered for the selection of the index (I) of the active transmit antenna that performs the transmission of the corresponding modulated signal (s). Consequently, the baseband transmission vector of SM, with dimensions $n_T \times 1$, becomes

$$\mathbf{s} = [0 \ \cdots \ 0 \ s \ 0 \ \cdots \ 0]^T \quad (2)$$

whose I th entry is non-zero only, where $(\cdot)^T$ stands for the transposition of a vector. The sparse structure of the SM transmission vector \mathbf{s} given in (2) not only reduces the detection complexity of its maximum likelihood (ML) detector in terms of complex operations but also allows the implementation of compressed sensing (CS)-based low/near-optimal detection algorithms for SM systems.

The receiver of the SM scheme has to deal with the following two major tasks: detection of the active transmit antenna for the demodulation of IM bits and detection of the data symbol transmitted over the activated transmit antenna for the demodulation of the bits mapped to the M -ary signal constellation. Unfortunately, the optimum ML detector of SM has to search jointly over all transmit antennas and constellation symbols to perform these two tasks [79]. As seen from Fig. 2, the ML detector of the SM scheme can be considered as the combination of n_T single-input multiple-output (SIMO) ML detectors, which correspond to n_T transmit antennas and demodulate the corresponding complex data symbol as \hat{s} . This detector finds the most likely activated transmit antenna by comparing the corresponding minimum decision metrics (m_1, m_2, \dots, m_{n_T}) and provides the detected activated antenna index (\hat{I}) as well as the estimated complex data symbol (\hat{s}) to the SM demapper for the retrieval of the incoming bit sequence. On the other hand, the primitive

suboptimal detector of SM deals with the aforementioned two tasks one by one, that is, first, it determines the activated transmit antenna, then, it finds the data symbol transmitted over this antenna [76], [80]. Therefore, the size of the search space becomes $n_T \times M$ and $n_T + M$ for the ML and suboptimal detectors, respectively. Although the suboptimal detector can obtain a significant complexity reduction for increasing number of transmit antennas and higher order constellations, its error performance is considerably worse than that of the ML detector. Therefore, the implementation of the suboptimal detector can be problematic for critical applications that require a low error rate. Additionally, the sparse structure of SM transmission vectors paves the way for the implementation of near/sub-optimal low-complexity detection methods for SM systems such as matched filter-based detection [81] and CS-based detection [82].

A. ADVANTAGES AND DISADVANTAGES OF SM

In light of the above discussion on the concept of SM, MIMO systems employing SM provide attractive advantages over their traditional counterparts [65]–[67], [83]. In the following, we list the main advantages of SM over classical MIMO systems:

- High spectral efficiency: Due to the use of transmit antenna indices as an additional way of conveying information, the spectral efficiency of SM exceeds that of SISO systems and orthogonal space-time block codes (STBCs).
- High energy efficiency: The power consumed by the SM transmitter is independent of the number of transmit antennas, while the information can be still transferred via these antennas. In other words, a higher number of transmit antennas can be exploited in a SM-MIMO system for data transmission without requiring additional

transmission energy. From this perspective, SM emerges as a green and energy-efficient MIMO technology. In terms of the energy efficiency in Mbits/J, improvements up to 46% compared to V-BLAST are reported for different type of base stations (BSs) equipped with multiple antennas [84].

- Simple transceiver design: Since only a single transmit antenna is activated during transmission, a single RF chain is sufficient for the SM scheme. Furthermore, inter-antenna synchronization (IAS) and inter-channel interference are completely eliminated and the decoding complexity of the SM receiver, in terms of the total number of real multiplications, grows linearly with the constellation size and number of transmit antennas. As an example, SM scheme achieves $200(n_T - 1)/(2n_T + 1)\%$ reduction in ML detection complexity compared to V-BLAST for an $n_T \times n_R$ MIMO system operating at a fixed spectral efficiency. This significant complexity reduction is achieved by the activation of a single transmit antenna in SM, i.e., the sparse transmission vectors of SM. A much simpler implementation solution can be obtained by transmitting information with only active transmit antenna indices and the resulting scheme is called space-shift keying (SSK) [19]. Compared to SM, SSK requires neither in-phase and quadrature (IQ) modulation nor pulse shaping.
- Operation with flexible MIMO systems: Unlike the V-BLAST scheme, which requires $n_R > n_T$ to operate with minimum mean square error (MMSE) and zero forcing (ZF) type linear detectors, SM can be implemented for any number of transmit and receive antennas. In other words, SM is well suited for unbalanced MIMO setups, such as downlink of next-generation wireless networks in which BSs are equipped with higher number of transmit antennas.

While the SM scheme has the aforementioned appealing advantages, it also has some disadvantages, which are summarized as follows:

- The spectral efficiency of SM increases logarithmically with n_T , while the spectral efficiency of V-BLAST increases linearly with n_T . Therefore, a larger number of transmit antennas are required for SM to reach the same spectral efficiency as that of V-BLAST. More importantly, the spectral efficiency of plain SM cannot compete with that of V-BLAST for higher order constellation sizes.
- The channel coefficients of different transmit antennas must be sufficiently different for an SM scheme to operate effectively. In other words, SM requires rich scattering environments to ensure better error performance. Related with this, for environments with increased Rician K or Nakagami- m factors, the bit error rate (BER) performance of SM degrades surprisingly in contrast to classical systems.
- Since SM transfers the information using the spatial domain, plain SM cannot provide transmit diversity

as STC systems. One solution is to consider transmit precoding, which requires channel state information (CSI) at the transmitter, while another direction is STC techniques that require at least two transmission phases.

Considering the advantages and disadvantages of SM systems mentioned above, we may conclude that SM scheme provides an interesting trade-off among encoding/decoding complexity, spectral efficiency, and error performance. As a result, SM technologies have been regarded as possible candidates for spectrum- and energy-efficient next generation wireless communication systems [2], [6].

III. PROMISING VARIANTS OF SPATIAL MODULATION

After the pioneering works of [7] and [19], which introduced SM and SSK schemes, respectively, the wireless community have shown remarkable interest in SM technologies. In the past seven years, numerous papers on SM have been published in which the focus is on generalized, spectrum- and energy-efficient SM systems [27], [34], [39], [53], low-complexity detector types [80]–[82], [85]–[87], block/trellis coded SM systems with transmit/time diversity [17], [44], [47], [88]–[92], link adaptation methods such as adaptive modulation [93], transmit antenna selection [94]–[96] and precoding [97], performance analysis for different type of fading channels [98]–[100] and channel estimation errors [101]–[103], information theoretical analyses [104], [105], differential SM schemes with non-coherent detection [57], cooperative SM systems, and so on. For a comprehensive overview of these studies, interested readers are referred to previous survey papers on SM [61], [65]–[67]. In this section, our aim is to review some of the recent as well as promising SM variants such as generalized, quadrature, enhanced and differential SM systems.

A. GENERALIZED SM

As mentioned in the previous section, one of the major disadvantages of SM is its relatively limited spectral efficiency compared to classical V-BLAST scheme for the same number of transmit antennas. Although it is possible to convey a considerable amount of information bits by the indices of the active transmit antennas, SM suffers a significant loss in spectral efficiency with respect to V-BLAST due to its inactive transmit antennas for higher order modulations and MIMO systems.

One of the first attempts to increase the spectral efficiency of SM as well as to ease the constraint on the number of transmit antennas, which has to be an integer power of two for classical SM, has been made by the generalized SM (GSM) scheme [27], [106]. In the GSM scheme, the number of active transmit antennas is no longer fixed to unity and the same data symbol is transmitted over selected multiple active transmit antennas. Since the same data symbol is transmitted from all active transmit antennas, inter-channel interference is also avoided for GSM. Denoting the number of active transmit antennas by n_A , where $n_A < n_T$, the spectral efficiency of

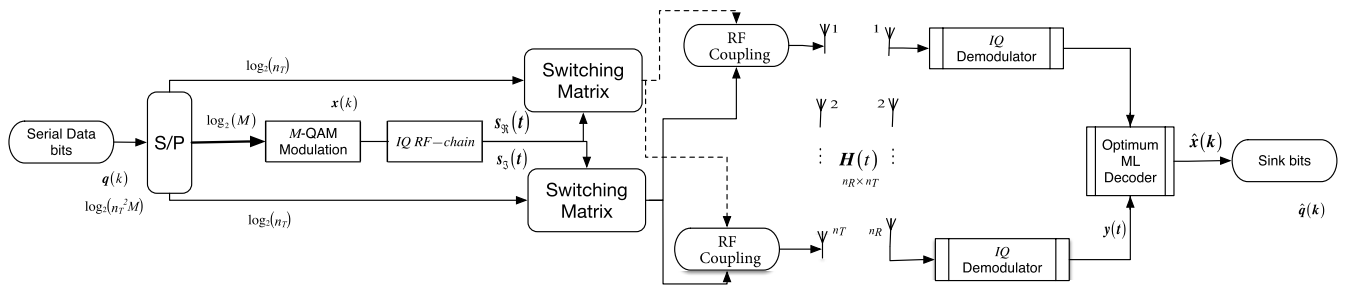


FIGURE 3. QSM system model with single RF chain, two RF switches, n_T transmit and n_R receive antennas.

GSM in terms of bits per channel use (bpcu) becomes

$$\left\lfloor \log_2 \binom{n_T}{n_A} \right\rfloor + \log_2(M) \quad (3)$$

where $\lfloor \cdot \rfloor$ is the floor operation and $\binom{\cdot}{\cdot}$ stands for the Binomial coefficient. It should be noted that SM is a special case of GSM with $n_A = 1$. Considering $\log_2(n_T) \leq \left\lfloor \log_2 \binom{n_T}{n_A} \right\rfloor$ for $n_T = 2^n$ ($n = 1, 2, \dots$), the spatial domain can be used in a more effective way by the GSM scheme. As an example, for the case of $n_T = 8$ transmit antennas, only three bits can be transmitted by the antenna indices in SM, while GSM can convey six bits with $n_A = 4$. The concept of GSM has been extended to multiple-active spatial modulation (MA-SM) in [39] by transmitting different data symbols from the selected active transmit antennas to further increase the spectral efficiency (the same scheme is also termed as multi-stream SM in [107] since each transmit antenna conveys its own stream). Consequently, the spectral efficiency of the MA-SM scheme is given as

$$\left\lfloor \log_2 \binom{n_T}{n_A} \right\rfloor + n_A \log_2(M) \quad \text{bpcu} \quad (4)$$

which is considerably higher than that of SM given in (1). It is interesting to note that MA-SM provides an intermediate solution between two extreme schemes: SM and V-BLAST, which are the special cases of MA-SM for $n_A = 1$ (only a single transmit antenna is activated) and $n_A = n_T$ (all transmit antennas are activated), respectively.

Considering the increasing demand for higher data rates in next-generation wireless networks and due to its flexible structure, GSM appears as a strong alternative to SM and V-BLAST schemes, which have their own advantages and disadvantages. As a result, GSM techniques have attracted considerable attention in the past few years. It has been shown that GSM can achieve better throughput and/or error performance compared to V-BLAST. Furthermore, percentage savings in terms of the required number of transmit RF chains have been reported by the authors of [108]. In [109], a closed form expression has been derived for the capacity of GSM and the error performance of GSM has been analyzed for correlated and uncorrelated, Rayleigh and Rician fading channels. More recently, antenna detection error probability and mutual information performance of GSM systems with

and without transmit precoding are investigated in [105]. Finally, researchers have also explored low complexity detection algorithms for GSM. More specifically, ordered block MMSE [110], CS [111], [112], reactive tabu search [113] and deterministic sequential Monte Carlo-based [114] low-complexity detectors of GSM, which provide near-ML error performance, are proposed.

B. QUADRATURE SM

Quadrature spatial modulation (QSM) is proposed in [51] as an enhancement to ordinary SM [7] by creating a new spatial constellation dimension. The new constellation diagram allows the transmission of an additional base two logarithm of the number of transmit antennas. In particular, the in-phase part of the modulated RF carrier is transmitted from one antenna determined by $\log_2(n_T)$ bits of the incoming source data. Similarly, the quadrature component of the RF carrier is transmitted from another antenna determined by another $\log_2(n_T)$ bits of the source data. A system model for the QSM technique is depicted in Fig. 3.

Let $\eta = 2\log_2(n_T) + \log_2(M)$ be the number of data bits to be transmitted through QSM at each time instant. Arbitrary complex constellation diagram can be considered such as QAM/PSK. The data bits are partitioned into three parts and processed simultaneously. The first group, which contains $\log_2(M)$ bits, modulate a complex symbol $x = x_R + jx_I$ from an M -QAM signal constellation.¹ The other two groups, each with $\log_2(n_T)$ bits, modulate the spatial constellation symbols, $\ell_R \in \{1, \dots, n_T\}$ and $\ell_I \in \{1, \dots, n_T\}$ that will respectively transmit x_R and x_I . It is important to note that even though two antennas might be active at one time instant, the inter-channel interference among transmitted data is entirely avoided since transmitted data are orthogonal thanks to the IQ components of the carrier signal. In addition and depending on the incoming data bits, one antenna might be active to transmit both data symbols as illustrated in [51]. Besides, a single RF chain transmitter is needed to implement the QSM scheme and the ML receiver complexity is the same as that of SM.

In Table 2, transmission vectors of QSM are given for two transmit antennas, where two additional bits (IM bits) are

¹For a complex variable x , its real and imaginary parts are denoted by x_R and x_I , i.e., $x = x_R + jx_I$.

TABLE 2. Transmission vectors of QSM.

IM Bits	QSM Tx. Vectors
{0, 0}	$[x_R + jx_I \ 0]^T$
{0, 1}	$[x_R \ jx_I]^T$
{1, 0}	$[jx_I \ x_R]^T$
{1, 1}	$[0 \ x_R + jx_I]^T$

transmitted in the spatial domain by using one of the provided four transmission vectors.

Quadrature space shift keying (QSSK) can be derived as a special case from QSM by transmitting an un-modulated carrier signal. In QSSK, the symbol $x = 1 + j$ is always transmitted, which contains no data and all data bits are modulated in the spatial domain. Hence, the data rate of QSSK becomes $\eta = 2\log_2(n_T)$.

The error performance of QSM has been studied in [51] and compared to the performance of SM and SMX. It has been demonstrated that QSM can achieve better performance than both schemes. A comprehensive framework for the performance analysis of QSM over $\eta - \mu$, $\alpha - \mu$ and $\kappa - \mu$ generalized fading channels assuming spatial correlation and imperfect channel estimation is recently presented in [115]. A general analytical formula for evaluating the performance of QSM system is derived and shown to be accurate over a wide range of SNR values for different system and channel parameters. A low complexity detection algorithm for QSM is proposed in [116] by using CS principles. Another low complexity algorithm for an OFDM system with in-phase/quadrature index modulation (OFDM-I/Q-IM) is presented in [20]. The proposed scheme is shown to alleviate the need of a priori knowledge of the noise variance and the possible realizations of the active sub-carrier indices. Furthermore, the novel dual IM concept of QSM has also triggered the research activities on the design of high-rate SM systems and a new SM scheme called double SM is proposed in [117]. More recently, a scheme termed space-time QSM is proposed in [59] to obtain transmit diversity for QSM by combining it with the Alamouti [77] and ABBA space-time block codes [118].

The impact of IQ imbalance on the performance of QSM is studied in [119]. It is shown that IQ imbalance can significantly degrade the performance of QSM. In addition, a practical model for IQ imbalance is presented and an analytical derivation for the average BER is proposed. Another study reported in [120] studied the impact of co-channel interference on the performance of the QSM-MIMO system. An anti-eavesdropping scheme based on QSM is recently studied in [121]. A scheme with better security properties is presented where it is demonstrated that QSM improved the secrecy while reserving the same hardware cost and receiver structure of a legitimate receiver.

The future wireless standards are anticipated to be based on mmWave and large scale MIMO systems. The applicability

of a line of sight (mmWave) QSM-MIMO scheme is studied in [122]. It is shown that the use of QSM in mmWave MIMO system promises significant boost in the achievable capacity. In the same work, a new mmWave channel design for unbalanced MIMO configuration, where there exist more transmit antennas than receive antennas, is proposed and shown to achieve significant performance advantages. In addition, the adoption of QSM for large scale MIMO configuration is considered in [123], where a low-complexity decoder is proposed and analyzed. Very recently, capacity analysis for QSM scheme over a three dimensional mmWave MIMO communication system is reported in [124]. It is shown that the theoretical capacity of QSM exceeds that of SMX system. Achieving such capacity is shown to be possible with proper design of the constellation symbols for each channel statistics.

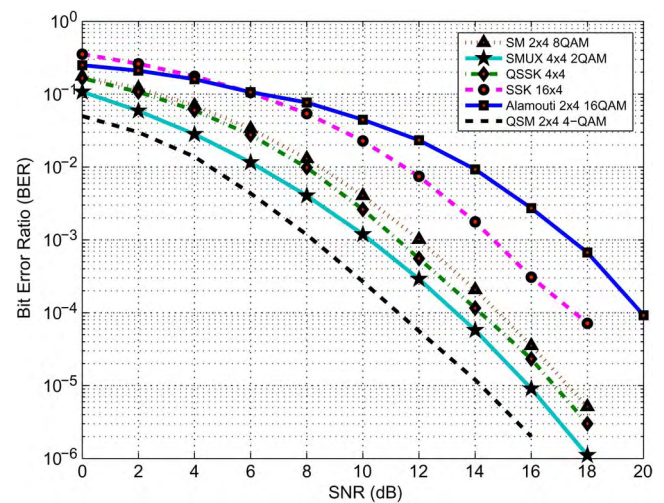


FIGURE 4. BER performance comparison of SM, SMX, QSSK, SSK, Alamouti's STBC and QSM schemes for 4 bpcu using ML detection (reproduced from [51] with permission).

In Fig. 4, BER performance of QSM is compared with SM, SMX, QSSK, SSK and Alamouti's STBC for 4 bpcu transmission. As seen from Fig. 4, while SM outperforms SSK and Alamouti's STBC, it is outperformed by QSSK and SMX schemes. On the other hand, QSM provides the best BER performance among all considered systems.

C. ENHANCED SM

Enhanced spatial modulation (ESM) scheme, whose main motivation is to overcome the limited spectral efficiency of SM, extends the classical SM by considering the signal constellations themselves by means of transmitting information [14]. Within this perspective, ESM introduces the concept of transmitting information bits by using combinations of transmit antennas and signal constellations. In the ESM scheme, the number of active transmit antennas can be one or two in each transmission interval and the information is conveyed not only by the active transmit antenna indices as in classical SM/SSK schemes but also by the selected

signal constellations used for transmission from these activated antennas. The main idea of ESM is the transmission of symbols from a primary M -ary signal constellation when a single transmit antenna is activated, while symbols from a secondary $\frac{M}{2}$ -ary signal constellation are transmitted when two transmit antennas are activated. The size of the secondary signal constellation is adjusted to be half that of the primary constellation in order to transmit the same number of information bits in each signaling interval. Furthermore, the design of primary and secondary signal constellations has a significant impact on the error performance of the system through the maximization of the minimum Euclidean distance between ESM transmission vectors.

TABLE 3. Transmission vectors of ESM.

IM Bits	ESM Tx. Vectors
{0, 0}	$[\mathcal{S}_4 \ 0]^T$
{0, 1}	$[0 \ \mathcal{S}_4]^T$
{1, 0}	$[\mathcal{S}_2 \ \mathcal{S}_2]^T$
{1, 1}	$[\mathcal{S}_2 e^{j\theta} \ \mathcal{S}_2 e^{j\theta}]^T$

In Table 3, transmission vectors of ESM are given for two transmit antennas and four bpcu transmission, where two additional bits (IM bits) are transmitted by the combinations of active antennas and signal constellations considering one quadrature PSK (QPSK, \mathcal{S}_4) and two binary PSK (BPSK, \mathcal{S}_2 and $\mathcal{S}_2 e^{j\theta}$) signal constellations. Here, \mathcal{S}_M denotes M -PSK constellation (or a symbol selected from this constellation) and $\theta = \pi/2$ is a rotation angle used to obtain a third signal constellation in addition to classical BPSK and QPSK signal constellations. It is interesting to note that the first two transmission vectors of the ESM scheme are the same as those of classical SM, $n_T = 2$ using QPSK with single activated transmit antenna, where the first and second transmit antennas are used for the transmission of a QPSK symbol, respectively. On the other hand, the third and fourth transmission vectors correspond to the simultaneous transmission of two symbols selected from BPSK and modified BPSK constellations, respectively. In [14], several design examples, which consider different numbers of transmit antennas and constellations, are provided for the ESM scheme. In all cases, since the number of antennas and signal constellation combinations is higher than the number of active antenna combinations of classical SM, a higher spectral efficiency and improved error performance can be obtained by utilizing IM more efficiently.

In the past two years, ESM has attracted the attention of the community and some follow-up studies have been conducted. The inventors of ESM have proposed the enhanced spatial multiplexing (E-SMX) scheme, which is based on the multiple signal constellations concept of ESM, to improve the performance of classical V-BLAST [24]. MA-SM and ESM concepts have been recently combined to obtain better error performance with the design of new signal constellations [125]. Moreover, the error performance of ESM has been investigated under channel estimation errors for

uncorrelated and correlated, Rayleigh and Rician fading channels and it has been shown that ESM exhibits improved tolerance to channel estimation errors [126].

D. DIFFERENTIAL SM

The full knowledge of CSI is necessary for the optimal coherent SM detection since it serves as a part of the transmitted information. The requirement of CSI, however, entails considerable pilot overhead and high-complexity channel estimation, especially for the scenarios of massive transmit antennas. Differential encoding of the transmitted symbols, which enables non-coherent detection while preserving the information embedded on the channel, appears as an attractive option for overcoming this limitation.

The idea of differential SM (DSM) was first introduced in [17], where a differentially encoded space-time shift keying (DSTSK) scheme is proposed. DSTSK extends the concept of SM to include both the space and time dimensions, by which the information bits are conveyed via both the indices of multiple pre-assigned dispersion matrices (DMs) and the signal constellation points. In DSTSK, the modulated symbol is limited to be real-valued to facilitate the Cayley unitary transform and transmitted repeatedly over multiple symbol durations. The limitation on the signal constellation was later relaxed in [127], where a more bandwidth-efficient DSTSK scheme that allows a complex-valued modulated symbol, is conceived. The single-symbol transmission property enables the DSTSK system to attain transmit diversity, but leads to a reduced transmission rate. Motivated by the MA-SM concept, the authors in [128] generalized the DSTSK in [17] by simultaneously transmitting multiple real-valued modulated symbols in conjunction with a subset of DMs, striking a more flexible trade-off between the diversity gain and transmission rate. Assuming two transmit antennas, the authors in [129] proposed a new DSM variant based on the DSTSK framework, in which a cyclic signal constellation is employed rather than the ordinary signal constellation as in [17], [127], and [128]. This scheme, usually referred to as cyclic-signaling-based DSM (CS-DSM) in the literature, encodes the information bits via matrices only, and is able to attain full diversity by sophisticatedly configuring the parameters associated with a cyclic signal constellation. Based on a sparse unitary structure, the DM sets can be constructed using algebraic field extensions, that can be applied to systems with an arbitrary number of transmit antennas. This so-called field-extension-based DSM (FE-DSM) scheme [130] is also capable of achieving different diversity-rate trade-offs via altering the number of modulated symbols for transmission per space-time block.

On the other hand, a number of research studies focused on the design of DSM schemes that operate with a single RF chain, thanks to its merits of backward compatibility with SM and high energy efficiency. The first attempt was inspired by the SM concept [131], in which two transmit antennas take turns to transmit two PSK symbols during two symbol durations, and the information bits are conveyed by both the

PSK constellation points and antenna activation orders. This idea was later enriched with an arbitrary number of transmit antennas in [57]. The schemes of [57] and [131] essentially obtain the DMs from a set of permutation matrices having only a single non-zero element that is drawn from a PSK constellation in every row and column, and thus, can be referred to as permutation-based DSM (P-DSM). In [132], the BER analyses for P-DSM with two transmit antennas show a performance loss within 3 dB compared to coherent SM at some specific transmission rates. As the number of transmit antennas increases, the size of DMs increases factorially and the optimal detection of P-DSM signals becomes quite involved. To reduce the detection complexity, some low-complexity detection methods have been proposed for P-DSM, including the single-symbol detection [133], Viterbi-like decoding [134] and the sphere decoding [135]. In [136], the Gray codes are applied to the antenna activation orders to attain a higher coding gain for P-DSM. With the aid of transmitter precoding, P-DSM has been further applied to the receiver side [137].

Recently, the concepts of P-DSM and its receive counterpart are extended to a dual-hop virtual MIMO relaying scenario, such that the first and the second hops constitute the receive-P-DSM and P-DSM frameworks, respectively. In this extension, no channel estimation is required at both the relays and destination in favor of the differential signaling [138]. More recently, P-DSM is applied to a two-way relaying scenario, in which the BPSK modulation is employed and the relays use the denoise-and-forward protocol without requiring any CSI [139]. Similar to the history of DSTSK, P-DSM initially supported PSK modulation only. To increase the transmission rate, the amplitude phase shift keying (APSK) modulation is suggested with two amplitude levels in [140] and multiple amplitude levels in [141]. An important point to note is that the APSK modulation has to be employed in conjunction with an additional power coefficient whose value adapts to the amplitude level selected in the previous symbol or block duration for balancing the average transmit power. Moreover, there have been continuous efforts in the academic community to improve the diversity performance of P-DSM [136], [142], [143]. In [136], the intersected Gray coding idea and coordinate interleaved orthogonal design (CIOD) principle are adopted to enhance the protection of the antenna activation orders and modulated symbols, respectively, improving the diversity order from unity to two. The authors in [142] proposed to exploit the transmit diversity by integrating the space-time block coded spatial modulation (STBC-SM) scheme [44] into P-DSM albeit, at the cost of multiple RF chains. This so called temporally- and spatially-modulated STBC (STBC-TSM) scheme is also able to improve the transmission rate of P-DSM as it introduces the temporal permutations of the STBC as an additional information-carrying mechanism. The DSTSK of [17] and the P-DSM of [57] are essentially two extreme realizations of DSM from the perspective of the number of modulated symbols carried on a transmit block.

By allowing a flexible selection of the number of modulated symbols, a unified DSM (U-DSM) architecture that subsumes the DSTSK of [17] and the P-DSM of [57] is designed in [143], where a fixed set of complex-valued permutation DMs is used in conjunction with a set of diagonal matrices, whose elements are drawn from a PSK constellation and allowed to be either dependent or independent. Naturally, U-DSM is capable of leveraging the transmission rate and diversity gain.

The common nature of all above mentioned DSM variants is the space-time block transmission, which favors differential encoding of SM signals, but incurs a considerable communication delay in massive transmit antenna scenarios. Recently, a new idea of implementing DSM while supporting instant communications is presented in [144]. By projecting a differentially encoded square matrix to its rectangular counterpart, the proposed scheme reduces the number of symbol durations needed for block transmission. Moreover, the rectangular transmission matrix may contain only a single non-zero element per column, enabling transmission with a single RF chain, and the transmission rate scales logarithmically with the number of transmit antennas similar to the coherent SM scheme. However, the inherent drawback is the error propagation effects induced in the differential decoding process at the receiver.

Remark: The reviewed four SM variants of this section, GSM, QSM, ESM and DSM, provide interesting trade-offs among complexity and error performance. GSM is an intermediate solution between SM and SMX schemes, and its system parameters can be adjusted to reach a target spectral efficiency at the cost of increasing complexity. QSM has the simplest transmitter structure with a single RF chain, while ESM can achieve a better error performance at the price of two RF chains. DSM achieves an inferior error performance than its coherent counterpart. However, it has a simpler detector that does not require the full knowledge of the CSI.

IV. APPLICATIONS AND PRACTICAL ISSUES FOR SM

In this section, first, we investigate the application of SM techniques to FD, cooperative networks and massive multi-user MIMO (MU-MIMO) systems. Then, we shift our focus from the RF domain to the optical domain and investigate the potential of IM techniques for visible light communication (VLC) systems by reviewing optical SM (OSM) and LED index modulation (LED-IM) concepts. Finally, we present practical implementation examples.

A. APPLICATION OF SM TO FULL-DUPLEX NETWORKS

To enable simultaneous transmission and reception at the same time and same frequency band, an FD node must be configured with at least two independent transmit and receive RF chains. Based on this architecture, it is possible to extend the SM concept to an FD node. This potential was first explored in [145], where an FD node of two antennas is considered and one more bit is introduced by SM to determine the function of each antenna at a symbol interval: whether to

receive or transmit. Higher efficiency in terms of outage and ergodic achievable rates is verified for this spatial modulated full-duplex (SMFD) system, and more benefits are expected when extended to a larger scale multiple-antenna system. The strong self-interference is the main limitation that hinders the practical implementation of FD communication systems. Through a combination of the signals received in successive time slots, the SMFD system is also able to convert the residual self-interference to simple inter-symbol interference without self-interference channel estimation [146], [147]. This conversion may lead to a reduction in the spatial degrees of freedom, but can be partially compensated by transmitting more bits using SM and involving more time slots in the self-interference cancellation.

The potential of SM for FD operation is developed in [148] and [149]. While both [148] and [149] exploit the inactive antennas in SM for signal reception, the application scenarios are quite different. More precisely, in [148], SM is employed by a base station (BS), which communicates with a mobile terminal that employs the CIOD, while in [149], a MIMO source-relay-destination network is considered, where the source node (S) forms a beam to the relay antennas that are inactive and the relay node (R) instantaneously forwards the previously decoded information using SM to the destination node (D) with the remaining antennas. The scheme of [149] can successfully operate as long as S knows its transmitted symbol at the last symbol interval. A similar idea to above has been applied to a distributed cooperative relay network in [150], where multiple geographically distributed single-antenna relays employ the distributed SM (Di-SM) technique and work in a virtual FD mode. In this scheme, S sends a new data to the relays, and meanwhile the relay that was activated using SM according to the previously decoded data, forwards it to D. To avoid the collision problem caused by two successive equal data transmission from S, an extra relay is added to the set of existing relays and this relay takes the role of the busy relay that is activated during two successive time slots. Recently, the SM technique is employed at the source nodes and R in an FD two-way relay channel [151], where the two sources send their own SM symbols to R, and in the meantime, R forwards an SM symbol that bears the information of the previously sent symbols from the sources back to them, who immediately decode their own desired signals upon reception. It is reported that a better error probability performance can be achieved by this scheme over its half-duplex (HD) counterpart. Even more recently, [152] and [153] investigated the performance of bi-directional FD systems using SM and SSK with FD amplify-and-forward (AF) relaying, respectively. More specifically, [152] investigated FD-SM systems in the presence of channel estimation errors and provided comparisons with conventional HD-SM systems. On the other hand, [153] proposed an SSK-based FD-AF scheme and examined its error performance in the presence of residual loop interference. It has been shown by the authors that SSK-based FD-AF systems outperform the conventional SSK with HD-AF relaying

systems as long as the efficiency of loop interference cancellation process is improved and/or the spectral efficiency is increased.

B. APPLICATION OF SM TO COOPERATIVE NETWORKS

Cooperative communications has been one of the hottest topics in wireless communications in the past decade. The basic principle of cooperative communication systems is the transmission of user information not only by its own antenna, but also by the active or passive nodes available in the network. Initially, cooperative communication systems have been considered to create virtual MIMO systems for the mobile terminals due to the problems such as cost and hardware associated with the employment of multiple antennas in mobile terminals [154]. However, due to the recent technological advances, multiple antennas can be employed at mobile terminals, and cooperative communication systems provide efficient solutions to achieve additional diversity gains and high data rates by improving the coverage. Therefore, several cooperative communication systems have been proposed in the literature during the recent years (see [155]–[158] and the references therein). Consequently, cooperative communications and relaying technologies have been incorporated to important wireless communication standards such as IEEE 802.16j Worldwide Interoperability for Microwave Access (WiMAX) [159] and Long Term Evolution-Advanced (LTE-A) [160] for increasing coverage, data rate and cell-edge performance [161].

Considering the effective solutions provided by SM techniques and cooperative communication systems, the combination of these two technologies naturally arises as a potential candidate for next-generation wireless networks. Due to the recent technological advances, cooperative SM systems can provide new implementation scenarios, additional diversity gains, and higher data rates without increasing the cost and complexity of the mobile and relay terminals. In the past few years, researchers have shown that SM techniques can be efficiently implemented for decode-and-forward (DF) and AF relaying based cooperative networks, distributed cooperation, dual- and multi-hop relay networks and network coding systems. In Fig. 5, possible implementation scenarios of the cooperative communication systems employing SM techniques are shown. In Table 4, we categorize the reviewed studies on spatially modulated cooperative communication systems in six main areas. Please note that the studies grouped under classical relay networks, consider the cooperative communication scenario of Fig. 5(b) (or the scenario of multi-antenna S and D with multiple single-antenna relays), while the ones under dual-hop systems consider the scenario of Fig. 5(a). Similarly, the studies grouped under PLNC & two-way systems and distributed systems consider the scenarios of Fig. 5(c) and Fig. 5(d), respectively.

One of the first studies on cooperative SM systems is performed in [63], in which a dual-hop SM (Dh-SM) scheme is proposed. In Dh-SM scheme, S, R and D are equipped with multiple antennas and the communications between S and D

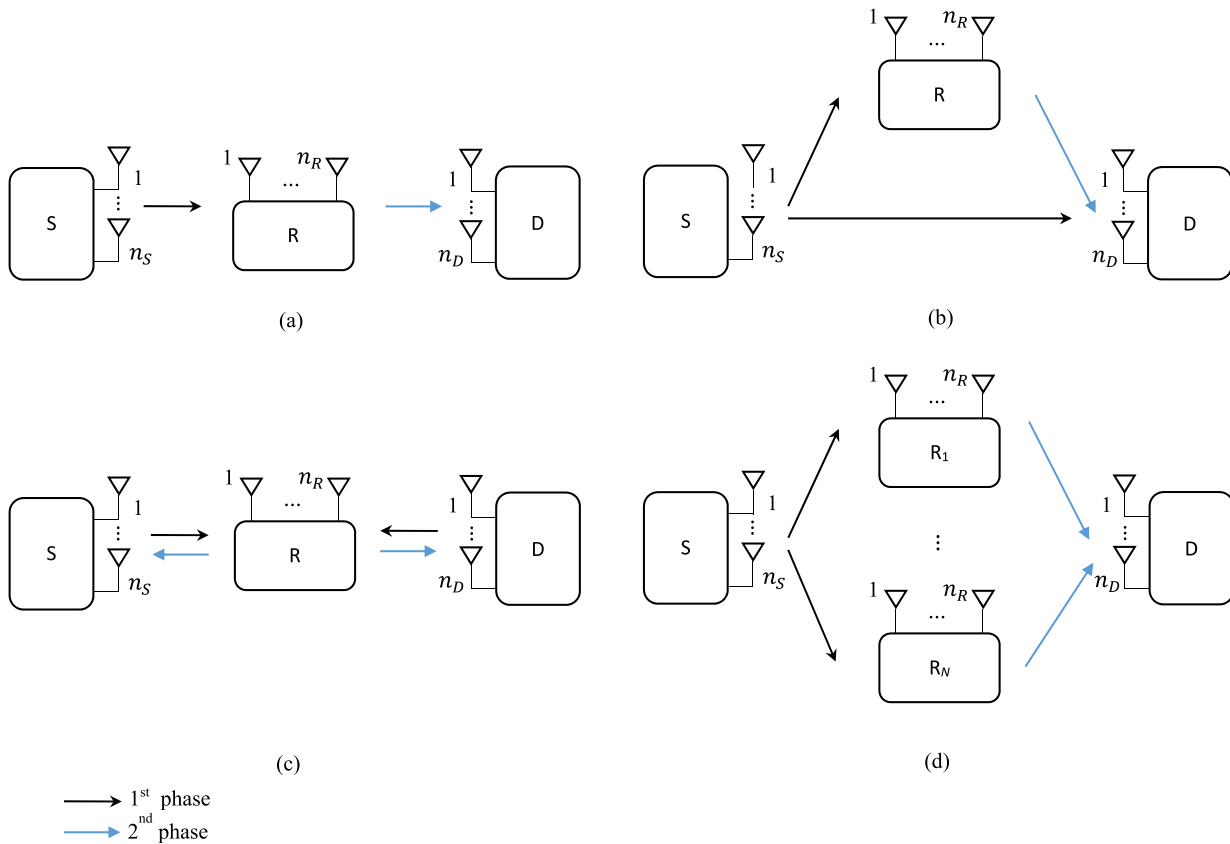


FIGURE 5. An overview of cooperative SM systems (a) Dual-hop SM with a single relay (multi-hop systems can be obtained by increasing the number of relays) (b) Cooperative SM with a direct link between S and D (c) Network-coded SM that supports two-way communications between S and D (d) Multi-relay and distributed SM. n_S , n_R and n_D denote the number of antennas for source (S), relay (R) and destination (D) nodes, respectively (Reproduced from [6] with permission).

TABLE 4. An overview of the studies on cooperative SM systems.

Area	Studies
Classical relay networks	[162], [163], [164], [165], [166], [167], [168], [169], [170], [171], [172], [173], [174], [175], [176]
Dual-hop systems	[63], [177], [178], [179], [180], [181], [182], [183], [184], [185], [138]
Incremental relaying	[186], [187], [188]
PLNC & two-way systems	[189], [190], [191], [192], [151]
Distributed systems	[13], [193], [194], [195], [23], [150], [196]
Multi-hop systems	[197], [198]

is performed over R with the use of the SM principle at S as well as R. Consequently, the decrease in spectral efficiency of classical dual-hop systems is mitigated by the use of SM. It has been shown via extensive computer simulations that by using the DF protocol at R, remarkable improvements can be obtained in error performance compared to classical dual-hop scheme.

In [162], the space-time shift keying (STSK) concept of [17] has been combined with cooperative communications. The authors investigated a cooperative system consisting of single-antenna S, D and multiple relay nodes, and considered cyclic redundancy check (CRC) encoding at S. In this scheme, the relays employ the DF protocol and using CRC codes, they are able to detect the potential decoding errors;

as a result, they prevent themselves from relaying to avoid error propagation in case of an erroneous detection. It has been assumed that S employs classical M -PSK/QAM, while the relays re-encode the bits they modulated using STSK technique. Finally, D employs ML detection considering the signals it received from S as well as the relay nodes. In [163], a successive relaying based DF cooperative multi-carrier STSK scheme is proposed not only to compensate the loss in the spectral efficiency of the traditional HD relaying schemes but also to cope with the dispersive effects of the wireless channels through code division multiple access (CDMA). In this scheme, a number of distributed relay nodes form two virtual antenna arrays and S successively transmits CDMA signals to one of the virtual antenna arrays in addition to

directly transmitting to D. On the other hand, CRC enabled relay nodes consider STSK principle to forward their signals.

SSK-based dual-hop AF relaying is investigated in [177]. In this study, it is assumed that S has multiple antennas, while the relays and D are equipped with a single antenna. In case of two transmit antennas at S, theoretical BER calculations are performed for uncorrelated Rayleigh fading channels. On the other hand, the authors derived a tight upper bound for the general case. In [178], the same authors investigated the scheme of [177] under correlated Rayleigh fading channels. Moreover, this scheme is generalized to a cooperative network with multiple relays in [179]. In order to overcome the loss in spectral efficiency caused by the use of orthogonal time channels for different relays, opportunistic relay selection is also proposed in [179]. In this scenario, the relay that provides the lowest instantaneous error probability is selected as the best relay and performs AF relaying. Theoretical analyses of conventional and opportunistic relaying schemes have been performed for the special case of two transmit antennas at S. In [180], the authors considered a multi-relay dual-hop SSK scheme, in which the selected best relay employs the AF protocol for transmission.

In [181] and [182], a dual-hop hybrid SM scheme, which employs receive SM [199] at S (in the first hop), while considering ordinary SM at R (in the second hop), is proposed. In this scheme, ZF precoding method is used at multi-antenna S and one of the multiple single-antenna relays is selected for the signal reception. In the second phase, only the receiving relay from the previous phase is activated to form a virtual SM scheme from the relays to D and the index of the receiving/activating relay is used as an additional way of transmitting information. The proposed scheme is also extended to a distributed architecture by removing the backhaul connection between the relays. Finally, [183] combined cooperative dual-hop AF relaying with QSM of [51]. It has been shown by the authors that the proposed cooperative QSM scheme outperforms the ordinary cooperative SM scheme while achieving higher spectral efficiency. A closed form average pairwise error probability (APEP) expression is derived for Rayleigh fading channels.

The authors of [184] considered the application of SSK to a dual-hop DF cooperative multicast network consisting of a single source, two relays and multiple destination nodes. In this scheme, all nodes are assumed to have multiple antennas and a relay selection method is proposed to use SSK in both S and R. For BPSK (i.e., two transmit antennas at S and the relays), the authors derived the exact closed form average bit error probability (ABEP) of this multicast AF system. In [185], DSM scheme of [57] is considered for dual-hop AF relaying, where a two-antenna S, single-antenna R and D are assumed. In this scheme, due to the use of DSM at S, D can use non-coherent detection without requiring the CSI. A general ABEP expression is obtained for this scheme and comparisons are performed with the coherent case. More recently, [138] generalized the scheme of [185] by considering multi-antenna S and D, as well as multiple

relay nodes. The authors used the DF protocol at the relay nodes with two different detection algorithms and formed a virtual MIMO scheme to convey the information from S to D.

In [186], incremental relaying has been adapted to SM. In this scheme, two users (U-1 and U-2) are considered, and one of these users communicates with D through the cooperation of the other user. For instance, when U-1 is active, in the first phase, U-1 performs transmission to U-2 and D. On the other hand, using CRC coding, D can determine whether the frame it received from U-1 is erroneous or not, and then, sends this information back to U-1 and U-2 over a feedback channel. If the frame is successfully decoded at S, the second phase is skipped. However, in case of erroneous detection, U-2 transmits U-1's frame to D in the second phase. The authors assumed that the transmission channel between U-1 and U-2 as well as the feedback link from D to the users are perfect.

In [187], a cooperative SSK scheme, in which S and R are equipped with two antennas, is considered. In the first time slot, S performs transmission to R and D, while in the second time slot, R performs incremental relaying according to the quality of the channel between S and D. Selection combining is considered at D to detect the active antenna index of S. More recently, SSK modulation is investigated with incremental DF and selective DF protocols in [188] and instead of considering the instantaneous SNR, a new criterion, which is based on the Euclidean distances between the different channel coefficients, is introduced. Comparisons are performed with the classical DF protocol and the criterion of [187], and the superiority of this new criterion is shown.

A new cooperative SSK system, which includes a direct transmission link between S and D, is considered in [164]. In this scheme, multiple-antenna S performs transmission using SSK in the first phase. In case of AF relaying with N relays, the relays successively perform fixed gain relaying to D, which requires $N + 1$ time slots. On the other hand, for DF relaying, the relays that correctly decode the active antenna index at S take part in the transmission. Theoretical analyses have been also performed for different number of antennas at S. Nevertheless, the authors of [165] considered SM instead of SSK for the network topology of [164]. In this scheme, S uses SM in the first phase, while the relays, which correctly decode the SM symbol of S (i.e., the antenna index and the modulation symbol), perform transmission in the second phase. Finally, in [166], for the network topology of [165], the authors considered imperfect channel knowledge at each relay and D, and theoretical pairwise error probability (PEP) expression of the system is obtained for different number of antennas at S.

A cooperative SM scheme, which consists of a multi-antenna S and single-antenna R and D, is considered in [167]. Considering the different importance of the antenna index and ordinary modulation bits in detection, three relaying protocols, namely the partial, hybrid and hierarchical modulation-based DF relaying protocols, are proposed. On the other hand, [168] considered a cooperative SSK network with

multi-antenna S, D and relays for the first time in the literature. In this scheme, a threshold-based relay selection is considered in the second time slot to transmit the data of S to D, and D exploits selection combining for the detection. The authors performed an exact theoretical error performance analysis for the case of two transmit antennas at S, while an analytical approximation is provided for the general case.

In [169], the authors considered the application of the STBC-SM scheme of [44] to AF relay networks with and without relay selection. On the other hand, [170] considered a selective DF-based cooperative scheme, which employs STBC-SM at S and R. The authors considered correlated Rayleigh fading channels and derived the end-to-end PEP, diversity order and optimal power allocation for this scheme. Improvements are shown compared to point-to-point STBC-SM scheme in both [169] and [170].

More recently, outage probability performance of the cooperative SM scheme is investigated for fixed DF and AF, selective DF and incremental relaying techniques in [171]. It is shown via computer simulations as well as theoretical derivations that SM and cooperative SM systems provide better outage probability performance compared to conventional systems. In [172], ABEP of a DF cooperative SM system, in which all nodes have multiple transmit and/or receive antennas, is theoretically derived. In this study, it is assumed that both S and R employ SM, and improvements are shown compared to classical systems through extensive computer simulations. The same authors extended their analysis of [172] by exploiting AF relaying in [173]. Even more recently, the authors of [174] considered QSM in a cooperative DF relay network consisting of a multi-antenna S and R with a single-antenna D, and analyzed the error performance of this system.

In the recent study of [175], a cooperative SSK scheme that employs transmit antenna selection at S, is proposed. The authors assumed that a multi-antenna S communicates with a multi-antenna D with the help of multiple single-antenna relays. Based on the channel coefficients between S and D, one of the disjoint subsets of the transmit antennas is selected at the first stage for SSK transmission at S. On the other hand, the relays that correctly decode the active antenna index of S take part in the transmission at the second stage. Closed form expressions are obtained for the symbol error probability, and the achievable diversity order of the proposed scheme is theoretically derived. The superiority of this scheme against conventional cooperative MIMO system with transmit antenna selection is shown by extensive computer simulations. Even more recently, for the same network topology of [175], the authors of [176] considered a cooperative AF relaying scheme that combines SSK with the best and partial relay selection. In this scheme, it is assumed that a relay, which is selected according to the best or partial relay selection techniques, applies the AF protocol to forward the signal of S to D. An improved error performance is reported compared to the corresponding conventional cooperative system.

A physical-layer network coded (PLNC) SSK scheme is proposed in [189]. In this scheme, two users (U-1 and U-2) equipped with multiple antennas exchange information over R in two phases. In the first (multiple access) phase, U-1 and U-2 transmit their own information to R using SSK. In the second (broadcast) phase, R considers a multi-to-one mapping rule according to the received signal and forwards the newly formed signal to U-1 and U-2. Due to the special mapping rule considered at R, the users can extract their own information from the signals they received from R. Using a graph-based approach, the mapping operator of R is optimized. In [190], SSK is combined with two-way AF relaying in a network consisting of two users with multiple antennas and a relay with a single antenna. Similarly, in the first phase, R collects the SSK signals transmitted by the users, while in the second phase, R considers the AF protocol to transmit the signal it received in the first phase to both users. In order to reduce the receiver complexity, a near-ML detection algorithm is proposed.

In [191], two transmission schemes are proposed for two-way relay networks by considering SM and CIOD principles. For both schemes, the authors considered the scenario of two-way communications between two nodes through a relay that is placed between them. It is also assumed that all nodes have only a single RF chain. In the first scheme, only R is equipped with two antennas and it applies CIOD-STBC with adaptive network coding. In the second scheme, all nodes are equipped with two antennas to achieve a higher diversity order and CIOD-STBCs are transmitted in both multiple access and broadcast phases. It is shown that the considered schemes outperform the existing analog network coding schemes in the presence of perfect and imperfect CSI. More recently, [192] considered the concept of SM in two-way relay networks, where two single-antenna source nodes exchange information through a multi-antenna R. Two different transmission strategies are proposed for R by considering SM transmission principles. An enhanced operation mode is also realized by exploiting multiple antennas at the source terminals. Achievable rate region and outage sum-rate analyses are performed for the proposed protocols in addition to BER results. Finally, [151] investigated an FD two-way relay network operating with SM to support bidirectional communications with high spectral efficiency. In this study, it is assumed that two source nodes as well as R, which are equipped with multiple antennas, uses SM in the transmission and operates in FD mode. Considering the effect of residual self-interference, the authors analytically derived the PEP of the system and performed comparisons with the HD two-way SM scheme. Furthermore, power allocation problem is investigated by the derivation of the optimal power allocation factor that guarantees the best ABEP.

In [13], a novel scheme called distributed SSK (Di-SSK), which consists of single-antenna S, two relays and D, is proposed. In the first time slot, S transmits its own one bit of information using BPSK modulation. In the second time slot, the relays implement a Di-SSK scheme after demodulating

the data of S . As an example, if the data bit of S is 1, the first relay is activated and vice versa. The authors proposed an optimum detection algorithm by considering the erroneous detection scenarios at the relays. The scheme of [13] is generalized in [193] by considering multiple relays, and various demodulation techniques, such as optimal as well as low-complexity, are proposed. The authors also provided analytical error performance analyses along with receiver complexity and energy consumption calculations. On the other hand, the authors of [194] considered SSK for a distributed network with multiple relays. In this scheme, all nodes have a single antenna and the relays transmit the data of S according to the SSK principle using their own indices. A one-to-one mapping is considered between M -ary constellation symbols and the relays for the operation of the system.

The scheme of [195] generalized the Di-SSK scheme of [13] by considering SM instead of SSK and using the direct transmission link between S and D . In this scheme, it is assumed that the relays also have their own information and form a virtual SM network to transmit the data of S as well as their own information. It is shown by analytical calculations that the Di-SM scheme achieves a diversity order of two by the employment of an optimal detector that takes into account demodulation errors at the relays. More recently, the Di-SM scheme is extensively studied in [23] by the calculation of the average energy consumption and rate, and extensive comparisons are performed with the state-of-the-art relay aided protocols. Recently, a new virtual FD Di-SM scheme, in which S and the relay nodes transmit their own data in every time slot, is proposed in [150]. This scheme consists of multiple single-antenna relays, which operate with a virtual FD mode by taking part in transmission at all time slots. It is shown by computer simulations that the proposed protocol is very close to that of traditional successive relaying in terms of the error probability at S ; on the other hand, a significant throughput increase is obtained since the relays also transmit their own data by exploiting Di-SM.

As an alternative to distributed STBCs, a distributed spatially modulated STBC scheme is proposed in [196]. In this scheme, the communications between S and D is performed by multiple relays, which are partitioned into a number of virtual sets consisting of two relays, and it is assumed that all nodes are equipped with a single antenna. In the first phase, S broadcasts its data to multiple relays, while in the second phase, the relays employ distributed STBC-SM. An error-aware ML detector, which is robust to demodulation errors at the relays, are formulated and the superiority of the proposed scheme compared to reference distributed schemes is shown.

In [197] and [198], SSK is considered for multi-hop systems for the first time in the literature. Two different multi-hop schemes are proposed in [198], where in the first scheme, S communicates with D over multiple relays by also considering multi-hop diversity [200]. It is assumed that the relays that decode the information of S correctly take part in the transmission to D as well as the other relays. On the other hand, the second scheme is a multi-hop multi-branch relaying

scheme, which contains a different number of relays at each branch. In this scheme, the authors assume that the relays can only forward to the corresponding next relay (the last relays at each branch forward to D). Exact theoretical expressions are obtained for these two schemes in case of two transmit antennas at S .

C. APPLICATION OF SM TO COGNITIVE RADIO NETWORKS

Spectrum sharing is a potential technique to use the available limited spectrum in a more efficient way. CR networks, which utilize spectrum sharing, are capable of overcoming the scarcity and inefficient usage of the wireless spectrum. CR networks consist of two types of users: licensed and unlicensed users, which are also reformed to as the primary and secondary users, respectively. The secondary users (SUs) (or CR users) are intelligent devices, which can sense the available spectrum as well as recognize the nearby environment with the purpose of adjusting their transmission parameters since they are allowed to use the same frequency band along with the primary users (PUs) under the condition of improving or at least, not degrading the performance of PUs [201]. Depending on the access strategy of SUs, there are three main network paradigms: underlay, overlay and interweave [202], [203]. In the underlay strategy, SUs can access the licensed spectrum band under an interference constraint to PUs. In the overlay strategy, SUs assist PUs through cooperation (i.e., by retransmitting the information of PUs) to improve the performance of the primary network. In the interweave strategy, SUs sense the licensed spectrum bands continuously, and exploits the holes in the spectrum to communicate in an opportunistic way. Since both users use the available spectrum concurrently in underlay and overlay strategies, one of the major problems of these strategies become the mutual interference generated by the users. SM techniques appear as promising alternatives to overcome the main limitations of traditional spectrum sharing systems.

The first study that investigates the application of SM techniques in CR networks is performed in [204]. The authors considered an underlay CR network that consists of a primary network as well as a secondary network. The primary network consists of multiple primary receivers (PRs) equipped with multiple antennas, while the secondary network consists of a single transmitter and a receiver with multiple antennas. It is assumed that the secondary transmitter (ST) uses SSK modulation for its transmission to the secondary receiver (SR); however, under a transmit power constraint not to exceed a predetermined threshold level for the interference it caused at PRs. The authors studied the ABEP performance of SSK under spectrum sharing environments with different number of PUs and provided exact analytical expressions.

In [205], the performance of SM aided underlay CR networks is investigated in the presence of PU interference constraint as well as channel estimation errors. The authors assumed a MIMO spectrum sharing network, which consists of an ST-SR pair along with a single-antenna PU. In this

network, ST uses SM for its transmission under a power constraint, which is determined according to the power of the interference channel between ST and PU. With computer simulations and analytical ABEP calculations, it is shown that SM is not only resistant to channel estimation errors but also improves the overall performance of the secondary network. The scheme of [205] is generalized into a network with multiple PUs in [206] with the assumption of partial CSI at ST and imperfect channel estimation at SR. In this network, SUs can use PUs' spectrum as long as the interference of ST to the mostly affected PR remains below a predefined threshold. On the other hand, in [207], the same authors considered a limited feedback MIMO spectrum sharing system consisting of the pairs of multi-antenna ST and SR as well as single-antenna primary transmitter (PT) and PR. In this study, the performance of the secondary system is investigated under mutual primary-secondary interferences in the presence of channel estimation errors with a limited feedback from PR to ST. Finally, [208] examined the error performance of a DF relaying-based CR-SM system in the presence of channel estimation errors, multiple PUs and multiple secondary relays. It has been shown in this study that SM can improve the error performance of the secondary system.

In [209], the adaptive SM (ASM) scheme of [55] is implemented for CR networks to improve the secondary system's energy as well as spectral efficiency. Similarly, it is assumed that a MIMO underlay secondary system operates in the presence of a single PU. Three different protocols are proposed in this study. In the first scheme, ST has the perfect CSI of the interference link between itself and PU, and applies power adaption to meet the maximum interference constraint along with ASM. Two other novel schemes with limited ST feedback are also proposed by the authors to enhance the performance of the secondary system while ensuring low system complexity as well as high data rate. The average spectral efficiency and the BER performance of all schemes are theoretically investigated and the trade-offs provided by the introduced schemes are supported via computer simulations.

Different from the previous works that focus on SM aided underlay CR networks, in [210] and [211], the authors investigated the application of SM for overlay CR networks in an effort to eliminate the interference between PUs and SUs by using the unique information carrying properties of SM. More specifically, a new cooperative overlay spectrum sharing scheme that avoids the mutual interference between PUs and SUs by exploiting SM at ST, is proposed. In this scheme, a single-antenna PT transmits its own information in the first time slot, which is received by a multi-antenna ST. In the second time slot, ST cooperates with the selective DF protocol and exploits SM to forward not only the information of PT to ST but also its own information to SR. At this point, ST considers antenna indices for the transmission of its own data bits while employing ordinary M -PSK modulation for the transmission of PT's information. Consequently, the

mutual interferences at PR and SR are eliminated by the use of SM. ABEP upper bounds are derived for PUs and SUs with optimal detectors, and the superiority of the proposed scheme is shown compared to cooperative DF spectrum sharing protocol that exploits superposition coding. Independently from [210], a similar network topology without a direct link between PT and PR is also considered in [212]. In this scheme, both PT and ST use SM in their transmissions, while ST exploits SM for interference mitigation. The authors of [213] considered an overlay CR network with single-antenna PT and multiple-antenna ST. In this scheme, ST also exploits the indices of the transmit antennas for the transmission of its own information bits as in [210], while it applies the AF protocol to forward the signals of PT to PR. The error performance of the optimal detectors at both PR and SR is analyzed and the effectiveness of SM for CR networks is shown by computer simulations. Recently, [214] generalized the scheme of [210] by considering multiple antennas at PR and SR. In this study, ST uses STBC-SM scheme of [44] instead of SM to increase the diversity order of PUs as well as SUs, while avoiding interference between them. Even more recently, [215] investigated a cognitive cross network design with PLNC and SM. In this scheme, the authors assumed that the receivers of both PU and SU are closer to the transmitter of the other user; however, the distances to their own transmitters are too large that an intermediate relay is required for reliable communications. For this purpose, SU shares its relay with PU by means of PLNC in exchange for access to the licensed band of PU. In this scenario, it is assumed that both PT and ST as well as R employs SM to improve the overall error performance of the network. The ABEPs of the users are derived and the advantages of SM are shown via computer simulations.

Finally, in some recent studies [216]–[219], the promising QSM concept of [51] is integrated to CR systems. More specifically, in [216] and [219], the performance of QSM aided MIMO CR systems is investigated with partial/full CSI at ST and imperfect channel estimation at SR. Similar to [206], the authors assumed the operation of the secondary system under the interference constraint of multiple single-antenna PUs. In [217], the same authors studied the performance of the spectrum sharing QSM system with AF cooperative relaying. In this scheme, multi-antenna ST, which employs QSM, communicates with SR with the cooperation of a secondary AF relay in the presence of multiple PUs. The theoretical ABEP performance of the secondary system is analyzed along with the derivation of an asymptotic PEP expression, which gives insights into the key parameters of the system. Finally, the performance of a QSM-based spectrum sharing system is investigated in [218] in the presence of mutual PU-SU co-channel interference. In this study, a CR network, consisting of multiple-antenna ST and SR as well as single-antenna PTs and PRs, is considered. Closed form expressions are derived for the ABEP of the secondary system with partial CSI at ST and co-channel interference of PUs at SR.

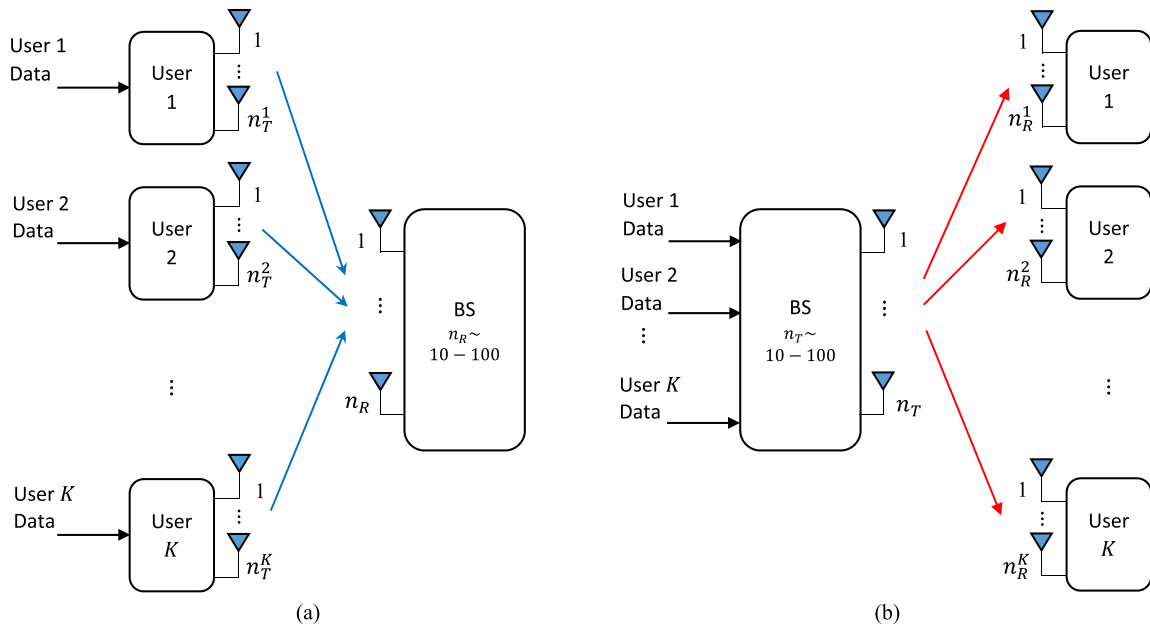


FIGURE 6. Massive MU-MIMO systems with SM (a) An uplink transmission scenario, where multiple users use SM techniques for their transmissions to the BS equipped with massive antennas (b) A downlink transmission scenario, where a BS equipped with massive antennas supports multiple users (Reproduced from [6] with permission).

D. APPLICATION OF SM TO MASSIVE MIMO AND MULTI-USER SYSTEMS

Massive MIMO systems have been regarded as one of the potential key technologies for next-generation (5G and beyond) wireless networks due to their appealing advantages such as very high spectral and energy efficiency by the employment of tens to hundreds of antennas at their BS [2], [220]. On the other hand, more practical MU-MIMO systems are gaining increasing attention compared to traditional point-to-point MIMO systems, in which two terminals communicate with each other. MU-MIMO systems are able to exploit the multiple antennas of a MIMO system to support multiple users concurrently.

Within this perspective, massive MIMO systems provide unique as well as appealing opportunities for SM systems since it becomes possible to transmit a significant number of information bits by the spatial domain with massive MIMO systems, even if the system operates with a limited number of RF chains [6]. Although the spectral efficiency of SM systems is considerably lower compared to that of traditional schemes such as V-BLAST for massive MIMO systems, the use of IM concept for the indices of the transmit antennas of a massive MIMO system can provide promising implementation solutions thanks to the inherently available advantages of SM systems such as high energy efficiency and low cost implementation. Furthermore, SM is well-suited to unbalanced massive MIMO configurations, in which the V-BLAST based systems cannot operate with linear detection methods such as ZF and MMSE detection. As seen from Fig. 6, SM techniques can be implemented for both uplink and downlink transmission of massive MU-MIMO systems. In the past few

years, several studies that focus on the implementation of SM techniques for massive MU-MIMO systems, have been performed in the literature. In the following, these studies will be briefly covered.

In [221]–[239], authors investigated the uplink transmission scenario of Fig. 6(a) and proposed novel SM-based solutions. In this scenario, the users are equipped with multiple antennas and employ SM (or its variants) with fewer RF chains, while BS has tens to hundreds antennas for signal reception. In most of these studies, the authors investigate low-complexity detection algorithms by considering the sparsity property of SM transmission vectors. On the other hand, the studies of [240]–[253] considered the downlink transmission scenario of Fig. 6(b) by introducing SM-based schemes. In these studies, the authors focused on precoding schemes to transmit the data of different users simultaneously.

In [221], the performance of SSK and generalized SSK (GSSK) modulation is investigated in MU interference environment for the first time in the literature. Interference unaware and aware ML detectors are proposed and ABEP of the system is studied for Rayleigh fading channels. It is shown by extensive computer simulations that SSK/GSSK modulations can outperform conventional schemes in the presence of multiple-access interference. In [222], the authors extended the point-to-point SM scheme into a two-user multiple-access SM scheme. An interference limited scenario is considered, in which two users simultaneously use SM for their transmissions. An ML detector, which does not suffer from the near-far problem and minimizes the BER for both users, is proposed. Reference [223] generalized the scheme of [222] for multiple users employing SM. In [224] and [225], uplink

transceiver design of an MU-massive SM scheme is performed for frequency-selective fading channels. The users consider single-carrier SM (SC-SM) with cyclic prefix (CP) in their transmission to BS with massive antennas. For MU detection, a low-complexity generalized approximate message passing detector, which exploits the sparsity of the transmitted signal and approaches the error performance of the ML detector, is proposed. An algorithm to optimize the system parameters, such as transmission power and number of antennas at BS, is also introduced towards the design of energy-efficient massive SM systems. In [226]–[229], GSM is considered for the uplink transmission of multiple users. An ABEP analysis is performed for ML detection and two belief propagation-based message passing detection algorithms are proposed. A local search-based detector is also introduced by the authors. It is shown by computer simulations that MU-GSM can outperform MU-SM as well as traditional MU-MIMO due to the use of IM more effectively. In [230], as an alternative to message passing and local search detection algorithms, a new low-complexity MMSE detector based on the nearest neighbor search is proposed. It is shown by computer simulations that this detector can reach the interference-free BER performance with much lower complexity than the aforementioned detector. In [231] and [232], a CS-based detector, SM matching pursuit, is proposed for MU-SM schemes to fully account for the complexity reduction that can be obtained by the CS algorithms. The complexity of the proposed detector is analyzed and it is shown that low-complexity CS-based detection can be considered as a promising alternative to increase the energy efficiency of massive MU-SM systems. In [233], a space-alternating generalized expectation maximization (SAGE) detector, which recursively performs data detection for each user with MU interference cancellation, is proposed for massive MU-SM schemes. It is shown by computer simulations that this SAGE-based detector can approach the SER performance of the single-user system.

The MU detection of massive SC-SM with low resolution analog-to-digital converters (ADCs) at the RF chains of BS receive antennas, is investigated in [234] and [254]. It is assumed that the system operates over correlated frequency-selective channels, and low-complexity MU detectors, which are capable of coping with the quantized measurements as well as the antenna correlations, are proposed. It is shown by computer simulations that the proposed message passing-based detector outperforms the MMSE detector and exhibits a close performance compared to the corresponding un-quantized system. In [235], to reduce the cost and power consumption, receive antenna selection is considered at BS, while the users employ single-RF chain SM. The authors proposed a joint transmission scheme for the users and a structured CS-based detector to exploit the sparsity of the transmitted signals. As an alternative to the detection algorithms of [224] and [234], a structured approximate message passing detection algorithm, which captures the inherent sparsity of the SM signals more efficiently, is proposed

in [236] for the MU detection of SM. The BER advantage of this detector compared to the other message passing and matching pursuit-based detectors is shown by computer simulations. More recently, a focal underdetermined system solver-based sparsity-exploiting detection algorithm is proposed for MU-GSM systems in [237]. It is shown by computer simulations that this detector outperforms MMSE and orthogonal matching pursuit-based detectors. In [238], a new algorithm called parallel orthogonal matching pursuit is proposed for MU-SM systems. With computer simulations, the superiority of this detector against the orthogonal matching pursuit-based detector in terms of SER performance is shown. Finally, a SAGE algorithm aided list-projection detector is proposed for multiple-access SM system in [239]. It is shown by computer simulations that the proposed detector achieves near-optimal performance, while achieving a much lower complexity than the optimal detector.

For the uplink of massive MU-SM, different from the transmission scenario of Fig. 6(a), a DSTSK-based DF MU-CDMA scheme is proposed in [255], where the authors consider successive relaying for the transmission of multiple users' data to the destination. Non-coherent detection is exploited at the relay nodes and D, and the relay nodes employ soft-input soft-output multiple-symbol differential sphere decoding and DSTSK in DF transmission. Recently, the authors of [256] studied GSM in multi-cell MU massive MIMO systems. The achievable sum rate of the system under practical imperfections is investigated and a comprehensive performance evaluation, which consider spectral, energy and economic efficiency, is carried out. A detection algorithm based on linear processing is proposed for the considered multi-cell system, and it is shown that, although its spectral efficiency is limited, SM achieves better energy efficiency than conventional MIMO scheme within its feasible spectral efficiency regime. Recently, [257] investigated the achievable uplink spectral efficiency of a multi-cell massive SM-MIMO system by considering correlated coefficients for the fading and interfering channels with respect to users' random distribution and pilot-reuse schemes. It has been shown that massive SM-MIMO systems can outperform conventional massive MIMO systems with single-antenna users. Even more recently, [258] investigated the benefits of adaptive power allocation on the uplink bandwidth efficiency of massive SM-MIMO systems and a new upper bound on the bandwidth efficiency is proposed. The authors also considered the problem of optimal power allocation to maximize the uplink bandwidth efficiency and reported considerable improvements over the conventional uniform power allocation schemes.

In [240], an MU-SM-OFDM scheme is proposed for LTE systems by exploiting different types of precoding methods such as channel inversion (ZF and MMSE) and block diagonalization to eliminate the MU interference. The performance of this system is compared with Alamouti coded and VBLAST type MIMO-OFDM systems, and BER advantage of the proposed SM-based scheme is shown by

computer simulations. In [241], a novel precoding scheme called exact channel information preservation is proposed for the MU-SM system. With this precoding scheme, the authors aimed to cancel the MU interference as well as preserve the information carried by the SM symbols. It is shown by computer simulations that the proposed precoding scheme achieves better BER performance than ZF precoding. Independently from [241], the same problem is investigated in [242]. An interference-aware MU detection technique that does not require CSI at the transmitter is also developed in this study. In both of [241] and [242], the available transmit antennas of BS are split into multiple blocks, where each block is allocated to a user. A different SM multiple-access scheme is introduced in [243] that adaptively allocates transmit antennas to different users to improve the capacity. Furthermore, the scheme of [243] considered users with multiple receive antennas in contrary to the scheme of [242], and the selection of the transmit as well as receive antennas are jointly implemented. It is shown by computer simulations that significant improvements can be obtained in BER performance compared to the MU-SM scheme of [242]. In [244], the authors generalized the precoding aided SM scheme of [259] into the case of an MU system, i.e., implemented receive SM for downlink MU systems. In this scheme, the index of the active receive antenna of each user is considered to transmit additional information. This operation is performed by considering ZF precoding at BS. In [245] and [246], a new MU-MIMO scheme that exploits multistream receive SM is proposed. In this scheme, only a subset of the available antennas of a user receive a nonzero signal, while all other antennas capture only the thermal noise. The diversity and coding gains of this new architecture are derived and it is proved theoretically as well as by computer simulations that this scheme outperforms the conventional MU-MIMO scheme in terms of BER performance. More recently, [247] generalized the schemes of [244] and [246], by transmitting a different constellation symbol for each active receive antenna to boost the spectral efficiency. In this scheme, the authors considered a common (multicast) information to be conveyed to all users, which is transmitted with the selection of a subset of the available transmit antennas at BS. This scheme also provided less stringent conditions for the total number of antennas of BS. Finally, [248] investigated the performance of receive SM in the shadowing MIMO broadcast channel. A theoretical criterion is obtained to determine the superiority of receive SM over V-BLAST for MU-MIMO systems.

In [249], a secure MU precoding aided SM scheme, which operates in the presence of a multi-antenna eavesdropper, is proposed. In order to improve the security, a fast-varying precoding matrix is constructed to degrade the eavesdropper's performance with no influence to the intended users. It is shown by secrecy rate analyses that secure communications is possible even if the eavesdropper has more antennas than the intended users. The authors of [250] investigated the BER performance of SM and its variants in multicast MIMO

systems in which a single BS sends a common information to the multiple users. Uncorrelated and correlated Rayleigh fading channels are considered in the analysis of BER and comparisons are performed with the V-BLAST type traditional multicast systems. As an alternative to parallel SM schemes of [241]–[243] that divides the available transmit antennas of BS into several groups to serve multiple users by using multiple RF chains, a layered SM scheme is proposed in [251] more recently. The authors assigned different sets of transmit antennas to convey the symbols of each user with a clever algorithm to ensure that only one antenna is active in each transmission interval to transmit information to several users at the same time. This scheme is further generalized to increase the spectral efficiency compared to SM-based MU-MIMO schemes. In [252], the interference scenario between SM and V-BLAST schemes is investigated for a two-user heterogeneous network. It is shown that the interference caused by SM has no fixed interference subspace and this causes problems for the implementation of conventional interference alignment techniques. For this reason, three interference alignment methods are proposed to overcome the interference caused by SM. Even more recently, multi-set STSK (MS-STSK) scheme of [38] is combined with MU transmission for the downlink of mmWave communication systems in [253]. The authors employed MU transmit precoding along with OFDM to serve multiple users that are angularly close enough to receive the same transmitted beam, which is an important constraint in mmWave communication systems.

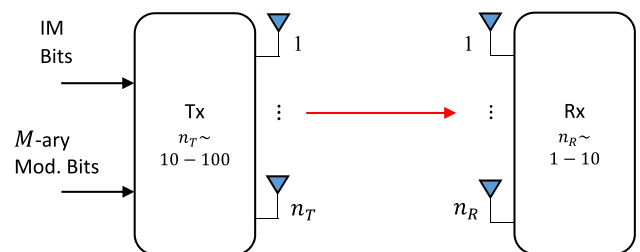


FIGURE 7. Point-to-point unbalanced massive SM-MIMO system with a fewer number of receive antennas than the number of transmit antennas ($n_T > n_R$).

In recent years, some other studies that focus on point-to-point massive SM systems, as shown in Fig. 7, have been also performed [113], [260]–[264]. In [260], the performance of GSM and SM schemes is studied for correlated Rayleigh and Rician fading channels in the presence of channel estimation errors. It is demonstrated that GSM is more suitable than plain SM for massive MIMO configurations, and it appears as an efficient candidate for massive MIMO systems. In [113], a low-complexity detection algorithm based on reactive tabu search is proposed for massive GSM-MIMO schemes. It is shown by theoretical derivations as well as computer simulations that massive GSM scheme can achieve better BER performance than massive SM and V-BLAST schemes. In [261] and [262], it is shown by information theoretical

analyses that SM achieves a capacity that is comparable to the open-loop massive MIMO system capacity due to the use of antenna indices as a means of transmitting information without CSI at the transmitter. The authors derived a closed-form upper bound for the capacity of SM with the assumption of a massive but unbalanced MIMO configuration in which the number of transmitters is much higher than the number of receivers and showed that this upper bound is achievable with only channel distribution information at the transmitter. More recently, [263] investigated the design of a low-complexity and near-optimal structured CS-based detector for massive SM systems as an alternative to CS-based SM detectors proposed earlier for small-scale SM systems [82], [111]. In order to ensure structured sparsity, the authors grouped multiple successive SM symbols to carry a common spatial constellation symbol (i.e., the same active antenna index or indices) while assuming mutually independent signal constellation symbols. It is shown by theoretical analyses and computer simulations that the proposed detector outperforms the existing CS-based SM detectors. Finally, [264] provided arithmetic coding-based algorithms to map the incoming bit stream into active antennas and vice versa to avoid huge look-up tables at both transmitter and receiver sides of massive GSM systems. Spatial and temporal segmentation methods are considered at the transmitter to allow low-complexity CS-based detection algorithms at the receiver. With spatial segmentation, the available antennas at the transmitter are divided into several blocks and all antennas within a block are activated or turned off. On the other hand, the active antennas remain constant during a period for temporal segmentation similar to method of [263]. It is shown by computer simulations that satisfactory BER results can be obtained with a two-stage (serial concatenated) coding scheme consisting of an outer turbo code an inner CRC code.

In [265] and [266], the authors investigated the performance of massive SM in high-speed railway systems. Since SM avoids inter-channel interference by the activation of a single transmit antenna, it is shown that SM helps to decrease the channel correlation by increasing velocity for high-speed railway scenarios [265]. The authors investigated the performance of massive SM for spatial-temporal correlated Rician fading channels by considering the impacts of the velocity and Rician K -factor. It is shown by extensive computer simulations as well as theoretical analyses that massive SM scheme can outperform the conventional massive V-BLAST scheme expect the case of low SNR with very high velocity. On the other hand, the same authors proposed a hybrid massive SM beamforming scheme for high-speed railway wireless communication systems at mmWave frequency bands in [266]. In [267] and [268], the authors focused on STSK aided MU systems composed of multiple transmit and receive users for frequency-selective Rayleigh fading dispersive channels. More specifically, an orthogonal frequency division multiple access (OFDMA)/single-carrier frequency-division multiple-access (SC-FDMA)-based STSK scheme is

considered in [267], while a multi-carrier CDMA (MC-CDMA)-based STSK configuration is proposed in [268].

E. OPTICAL SM

Wireless transmission via optical carriers has attracted significant interest in the past few years. The abundance of a huge unregulated spectrum opens doors of opportunity in areas as yet largely unexplored. Integrating optical carriers with wireless technology is anticipated to play a significant role in future heterogeneous communication networks supporting a wide range of wireless services and applications. Such combination offers significant technical and operational advantages. A hybrid optical RF wireless system is widely investigated in the past few years. Different models of OW are proven to be suitable for a wide range of communication applications ranging from file transfer between mobile phones, indoor positioning and tracking, and for communications in RF sensitive environments such as airplanes and hospitals [269].

In OW communications, data is transmitted through modulating the intensity of the radiated light in free space. Wavelengths ranging from infrared (IR) to ultraviolet (UV) including the visible light spectrum can be used as optical carriers to convey information. The transmitter converts the electrical signal to an optical signal and the receiver reverses this operation to retrieve data. The technology is generally called VLC for indoor application and free space optics (FSO) for outdoor communication. In VLC, the transmitter light source is basically an LED, which relaxes safety regulations and can be deployed with very low cost and high reliability. On the other hand, laser diodes (LDs) are generally considered in FSO. Simple and low cost optical carrier modulation and demodulation are usually achieved through intensity modulation with direct detection (IM/DD). The desired waveform is modulated onto the instantaneous power of the optical carrier [270]–[274].

Considering SM in OW communications was proposed in [12], [275], and [276]. In OW communications, transmitted signals should be real and positive as they represent light intensities. Hence, typical communication schemes used in RF communications such as QAM/PSK cannot be considered. Pulse amplitude modulation (PAM), pulse position modulation (PPM) [277], on-off keying (OOK) and similar modulation schemes can be used for OW communications.

SSK can be directly used for OW systems, where multiple spatially separated light sources are considered in lieu of multiple transmit antennas and SSK can be applied straight-away. The schemes introduced in [12], [276], [278], and [279] consider an SSK protocol with multiple transmit light sources to convey information using light intensities. A study considered in [280] shows that repetition coding (RC) scheme outperforms orthogonal STBCs, SMX, and SSK for FSO communications using IM/DD over Gamma–Gamma (G-G) fading channels. However, this conclusion is drawn for a spectral efficiency of 1 bps/Hz only. Another study in [281]

proposed a new scheme called spatial pulse position amplitude modulation (SPPAM) for FSO links. It is shown in the study that SPPAM outperforms SSK for spectral efficiencies of 2 bits/s/Hz or less. Finally, a GSSK scheme for indoor VLC has been studied in [282].

The use of SM, however, requires special consideration of the adopted modulation technique to facilitate intensity modulation. SM-MIMO system for indoor OW communications using OFDM modulation is studied and analyzed in [276] and [12]. An SM scheme considering M -PAM modulation is studied in [278] and [283] where it is shown that SM outperforms RC for spectral efficiencies greater than 4 bps/Hz. Coherent SM FSO systems over generalized H-K distribution is studied in [284] where a tight upper bound is derived for the error probability. A hybrid subcarrier intensity modulation and SM system is proposed and evaluated in [285]. Obtained results show that the proposed system outperforms subcarrier intensity modulation system at the spectral efficiency of 4 bps/Hz using less number of receivers.

The major issue in applying SM or SSK in OW communications is the high spatial correlation among different channel paths from different transmit light sources to multiple receivers. Uncorrelated channel paths can be created by properly spacing transmitters and receivers, such that the spacing is larger than the fading correlation length. In addition and in particular for OW communication, the total length of the transmitters must not exceed the capture zone of the receiver, which is given by θL with θ denoting the field of view (FOV) of the receiver in radians that is located L meters away from the transmitter [286]. Besides, designing such an OW communication setup may not be feasible in practical systems since the available spacing among different transmitters may not be adequate for these requirements [287]. An exponential correlation is generally considered in the literature, which corresponds to the scenario of a multichannel transmission from linearly equispaced transmitters. A study conducted in [288] considered imaging receivers to enhance the performance of optical SM and SMX-MIMO systems. A huge gain of more than 40 dB is reported through using imaging receivers. Besides, optical SM (OSM) has been studied over turbulence fading FSO channels in [289]. It is revealed that OSM offers better power and spectral efficiencies than conventional MIMO optical modulation methods.

Another approach that attracted significant interest in literature to de-correlate OW MIMO channel paths consists of applying an imaging receiver [290]–[292]. Imaging receivers are shown to be efficient in eliminating the effects of ambient light noise, co-channel interference, and multipath distortion. Such advantages are attained through allowing signals arriving from certain angles to be passed and all other signals are discarded. In a similar way the imaging receiver technique is applied to SMX-MIMO system, in which the signals coming from different transmit sources are decoupled through an imaging lens to de-correlate MIMO channel paths. An imaging receiver can be designed by using multiple non-imaging receivers aligned to different directions.

However, such design necessitates a separate optical concentrator for each receiving element, which significantly increases the dimension and the cost of the receiver [293]. A better approach is proposed in [294] where a receiver is designed from single imaging concentrator, lens, which creates an image of the received light on a collection of photo-detectors (PDs). Thereby, signals arriving from different directions are separated. The study presented in [288] considered the performance of SM and SMX with imaging receivers. Reported results reveal that the use of imaging receiver enhances the SNR performance of OSM by about 45 dB.

F. LED INDEX MODULATION FOR OPTICAL OFDM

VLC, which involves simultaneous illumination and communications, is a promising technology for next-generation wireless communication systems due to its attractive advantages over RF-based systems such as operation in an unregulated and very wide spectrum and energy efficiency [295]. Consequently, VLC techniques have been extensively studied in the past decade and VLC technologies have started to revolutionize the way we used the light. Off-the-shelf LEDs can be effectively used in indoor environments for both illumination and communications purposes. In order to provide adequate illumination, the use of multiple LEDs is very common in current indoor lighting setups, which can inherently lead to MIMO-VLC systems [278], [296].

In RF-based OFDM systems, due to the inverse fast Fourier transform (IFFT) operation at the transmitter, the transmitted signals become complex and bipolar; however, for IM/DD-based VLC systems, they must be real and positive since the intensity of the LEDs are modulated. This has been the major design challenge for optical OFDM systems and some different solutions have been considered for the adaptation of the classical OFDM to VLC systems. In these modified systems, Hermitian symmetry [297]–[300] is applied to the frequency domain OFDM frame to obtain real-valued time-domain OFDM signals after IFFT operation. In order to make the resulting signal positive for IM, either a direct current (DC) bias can be added on it as in the DC biased optical OFDM (DCO-OFDM) scheme or the signal can be clipped at zero level and only positive-valued signals can be transmitted as in the asymmetrically clipped optical OFDM (ACO-OFDM) scheme, where both techniques have their own pros and cons [269], [275], [276], [297].

As an alternative to DCO-OFDM and ACO-OFDM techniques, the unipolar OFDM (U-OFDM) scheme has been proposed by considering some sort of subcarrier indexing for the transmission of positive and negative valued time-domain OFDM samples [15]. Using this subcarrier indexing mechanism, U-OFDM scheme requires neither DC biasing nor asymmetrical clipping. In U-OFDM scheme, each time-domain OFDM sample is transformed into a pair of new time-domain OFDM samples and the sign of original time sample, which could be positive or negative, determines the position of the non-zero (active) element of the new pair.

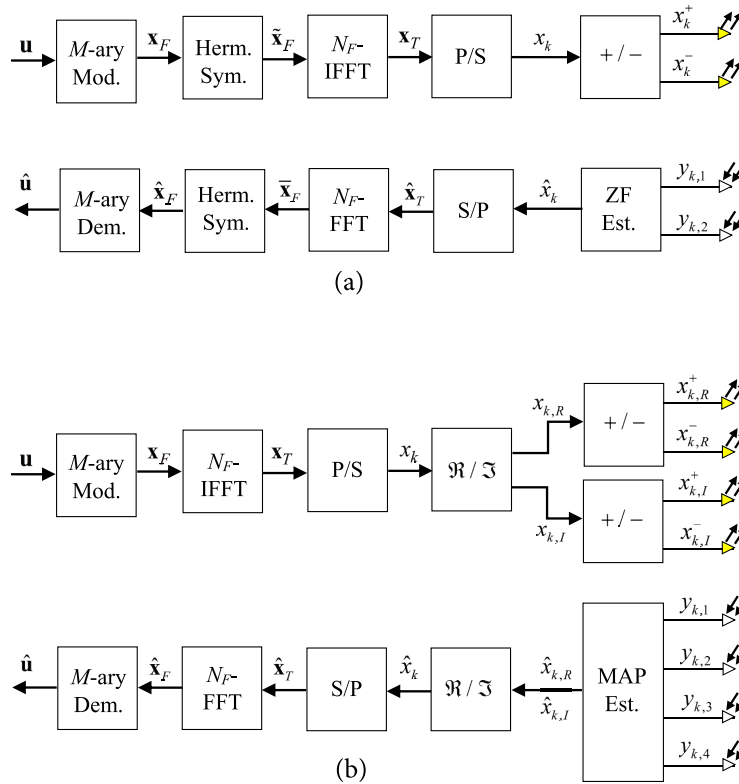


FIGURE 8. Block diagrams of (a) NDC-OFDM and (b) GLIM-OFDM schemes for 2×2 and 4×4 MIMO-VLC systems. (M : modulation order, N_F : FFT size, \mathbf{u} : information bit vector, \mathbf{x}_F : frequency-domain OFDM frame, \mathbf{x}_T : time-domain OFDM frame, $x_k = x_{k,R} + jx_{k,I}$: time-domain OFDM sample, x_k^\pm or $x_{k,R(I)}^\pm$: unipolar time-domain OFDM sample, $y_{k,i}$: received signals after the direct detection, $i \in \{1, 2\}$ for NDC-OFDM and $i \in \{1, 2, 3, 4\}$ for GLIM-OFDM, $+/-$: positive-negative separator, \Re/\Im : real-imaginary separator ($\hat{\cdot}$: stands for the corresponding estimates at the receiver).

This non-zero element simply transmits the absolute value of the original time domain sample, resulting the unipolarity of the new OFDM samples. From this perspective, U-OFDM scheme can be considered as an application of IM to the indices of OFDM time samples. Later, an enhanced U-OFDM (eU-OFDM) scheme has been proposed [25], [301], [302], which utilizes the special frame structure of the U-OFDM scheme and allows the superimposition of multiple U-OFDM frames on top of each other in order to not sacrifice from the spectral efficiency. More recently, eU-OFDM is combined with MIMO transmission techniques [303] with the introduction of the MIMO-eU-OFDM scheme to further boost the spectral efficiency.

Non-DC-biased OFDM (NDC-OFDM) [22] and generalized LED index modulation OFDM (GLIM-OFDM) [30] schemes appear as promising optical OFDM alternatives that directly exploit the principle of LED-IM for MIMO-VLC systems by going one step further than OSM. The transceiver block diagrams of NDC-OFDM and GLIM-OFDM schemes are shown in Fig. 8 (a) and (b), respectively. NDC-OFDM scheme, which transmits the absolute values of the positive and negative time-domain OFDM signals from different

LEDs, is proposed to solve the DC biasing problem of DCO-OFDM and to achieve a higher spectral efficiency than ACO-OFDM. In other words, NDC-OFDM scheme selects the active LED according to the sign of time-domain OFDM signal x_k exploiting LED-IM principle as follows:

$$x_k^+ = \begin{cases} x_k & \text{if } x_k > 0 \\ 0 & \text{if } x_k < 0 \end{cases} \quad x_k^- = \begin{cases} 0 & \text{if } x_k > 0 \\ -x_k & \text{if } x_k < 0 \end{cases} \quad (5)$$

where x_k^+ and x_k^- are the signals transmitted from LED 1 and LED 2, respectively. Consequently, only one of the two LEDs is active in a given signaling interval for the NDC-OFDM scheme. NDC-OFDM provides an efficient solution in terms of spectral efficiency compared to U-OFDM scheme by eliminating the need for time-domain extension of the OFDM frame. However, due to the use of Hermitian symmetry, the spectral efficiency of NDC-OFDM scheme is still limited.

GLIM-OFDM scheme cleverly overcomes the main limitation of NDC-OFDM in the spectral efficiency by exploiting LED-IM in a more effective way with four available LEDs. Contrary to DCO/ACO-OFDM and NDC-OFDM schemes, GLIM-OFDM scheme does not require Hermitian

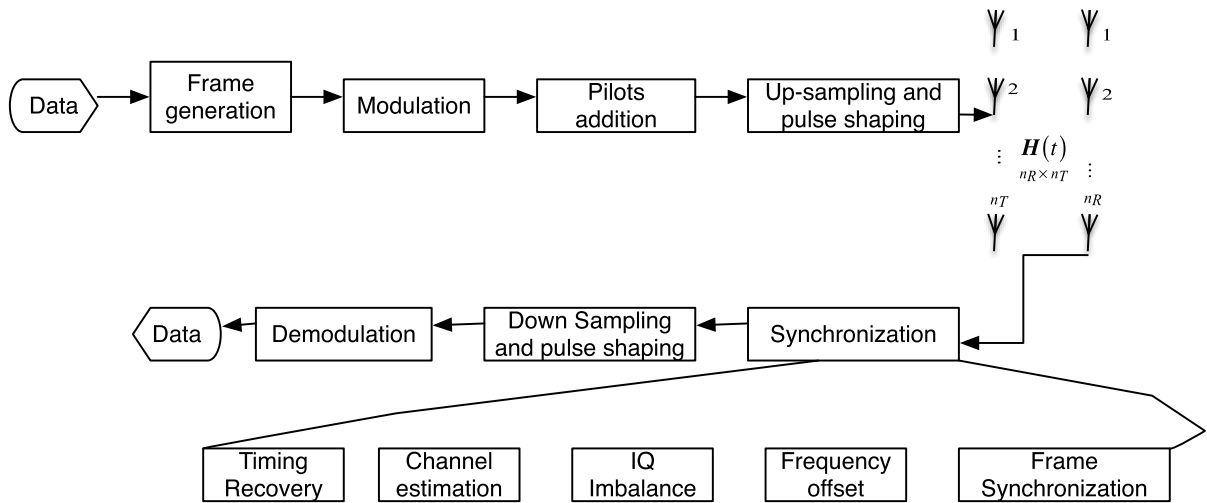


FIGURE 9. Required hardware components to implement MIMO-IM techniques.

symmetry to produce real-valued OFDM samples. Since the time-domain OFDM frame \mathbf{x}_T cannot be transmitted directly over an optical channel due to its complex and bipolar (positive and negative valued) elements, after parallel-to-serial (P/S) conversion, first, the real and imaginary parts of the complex time-domain OFDM signal $x_k = x_{k,R} + jx_{k,I}$ are separated. After this point, the resulting real, but bipolar signals $x_{k,R}$ and $x_{k,I}$ are given to the positive-negative (+/-) separators to obtain the following unipolar signals using LED-IM principle:

$$\begin{aligned}
 x_{k,R}^+ &= \begin{cases} x_{k,R} & \text{if } x_{k,R} > 0 \\ 0 & \text{if } x_{k,R} < 0 \end{cases} & x_{k,R}^- &= \begin{cases} 0 & \text{if } x_{k,R} > 0 \\ -x_{k,R} & \text{if } x_{k,R} < 0 \end{cases} \\
 x_{k,I}^+ &= \begin{cases} x_{k,I} & \text{if } x_{k,I} > 0 \\ 0 & \text{if } x_{k,I} < 0 \end{cases} & x_{k,I}^- &= \begin{cases} 0 & \text{if } x_{k,I} > 0 \\ -x_{k,I} & \text{if } x_{k,I} < 0. \end{cases}
 \end{aligned} \tag{6}$$

These unipolar signals ($x_{k,R}^+, x_{k,R}^-, x_{k,I}^+, x_{k,I}^-$) can be transmitted simultaneously from four LEDs. According to the principle of GLIM-OFDM, only two out of four LEDs are active in a given signaling interval, and due to the use of LED-IM in a more efficient way with the utilization of four LEDs, the spectral efficiency of GLIM-OFDM becomes $\log_2(M)$ [bits/s/Hz], which is twice as that of NDC-OFDM and DCO-OFDM.

The task of the receivers of NDC-OFDM and GLIM-OFDM schemes is to not only estimate the transmitted OFDM signals but also determine the index or the indices of the active LEDs, similar to their RF counterparts that relentlessly search for the indices of active transmit antennas. Effective solutions are provided in [22] and [30] by exploiting ZF and maximum a posteriori (MAP) estimators for the receiver implementation. More recently, the authors of [36] investigated the performance of GLIM-OFDM for both analytical and computer software aided physical frequency-flat and frequency-selective VLC channels.

For frequency-selective VLC channels [304], the receiver of GLIM-OFDM given in Fig. 8 (b) is modified since it is not feasible to directly estimate the real and imaginary parts of the transmitted OFDM samples in this case. The resulting new system, which is term as enhanced GLIM-OFDM (e-GLIM-OFDM) in [36], is shown to provide satisfactory BER performance in the presence of frequency-selective MIMO-VLC channels.

G. PRACTICAL IMPLEMENTATION OF INDEX MODULATION TECHNIQUES

Practical implementation of different IM techniques has attracted significant research interest in the literature [66], [226], [234], [305]–[313]. The required block diagrams for the practical implementation of different IM techniques are illustrated in Fig. 9. The generated data to be transmitted are first grouped in frames to be modulated through arbitrary modulation diagram such as QAM/PSK or others. Proper pilots are then added to facilitate time and frequency synchronization in addition to the channel estimation. Then, pulse shaping and up-sampling techniques are applied followed by the RF modulation and baseband–bandpass conversion. To facilitate the use of a single RF chain for different IM techniques, proper RF switching matrices need to be designed considering the number of transmit antennas and the considered mapping table of spatial and signal bits. The generated RF signals are then transmitted over the MIMO channel and received by the multiple receive antennas. At the receiver, RF down conversion is first applied with proper filtering and synchronization followed by down-sampling and matched filtering. The transmitted pilots are extracted and utilized for channel estimation. In addition, synchronization pilots are utilized to correct for any time and frequency mismatch including frequency offset, IQ imbalance, timing recovery and others. Recovered data are demodulated and joint spatial and signal symbols are used to retrieve the transmitted information.

The first hardware implementation and measurement data for IM techniques are reported in [305], in which the performance of SM is experimentally investigated over a MIMO system with four transmit and two receive antennas using National Instruments (NI) PXI development system. Reported results were significant in proving the concept and the applicability of SM and similar IM techniques. Besides, the impact of different hardware imperfections such as channel estimation errors, spatial correlation and IQ imbalance are discussed and analyzed. Reported results reveal that special care needs to be taken when implementing different IM techniques considering their unique operating mechanism. However, the implementation study in [305] has not considered the special nature of SM where a single RF chain is required at the transmitter. Instead, a conventional MIMO scheme where each antenna is driven by its RF chain is implemented and the complete RF chain is turned on and off to facilitate SM transmission. To the best of our knowledge, hardware implementation of single RF chain transmitters for different IM techniques has not addressed yet in the literature.

General implementation guidelines for different IM techniques are discussed in [66] and [67]. The implementation of a large-scale MIMO system based on SM and MU detection using low resolution ADCs is reported in [234]. It has been shown that massive MIMO-based SM system is more robust to channel estimation errors and a low complexity detection method is proposed. In [308], an implementation of LOS mmWave communication system applying SM technique is presented and studied. Significant results are reported in [309] where the impact of antenna switching on the performance of IM techniques is addressed. Reported theoretical results anticipated that switching time can significantly influence the achievable data rate of IM techniques. It is concluded in the same study that further studies on IM techniques targeting minimum transition of antennas at a time are needed to enhance the performance of high data rate wireless systems. Realistic performance measurements for body-centric SM links are presented in [312]. Also, a recent testbed for wireless communication systems applying receive antenna SSK is recently proposed in [313]. Finally, a theoretical analysis regarding the impact of IQ imbalance on the performance of QSM system is recently conducted in [119].

V. RECONFIGURABLE ANTENNA-BASED INDEX MODULATION TECHNIQUES

Reconfigurability can be thought of as software-defined functionality, where flexibility is controlled predominately through the specification of bit patterns. Reconfigurable systems can be as simple as a single switch, or as abstract and powerful as programmable matter [314]. One of the most prevalent pursuits in reconfigurable RF research has been in the development of antennas, which have been studied extensively [315]. For the most part, a RA is a set of passive structures infused with switches, which are opened and closed to elicit desired resonances for end-user applications. Reconfigurability has become an important and desired feature of

modern, agile, RF systems for wireless communications and sensing. The use of RAs can significantly reduce the number of components, and, thus, hardware complexity, size, and cost compared to today's radio technology, which are based on communication systems with inflexible (non-reconfigurable) hardware. In the burgeoning IoT, the size of the mobile devices (the objects) will continue to shrink compared to the past while their data rate and energy efficiency capabilities will continue to rise in light of the envisioned use cases. The IoT will likely create an enormous demand for small wireless systems with sizes comparable to those of tiny sensors but with higher data rate requirements and similar or higher energy efficiency requirements. In this context, RAs are expected to better design communication systems satisfying the conflicting trade-offs of reducing the size, power consumption, and cost of the IoT, while simultaneously increasing their data rate through innovative multiple-antenna technologies [83].

The idea of using RAs for implementing and generalizing the SM principle was introduced in [66] with the twofold attempt of potentially increasing the achievable data rate and of reducing the implementation complexity, e.g., by avoiding the need of using mechanical or RF switches. In this section, the idea of using RAs for application to SM systems is summarized and ongoing research activities are discussed. Furthermore, the recently proposed space-time channel modulation (STCM) concept, which combines RAs with MIMO transmission principles, is reviewed and potential future research directions are highlighted.

A. RECONFIGURABLE ANTENNAS - PRELIMINARIES

Before going into the details of applying RAs to SM systems, we briefly summarize the fundamental working principle of RAs and illustrate a simple example of the RA system.

In general terms, reconfiguring an antenna is achieved through deliberately changing its radiation characteristics, e.g., its far field radiation pattern. In practice, this change is obtained in a controlled manner, by adequately redistributing the antenna currents and, thus, altering the electromagnetic fields of the antenna's effective aperture. In other words, thus, the far field antenna radiation pattern can be controlled by appropriately controlling the distribution of the current of the antennas. Based on [315], e.g., there are several techniques for obtaining RAs, which include i) electrically-reconfigurable, ii) optically-reconfigurable, iii) physically-reconfigurable, and iv) material-reconfigurable antennas. Among the many potential benefits of RAs, important peculiarities for application to the IoT include the minimization of cost, volume requirements, and a simplified integration. It is worth mentioning, in addition, that RAs are different from smart antennas, since the reconfiguration process lies inside the antenna rather than in the external network as in beamforming network.

In Fig. 10, we illustrate a simple example of reconfigurable dipole antenna, where the radiation pattern

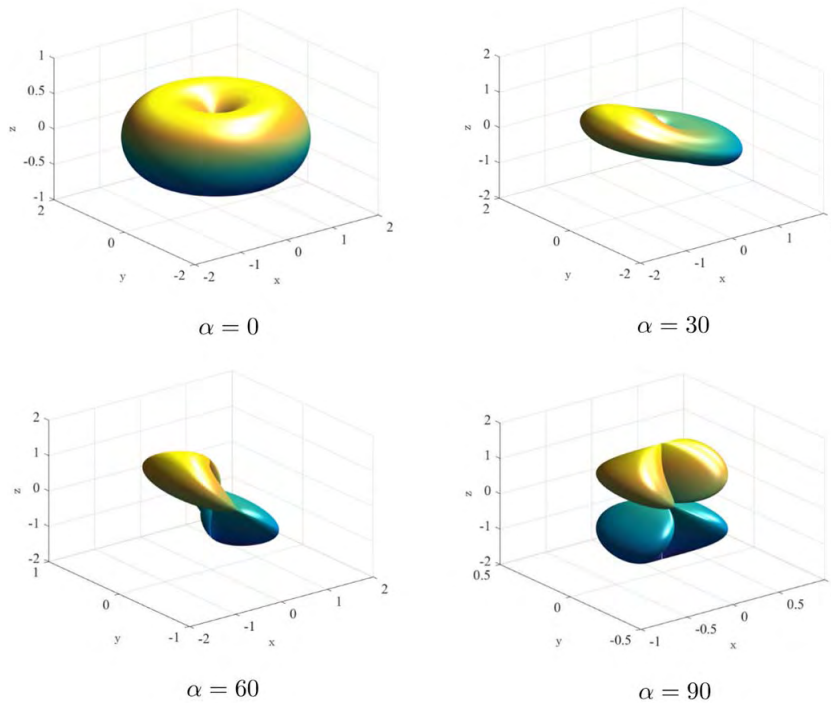


FIGURE 10. Example of different radiation patterns of a reconfigurable antenna (dipole). Two bits can be mapped into the realization of four different radiation patterns: “00” $\rightarrow \alpha = 0$, “01” $\rightarrow \alpha = 30$, “10” $\rightarrow \alpha = 60$ and “11” $\rightarrow \alpha = 90$.

(vertical polarization) depends on the inclination angle (α) of the dipole antenna itself (the so-called polarization parameter) [316].

B. INDEX MODULATION BASED ON RECONFIGURABLE ANTENNAS - MAIN CONCEPT

The idea of using RAs for providing a low-complexity implementation solution for realizing SM systems was proposed in [66]. In this subsection, we briefly discuss the idea with the aid of Fig. 10 and by considering the simplest case study.

Let us assume that the transmitter is equipped with a RA that is capable of producing the far field radiation patterns depicted in Fig. 10. For ease of illustration, let us assume that the data stream to be transmitted is encoded exclusively into one of the four radiation patterns of Fig. 10. For example:

- If “00” needs to be transmitted, the polarization parameter α is set equal to 0 degrees and the corresponding antenna radiation pattern is generated and used for transmission.
- If “01” needs to be transmitted, the polarization parameter α is set equal to 30 degrees and the corresponding antenna radiation pattern is generated and used for transmission.
- If “10” needs to be transmitted, the polarization parameter α is set equal to 60 degrees and the corresponding antenna radiation pattern is generated and used for transmission.
- If “11” needs to be transmitted, the polarization parameter α is set equal to 90 degrees and the corresponding

antenna radiation pattern is generated and used for transmission.

It is known that the characteristics of multipath radio channels are determined by the distribution of the scatterers in the RF propagation environment and by the interplay between multipath components and antenna radiation patterns. More precisely, the transmitted electromagnetic wave is radiated by the RA according to the radiation pattern in Fig. 10 and it then interacts with the scatterers that are spatially distributed in the environment. Depending on the radiation pattern being activated by the data stream to be transmitted, as a result, the received signal depends on the interaction between the spatial distribution of the scatterers and the directional characteristics of the antenna. In general, different radiation patterns interact with different scatterers, which results in a unique received signal (fingerprint) for every possible radiation pattern. This is another way of exploiting the SM principle [65] and of encoding the information not only in the impulse response of the channel, but in the interplay between antenna radiation pattern and nearby scatterers. Similar to the conventional SM principle [65], the receiver can retrieve the information by solving a hypothesis testing problem based on the four radiation patterns depicted in Fig. 10.

The potential advantage of this approach compared to conventional SM is the possibility of realizing very compact and low-complexity antennas that are inherently used for modulating data. In addition, the use of RAs may avoid the need of using mechanical switches, which, on the other hand, are replaced by appropriate circuits that are integrated

in the antenna design and that are capable of changing the distribution of the current of the RAs.

These peculiarities are suitable for IoT applications and the research project SpatialModulation, led by Orange Labs in France, is focused on designing and optimizing RAs for realizing this vision and for applying SM to IoT, 5G and WLAN systems [317]. Further details are provided in Subsection V-C.

C. STATE-OF-THE-ART: THEORETICAL AND EXPERIMENTAL ACTIVITIES

Even though the idea of using RAs in the context of SM research was proposed just recently, quite a few theoretical and experimental activities are currently available. They are briefly summarized in this subsection.

In [318], a distributed antenna system is proposed, where a single-RF RA is employed at the transmitter. More specifically, the use of a single-RF RA, capable of switching/forming multiple antenna patterns, is used to create virtual multiple-antenna channels without relying on the cooperation with other nodes. The author showed that the proposed technique is capable of outperforming classical virtual multiple-antenna systems. The proposed scheme, in addition, is generalized to its non-coherent detection-based counterpart, which uses differential encoding of unitary pattern-time codewords. The proposed non-coherent scheme is capable of dispensing channel state information estimation at the receiver.

In [140], a DSM scheme is developed for APSK modulation with better throughput or performance compared with conventional PSK modulation. The impact of time-varying fading is studied and it is shown that the performance degrades if the fading is too fast due to differential detection. The impact of a long outer error control code is also considered. It is shown that its performance is limited by the slowly varying channel required for differential detection. The author suggested using RAs to periodically change the channel conditions and hence, significantly improve coded performance for DSM systems.

In [29], the authors considered the application of RAs for data modulation. More precisely, the effect of RAs on the channel consists of changing the Rician K -factor of the channel itself. Based on this observation, the authors propose a system that encodes the information into the variation of the Rician K -factor. A mathematical framework for computing the bit error probability is proposed, and it is shown that the proposed scheme is capable of enhancing the system performance. In [319], the same authors of [29] extended their proposed modulation scheme for application to spectrum sharing systems and proved that the performance of SUs can be improved while still satisfying the constraints on PUs.

In addition to these theoretical studies, some experimental activities that are aimed to design new RAs specifically tailored for SM applications, have been proposed. In addition, preliminary testbed implementations have been realized.

In [320], the authors designed a compact RA suitable for communication systems based on the SM principle. The RA is based on a meander line radiating element surrounded by two L-shaped wire resonators connected to a metallic ground plane with two PIN diodes. By switching the PIN diodes, the proposed printed antenna is capable of generating four different radiation patterns. The cross-correlation between the different patterns is shown to lie in the range 11%-80%, which is shown to be acceptable for SM applications. Other antenna geometries are proposed in order to increase the number of radiation patterns that can be generated while still preserving good correlation properties for practical communication applications.

In [321], the authors reported the world's first "visual" demonstration of a testbed implementation that adopts RAs for realizing the SM principle. Different new RAs are used for encoding the information bit stream and their different "energy patterns" are visualized with the aid of an innovative radio wave display that is capable of measuring the received power. The display clearly shows that distinct received energy patterns are obtained when different radiation patterns of RAs are activated at the transmitter. This world's first demonstration was showcased at the *21th Int. ITG Workshop on Smart Antennas* in Berlin, Germany, on March 2017.

D. THE CONCEPT OF CHANNEL MODULATION

Media-based modulation (MBM) is a term coined by Khandani in [322] with the aim of implementing the data transmission concept based on RAs from an information theoretic perspective. As mentioned in the previous subsections, the concept of RAs is well-known in the field of electromagnetics and has become increasingly popular in the past decade; MBM, however, has been put forward explicitly for the application of RAs to carry additional information through IM. In order to resolve the ambiguity between MBM and data modulated RAs, which are actually the same concepts, the more general term of *channel modulation* has been recently introduced in [11] for the family of SSK and MBM/RA variations since in all of these schemes, a carrier signal with constant parameters is transmitted while the realizations of the wireless channel carry the information. Interestingly, it has been proved that MBM and SSK schemes are identical when their individual system parameters are adjusted accordingly [11]. As an example, the MBM scheme that employs the radiation patterns of Fig. 10 to transmit two information bits per channel use (bpcu), is identical to an SSK scheme with four transmit antennas under the assumption of independent and identically distributed fading channels for different radiation patterns and transmit antennas of MBM and SSK systems, respectively. From a broader perspective, since all of the concepts mentioned above can transmit additional information bits by using the indices of the building blocks of a given communication system, which are RF mirrors and transmit antennas for MBM and SSK systems, respectively, they can be considered as members of the IM family [6]. In Fig. 11, the transmitter block diagrams

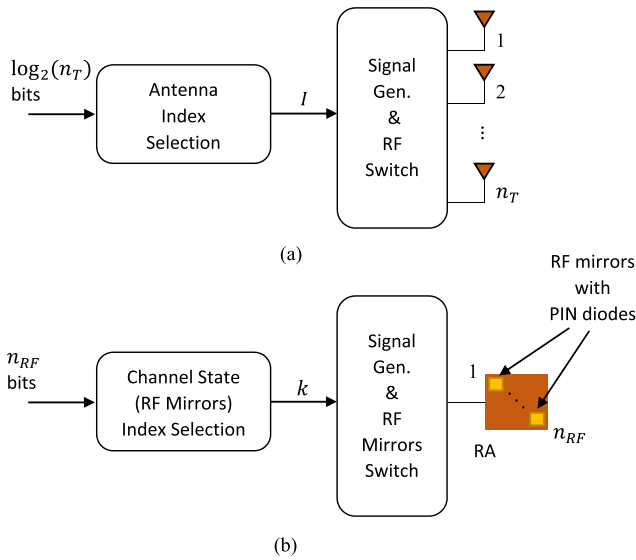


FIGURE 11. Block diagrams of (a) SSK and (b) MBM transmitters.

of SSK and MBM schemes are provided, where the SSK scheme operates with n_T transmit antennas while the MBM scheme exploits a single RA with n_{RF} RF mirrors that are equipped with PIN diodes. The index of the activated transmit antenna, which is determined according to $\log_2(n_T)$ bits, is denoted by $I \in \{1, 2, \dots, n_T\}$ for SSK while the index of the active channel state, which is determined according to n_{RF} bits, is shown by $k \in \{1, 2, \dots, 2^{n_{RF}}\}$ for MBM. It should be noted that the incoming n_{RF} bits determine the on/off status (0 \rightarrow off and 1 \rightarrow on) of the available n_{RF} RF mirrors, whose different on/off realizations correspond to a different channel state for MBM.

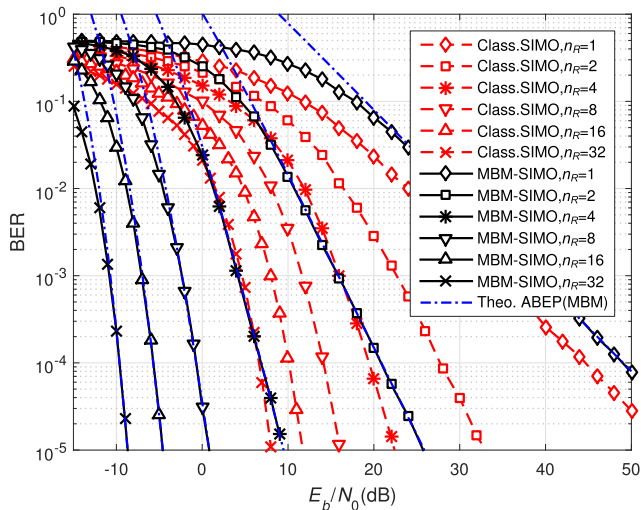


FIGURE 12. BER performance comparison of classical SIMO and MBM-SIMO schemes for different number of receive antennas, 8 bpcu transmission (class. SIMO with 256-QAM, MBM-SIMO with $n_{RF} = 8$ RF mirrors). (reproduced from [11] with permission).

In Fig. 12, we compare BER performances of classical SIMO and MBM schemes for different number of receive antennas. As seen from Fig. 12, MBM scheme is

outperformed by the classical SIMO scheme for only the case of SISO transmission ($n_R = 1$). However, it provides significantly better BER performance in all other cases, since it benefits more from increasing number of receive antennas due to the transmission of the data with channel realizations (states).

Although early attempts have been made to transmit information by using parasitic elements for data modulation [323] as well as by the variations of antenna radiation patterns with a scheme called aerial modulation [324], [325], which combines signal modulation with pattern switching by using a single RF frontend surrounded by parasitic elements, the transmission of data bits effectively with the variations of the transmission media (channel states) is introduced in [322], in which the term MBM is coined for the first time. In this study, the advantages of SIMO-MBM over traditional MIMO systems is clearly demonstrated through information theoretical analyses. In [326] and [327], it has been shown that SIMO-MBM with n_R receive antennas achieves the capacity of n_R parallel AWGN channels and MBM schemes can be realized using antennas that are equipped with RF mirrors. Then, MBM is adapted into MIMO systems to reduce the implementation complexity associated with the hardware and training overhead as well as to increase the system flexibility [21], [328]. It has been reported in [329] that SIMO- and MIMO-MBM schemes provide considerable performance improvements compared to traditional SIMO/MIMO as well as SM systems.

More recently, the studies of [41] and [330] considered the combination of GSM techniques with MBM from a signal processing perspective. The authors proposed an RF mirror activation pattern selection procedure as well as feedback-based phase compensation and constellation rotation techniques for MBM to obtain additional diversity gains. It has been shown that GSM-MBM can achieve a better error performance than MIMO-MBM. Similarly, a dual-polarized SM (DP-SM) scheme is proposed in [49] by considering the dimension of polarization for the transmission of additional information bits for correlated Rayleigh and Rician fading channels under channel estimation errors. In this simple but yet effective DP-SM scheme, one additional information bit is mapped to the selection of the polarization such as vertical or horizontal. The authors of [331] investigated the performance of MBM for the uplink of massive MU-MIMO systems and considerable improvements are reported over conventional systems. Even more recently, the multidimensional IM concept is introduced in [32], where the authors proposed time-indexed SM (TI-SM), time-indexed MBM (TI-MBM), SM media-based modulation (SM-MBM) and time-indexed SM-MBM (TI-SM-MBM) schemes by considering the combination of IM techniques for transmit antennas, time-slots and RF mirrors to further exploit the promising advantages of IM. Furthermore, the authors investigated load modulation schemes, which modulate the antenna impedances that control the antenna currents. Finally, a differential MBM scheme is proposed in [332] to overcome one of the main

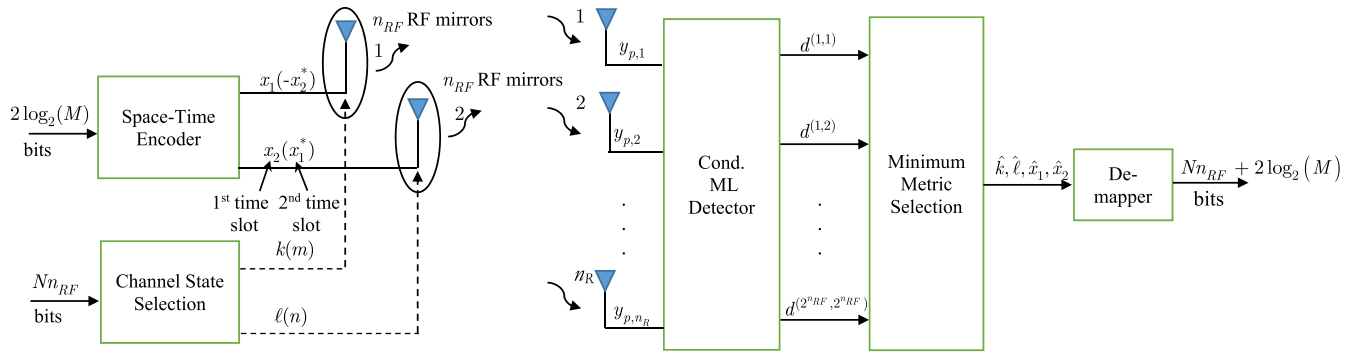


FIGURE 13. Transceiver structure of the STCM scheme for a $2 \times n_R$ MIMO system. n_{RF} : number of RF mirrors at each transmit antenna, M : constellation size, k, l, m, n : selected channel states, $N = 1$ for Scheme 2 and $N = 2$ for Schemes 1 and 3, $d^{(k,l)}$: the minimum ML decision metric for a given pair of (k, l) (Reproduced from [11] with permission).

TABLE 5. System parameters of different STCM schemes.

Scheme	Channel state selection		Data rate (bpcu)	Tx div. order	ML dec. complexity
	1st Tx antenna	2nd Tx antenna			
Scheme 1	1st time slot	k	$n_{RF} + \log_2 M$	1	$2^{2n_{RF}+1} M$
	2nd time slot	l			
Scheme 2	1st time slot	k	$0.5n_{RF} + \log_2 M$	2	$2^{n_{RF}+1} M$
	2nd time slot	k			
Scheme 3	1st time slot	k	$n_{RF} + \log_2 M$	2	$2^{2n_{RF}} M^2$
	2nd time slot	l			

shortcomings of the MBM scheme, which is the knowledge of the different channel fading realizations for increasing number of RF mirrors, i.e., the problem of channel sounding. The differential MBM scheme does not require the knowledge of CSI at the receiver by benefiting from differential encoding of consecutive MBM blocks and uses a low-complexity ML detector at the receiver, which achieves approximately 2-4 dB worse BER performance than the coherent MBM scheme.

E. SPACE-TIME CHANNEL MODULATION

As an alternative to SM-based RA (MBM) systems [41], [330] and SSK-based RA systems [29], [319], [333], a new RA-based MIMO scheme, which is called STCM, is proposed in [11] by jointly using RAs and STBC. In this subsection, we briefly cover the concept STCM and demonstrate its promising potential for future wireless networks.

Although MBM exhibits appealing advantages such as improved error performance and significant energy savings with using fewer transmit antennas compared to classical modulation schemes, plain MBM scheme cannot provide transmit diversity, which could be of critical importance for applications that require high reliability. In order to overcome this main limitation of MBM/RA systems, the scheme of STCM is proposed in [11] by exploiting both space, time and channel states domains. The use of channel states through the principle of MBM allows the STCM scheme to reach a high spectral efficiency, while the use of space and time domains paves the way for obtaining transmit diversity.

In Fig. 13, the transceiver of the STCM scheme is given, where Alamouti’s STBC [77] is used as the generic STBC for

two transmit antennas. As seen from Fig. 13, STCM can be considered as a dynamic STBC scheme in which the states of the wireless channels can be adjusted through RAs that are equipped with n_{RF} RF mirrors. In the first time slot, complex data symbols x_1 and x_2 are transmitted from the first and second transmit antennas, respectively, where their corresponding channel states are selected as k and l , where $k, l \in \{1, 2, \dots, 2^{n_{RF}}\}$. In the second time slot, according to the STBC principle, $-x_2^*$ and x_1^* are transmitted from the first and second transmit antennas, respectively; however, their corresponding channel states are selected as m and n for this time, where $m, n \in \{1, 2, \dots, 2^{n_{RF}}\}$. In other words, there are two information carrying units for STCM: the complex data symbols drawn from M -QAM constellations and the selected channel states (on/off status of the available RF mirrors). Three novel STCM schemes are proposed based on the transceiver structure of Fig. 13. For these three schemes, three unique channel state selection rules are defined, which are summarized in Table 5 along with other system parameters. As seen from Table 5, for Scheme 1, the same channel states are selected in the second time slot, while a cross selection strategy is considered for Scheme 3. On the other hand, the same channel state is used for both time slots and transmit antennas for Scheme 2. It is also worth mentioning that these three STCM schemes provide interesting trade-offs among decoding complexity, spectral efficiency and transmit diversity order (error performance).

At the receiver side, the received signals at n_R receive antennas, $y_{p,r}$ for $p = 1, 2$ and $r = 1, 2, \dots, n_R$, are processed by the conditional ML detector to obtain the minimum

decision metrics for all possible channel state combinations. The minimum metric selector determines the most likely channel states as well as the data symbols and passes these estimates to the demapper, which provides an estimate of the input data bit stream.

It has been shown in [11] by extensive computer simulations that STCM schemes outperform classical Alamouti's STBC [77], STBC-SM scheme of [44] as well as SIMO- and MIMO-MBM schemes of [21] and [326], due to the flexibility they offer in the system design. Considering the conceptual similarity between MBM and SSK schemes, STCM scheme is also analogous to the STBC-SM scheme, which requires more than two transmit antennas to convey additional information bits by the indices of the selected transmit antennas. However, STCM cleverly overcomes the main limitation of the STBC-SM scheme by considering IM for channel states instead of transmit antennas and exhibits an improved error performance with only two transmit antennas.

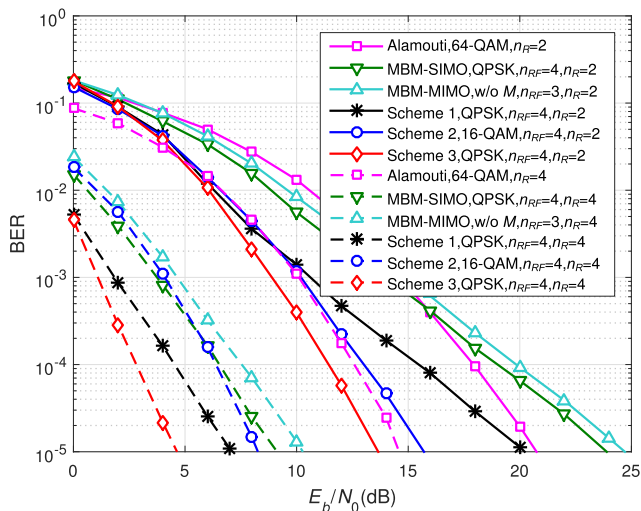


FIGURE 14. BER performance comparisons for STCM schemes with 6 bpcu, $n_R = 2$ and 4. (reproduced from [11] with permission).

In Fig. 14, we investigate the BER performance of STCM schemes for 6 bpcu transmission and compare the results with classical Alamouti's STBC, MBM-SIMO and MBM-MIMO schemes. As illustrated in the figure, STCM schemes provide remarkable improvements in BER performance compared to MBM-SIMO scheme, which does not provide transmit diversity. Due to the information bits carried by the active channel states, STCM schemes can outperform the classical Alamouti's STBC, which requires higher order M -QAM constellations to reach a target data rate.

F. OPEN ISSUES AND RESEARCH CHALLENGES

In spite of these pioneering contribution towards the application of RAs to SM as well as MIMO systems, major theoretical, algorithmic, and implementation issues need to be addressed. This includes, a deeper understanding of the achievable performance of SM systems based on RAs, the

development of low-complexity demodulation schemes, e.g., without requiring channel state information at the receiver, and the implementation and test of RAs-array having multiple radiation patterns with controllable characteristics. For example, at the time of writing, there is no general understanding on the impact of the radiation pattern on the achievable performance if realistic (three-dimensional) multipath fading channels are considered. For the STCM framework, interesting research problems such as the generalization and optimization of STCM schemes, the formulation of low-complexity detection algorithms and analyses for correlated channel states as well as MIMO fading channels remain to be solved. In addition, all the activities conducted so far are based on the sub-6 GHz band, while no studies and results are available for higher transmission bandwidths. The promising results recently reported in [124], [308], and [334]–[336] on the application of SM to the mmWave band highlight that this technology may be used for high frequencies as well, where the use of appropriate RAs may be even more beneficial.

VI. THE CONCEPT OF OFDM WITH INDEX MODULATION

In this section, we consider IM applied to the subcarriers of an OFDM system. OFDM has become one of the most popular multi-carrier transmission techniques in the past decade and it is widely considered to satisfy the increasing demand for high data rate wireless communication systems. Thanks to its attractive features such as efficient implementation and robustness to inter-symbol interference (ISI), OFDM has been adopted in many standards such as LTE, IEEE 802.11x wireless local area networks (WLAN), digital video broadcasting (DVB) and IEEE 802.16e-WiMAX. After a long debate on alternative waveforms for 5G wireless networks in the past few years, OFDM and its modified versions also appear as very strong candidates for the next-generation mobile networks.

OFDM-IM is a multi-carrier transmission scheme that has been proposed inspiring by the concept of SM [8], [337], [338]. Similar to SM, the incoming bit stream is split into subcarrier index selection and M -ary constellation bits. Considering the index selection bits, only a subset of available subcarriers is activated, while the remaining subcarriers are set to zero and not used for conveying information through ordinary modulation. The active subcarriers are modulated as in classical OFDM according to M -ary constellation bits. In other words, OFDM-IM conveys information not only by the data symbols as in classical OFDM, but also by the indices of the active subcarriers that are used for the transmission of the corresponding M -ary data symbols.

For an OFDM system consisting of N_F available subcarriers, one can directly select the indices of the active subcarriers similar to SM-based schemes such as MA-SM and GSSK. Considering the structure of OFDM frames with many available subcarriers, IM techniques can be implemented in a more flexible way for OFDM-IM compared to SM. However, keeping in mind the practical values of N_F , which can take 128, 256, 512, 1024 or 2048 values as in LTE-A standard [339],

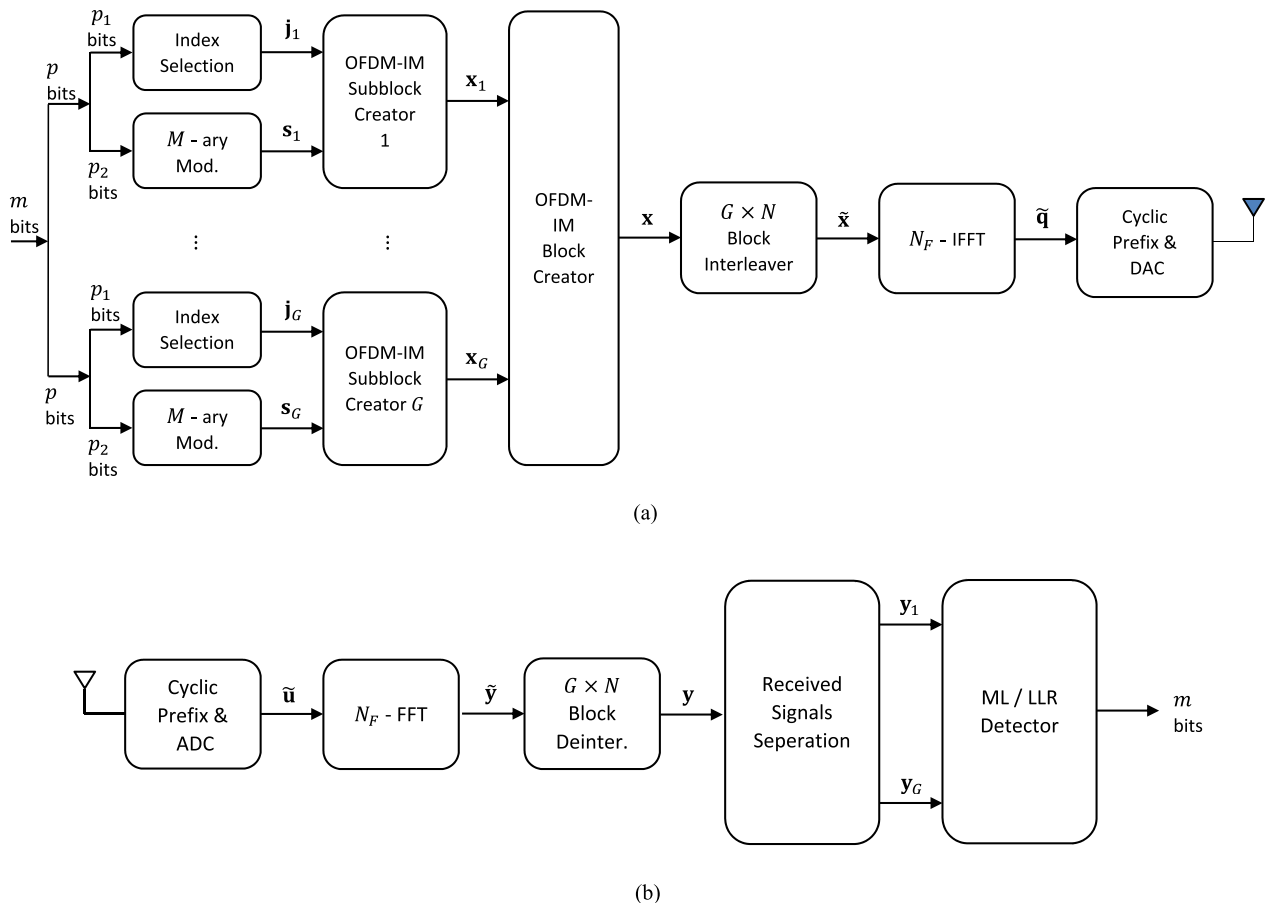


FIGURE 15. Transceiver structure of the OFDM-IM scheme (a) transmitter structure (b) receiver structure (Reproduced from [6] with permission).

if subcarrier IM is directly applied to the overall OFDM frame, there could be trillions of possible active subcarrier combinations. For instance, to select the indices of 512 active subcarriers out of $N_F = 1024$ available subcarriers, one should consider 4.48×10^{306} possible different combinations of active subcarriers, which make the selection of active subcarriers an impossible task. For this reason, the single and massive OFDM-IM block should be divided into G smaller and manageable OFDM-IM subblocks for ease of implementing OFDM-IM. In this divide-and-conquer approach, each subblock contains N subcarriers to perform IM, where $N_F = G \times N$. For each subblock, we select K out of N available subcarriers as active according to

$$p_1 = \left\lceil \log_2 \binom{N}{K} \right\rceil \quad (7)$$

index selection bits, where for ease of practical implementation, typical N values can be 2, 4, 8, 16, 32 and 64 with $1 \leq K < N$. It should be noted that classical OFDM becomes a special case of OFDM-IM with $K = N$, i.e., when all subcarriers are activated, where a total of $N \log_2 M$ bits can be transmitted per frame. On the other hand, the total number of bits transmitted per OFDM-IM frame is

given by

$$m = pG = \left(\left\lceil \log_2 \binom{N}{K} \right\rceil + K \log_2 M \right) G \quad (8)$$

where $p = p_1 + p_2$ and $p_2 = K \log_2 M$. The block diagrams of OFDM-IM transmitter and receiver structures are shown in Figs. 15(a) and 15(b), respectively, where \mathbf{j}_g and \mathbf{s}_g denote the vectors of selected indices and M -ary data symbols with dimensions $K \times 1$, respectively. In the following, we summarize the operation principles of OFDM-IM.

As seen from Fig. 15(a), for the transmission of each OFDM-IM frame, a total of m bits enter the transmitter. First, the OFDM-IM subblock creator obtains the OFDM-IM subblocks $\mathbf{x}_g \in \mathbb{C}^{N \times 1}$ for $g = 1, \dots, G$ by considering \mathbf{j}_g and \mathbf{s}_g . Then, the OFDM-IM block creator forms the main OFDM-IM frame $\mathbf{x} \in \mathbb{C}^{N_F \times 1}$ by concatenating these G OFDM-IM subblocks. After this point, $G \times N$ block interleaving is performed to ensure that the subcarriers of a subblock undergo uncorrelated wireless fading channels to improve the error performance of the detector. It is important to note that the original OFDM-IM scheme of [8] did not contain block interleaving, while this is introduced in [340] and [341]. Finally, IFFT, CP insertion, and digital-to-analog conversion (DAC) procedures are performed for the transmission of the

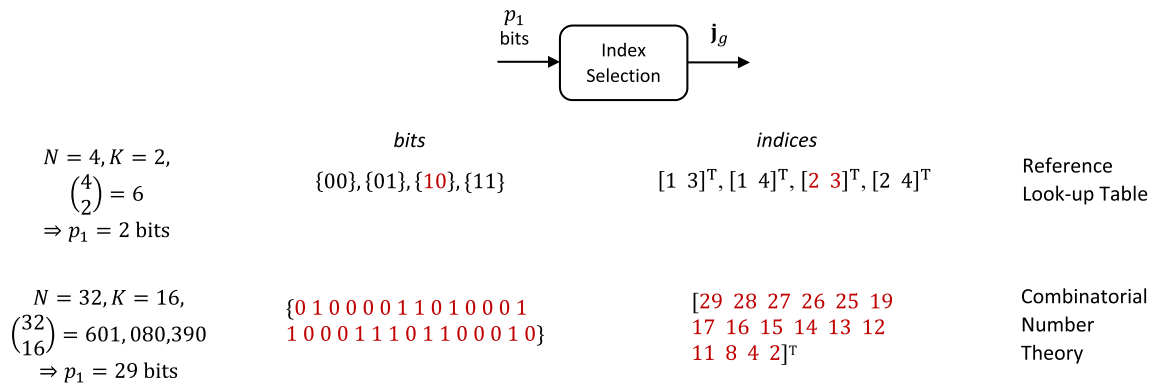


FIGURE 16. Two different index selection procedures for OFDM-IM (Reproduced from [6] with permission).

signals through the wireless channel as in classical OFDM systems.

The selection of active subcarriers is not a straightforward issue for OFDM-IM systems. For this purpose, two different index selection procedures are proposed for OFDM-IM depending on the size of the subblocks: i) reference look-up tables for smaller subblock sizes and ii) combinatorial number theory method for larger subblock sizes. Examples of these two methods are provided in Fig. 16. In the first example, two out of four subcarriers are selected as active by considering a reference look-up table that consists of four entries ($N = 4, K = 2$), where two bits determine the indices of two active subcarriers. In the second example, to select the indices of 16 active subcarriers out of 32 available subcarriers, the index selector considers 29 bits. First, these 29 bits are converted into a decimal number, and then, this decimal number is processed by the combinatorial algorithm, which provides the corresponding active indices.

The task of the OFDM-IM receiver is to determine the indices of the active subcarriers as well as the corresponding M -ary data symbols conveyed by these active subcarriers in conjunction with the index selection procedure used at the transmitter. After applying inverse operations (analog-to-digital conversion (ADC), CP removal, fast Fourier transform (FFT), and block deinterleaving), first, the received frequency-domain OFDM frame \mathbf{y} is split as \mathbf{y}_g for $g = 1, 2, \dots, G$, since the detection of different subblocks can be performed independently. Unfortunately, the optimal detection of OFDM-IM in a subcarrier-by-subcarrier fashion is not possible as in classical OFDM due to the index information carried by subblock realizations, and the receiver must process the OFDM-IM subblocks as a whole for detection. The optimum but high-complexity ML detector performs a joint search by considering all realizations of subcarrier activation patterns (SAPs) as well as complex data symbols. On the other hand, low-complexity log-likelihood ratio (LLR) calculation-based near-optimal detector handles each subcarrier independently and determines the indices of the active subcarriers first, and then, it detects the corresponding data symbols. This detector calculates a probabilistic

measure (LLR) on the active status of a given subcarrier by considering the following two possible scenarios: an active subcarrier (carrying an M -ary constellation symbol) or an inactive one (that is set to zero). This detector is classified as near-optimal since it does not consider the set of all legitimate subcarrier activation combinations. As we will discuss in Subsection VII-A, to reduce the cost of its practical implementation, new low-complexity near/sub-optimal detection methods are also proposed for OFDM-IM in recent times.

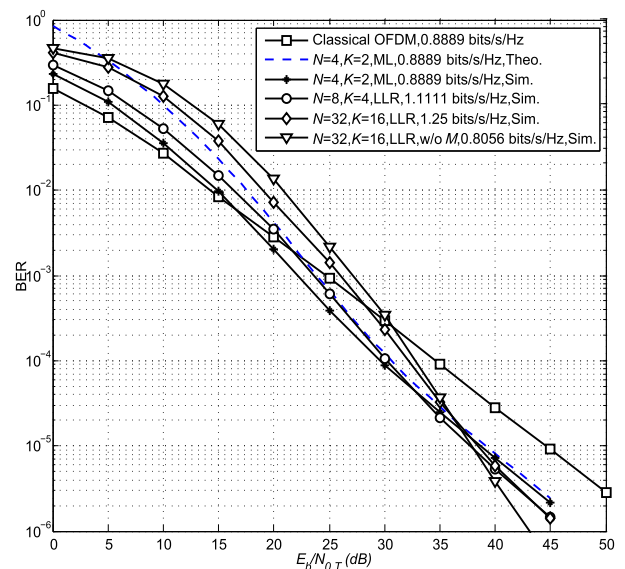


FIGURE 17. BER performance of OFDM-IM with different configurations using BPSK. (reproduced from [8] with permission).

In Fig. 17, we evaluate the BER performance of OFDM-IM scheme with different configurations and make comparisons with classical OFDM, where $N_F = 128$, number of channel taps is 10 (uniform power delay profile) and the length of the CP is 16. As seen from Fig. 17, OFDM-IM provides a significantly better BER performance than classical OFDM for this configuration due to the improved error performance of the bits transmitted via IM, which is more effective at high

SNR. It should be noted that while we employ ML detector for $N = 4, K = 2$ case, for the cases of $N = 8, K = 4$ and $N = 32, K = 16$, we use LLR detector along with combinatorial algorithm. It is also interesting to note that bypassing M -ary modulation and transmitting data with only active subcarrier indices, OFDM-IM scheme can provide a transmit diversity of two.

A. ADVANTAGES AND DISADVANTAGES

The main reason for the rise of OFDM-IM and its variants in the past few years is the appealing advantages they offer compared to classical multi-carrier systems. At the first glance, OFDM-IM appears as a modified version of OFDM with a much less complicated structure compared to emerging waveforms such as generalized frequency division multiplexing (GFDM) [342], filter-bank multi-carrier (FBMC) [343] or universal filtered multi-carrier (UFMC) [344]. However, the main feature of OFDM-IM lies in its simplicity and the resulting efficiency. In the following, we list the main advantages of OFDM-IM over classical OFDM:

- The major difference between classical OFDM and OFDM-IM schemes is the adjustable number of active subcarriers of the latter. Consequently, the number of active subcarriers of OFDM-IM can be adjusted accordingly to reach the desired spectral efficiency and/or error performance. From this perspective, OFDM-IM provides an interesting trade-off between error performance and spectral efficiency with its flexible system design.
- OFDM-IM can provide a better BER performance than classical OFDM at the same low-to-mid spectral efficiency value with a comparable decoding complexity using the near-optimal LLR detector. This BER improvement can be attributed to the fact that the information bits carried by IM have lower error probability compared to ordinary M -ary constellation bits.
- Thanks to IM, OFDM-IM can provide better performance than classical OFDM in terms of ergodic achievable rate.
- Due to inactivation of some of the available subcarriers, OFDM-IM not only reduces the peak-to-average power ratio (PAPR), but also is more robust to inter-carrier interference (ICI) compared to traditional OFDM.
- OFDM-IM is also well-suited to MIMO, MU and high mobility setups as well as to OW, vehicular, machine-to-machine (M2M), device-to-device (D2D) and underwater acoustic (UWA) communication systems, and it can provide attractive advantages over OFDM-based traditional systems.
- The improvements offered by the OFDM-IM scheme in BER performance as well as the flexibility of the overall multi-carrier system can be further increased by utilizing generalized/enhanced OFDM-IM variants, which are proposed in the past 1-2 years.

As seen above, OFDM-IM comes with attractive advantages for next-generation wireless networks. On the other

hand, OFDM-IM also has some inherent drawbacks, which are given as follows:

- The spectral efficiency of the plain OFDM-IM cannot compete with that of classical OFDM for increasing modulation orders due to inactive subcarriers of the former. Therefore, the beneficial operating interval of OFDM-IM compared to classical OFDM, in terms of the spectral efficiency, is limited. On the other hand, generalized/enhanced OFDM-IM structures obtain higher spectral efficiency and overcome this limitation.
- Uncoded/coded error performance of OFDM-IM is generally worse than classical OFDM for low SNR values. This is a common trend observed in IM-based schemes and is also valid for OFDM-IM.
- The detection complexity of the optimal detector of OFDM-IM is considerably high compared to classical OFDM. The low complexity LLR calculation-based detector provides comparable complexity, however, at the cost of an error performance loss.
- The determination of the active subcarrier indices can be a problem for increasing subblock sizes due to combinatorially increasing number of possible subcarrier activation patterns.
- OFDM-IM and OFDM schemes exhibit very similar PAPR performance for Gaussian input symbols. Similarly, OFDM-IM is outperformed by classical OFDM in terms of achievable rate for Gaussian input symbols.

Considering the above advantages and disadvantages, we conclude that OFDM-IM can be regarded as a possible candidate for emerging high-speed wireless communication systems. Furthermore, OFDM-IM is able to address a variety of user applications and channel conditions, and provides an attractive flexibility support, which is foreseen for 5G and beyond radio access technologies [345]. Within this perspective, OFDM-IM has the potential to be well-suited to M2M and D2D communication systems of next-generation wireless networks that require low power consumption.

VII. RECENT ADVANCES IN OFDM-IM

The concept of IM for OFDM subcarriers has attracted significant attention from the wireless community in recent times since its widespread introduction in [8].² Furthermore, OFDM-IM has also triggered the spread of IM technologies to many different areas and systems. In this section, we provide a detailed summary of the recent advances in OFDM-IM and related technologies and then, focus on the following promising variants of OFDM-IM that try to overcome the main disadvantages of plain OFDM-IM:

²To the best of our knowledge, the concept of OFDM-IM also appears in the literature with following past and present terminologies: subcarrier index modulation OFDM (SIM-OFDM), index modulated OFDM (IM-OFDM), multi-carrier index keying OFDM (MCIK-OFDM), OFDM with subcarrier index modulation (OFDM-SIM), selecting subcarrier modulation (SScM), subcarrier index coordinate expression (SICE), parallel combinatory OFDM and selecting subcarriers modulation (SSCM). To avoid ambiguity, we use the generic and the most common term of OFDM-IM throughout this paper.

TABLE 6. An overview of the studies on OFDM-IM and related literature.

Area	Studies
Old IM attempts	[346], [347], [348], [349]
Origins	[350], [351], [352], [337], [8]
Generalization & enhancement	[340], [353], [354], [28], [355], [356], [20], [357], [35], [31], [37], [358], [359], [40], [42]
Performance analysis	[8], [338], [360], [361], [362], [363], [364], [365]
PAPR/ICI/CFO issues	[366], [367], [368], [369], [370], [371], [372], [373], [374], [375], [376]
Low complexity detection	[377], [378], [379], [380], [381]
Coded realizations	[382], [383], [384], [385]
V2V, V2X, UWA, D2D, IoT apps.	[386], [387], [341], [388], [389], [390], [391], [392], [393]
MIMO implementations	[48], [307], [394], [395], [396], [397], [52], [398], [399], [400], [401], [402], [43], [45]
Optical wireless apps.	[58], [403], [404], [405]
FQAM	[406], [407], [408], [409], [410]
Code IM	[18], [26], [411], [412]
Precoder IM & precoded apps.	[413], [16], [414], [415], [416], [417], [418], [40]
Extensions	[419], [54], [420], [46], [60], [62], [50], [64]
Other apps.	[421], [422], [423], [424]

OFDM with in-phase/quadrature IM, coordinate interleaved OFDM-IM, dual-mode OFDM and multiple-input multiple-output OFDM-IM (MIMO-OFDM-IM) systems.

A. AN OVERVIEW OF OFDM-IM AND RELATED LITERATURE

Similar to the case of SM systems, the concept of subcarrier IM for multi-carrier systems had appeared earlier in the literature [346], [347]. The parallel combinatory OFDM scheme of [346] considered subcarrier level IM for the transmission of additional information bits as well as for the reduction of PAPR by inspiring from the IM concept of [348] that considered spread-spectrum systems. Similarly, frequency and QAM (FQAM) scheme, which combines frequency shift keying (FSK) and QAM, can be considered as an application of IM to the available frequency tones [349]. However, the true potential of OFDM-IM schemes had not been discovered by the community with these initial studies until SM and its variants sparked a new wave of alternative digital modulation schemes that exploit the indices of the transmit antennas to convey information. Inspired by the SM concept, a primitive subcarrier IM-OFDM scheme is proposed in [350], in which each subcarrier carries one additional IM bit and the subcarriers associated with the majority bit value (0 or 1) are activated. However, the number of active subcarriers varies from block to block for this scheme, and perfect feedforward is assumed to be available from the transmitter to the receiver via excess subcarriers to explicitly indicate the value of the majority bit. An enhanced subcarrier IM-OFDM scheme, which does not require feedforward signaling from the transmitter to the receiver, is proposed in [351]. Unfortunately, the spectral efficiency of this scheme is quite limited compared to classical OFDM for higher modulation orders since only one IM bit is conveyed via each subcarrier group that consists of two subcarriers. Another attempt was made independently in [352] to decrease the energy consumption and PAPR of classical OFDM by reducing the number of active subcarriers via IM. The concept of OFDM-IM has appeared at this

time³ [8], [337], [338] to overcome the limitations of the aforementioned schemes and to provide more flexibility in the system design. For a more detailed historical overview of subcarrier IM concepts, readers are referred to [368].

After its widespread introduction in the works of [8] and [337], the concept of IM for OFDM subcarriers has attracted remarkable attention from the wireless community in the past few years and several follow-up studies have been performed by the researchers. These studies can be categorized as follows: generalized and enhanced OFDM-IM variants, performance analyses with/without system impairments such as ICI and carrier frequency offset (CFO), low complexity detectors, applications for vehicle-to-vehicle (V2V), vehicle-to-vehicle and vehicle-to-infrastructure (V2X), D2D and UWA communication systems, adaptation of OFDM-IM and its variants to MIMO setups and coded implementation of OFDM-IM. Furthermore, OFDM-IM concept has triggered the research activities for the application of IM to other communication systems such as optical OFDM, direct-sequence spread spectrum and emerging single/multi-carrier communication systems such as GFDM, FBMC systems and so on. In Table 6, we categorized all of the studies available in the current literature on OFDM-IM as well as the OFDM-IM inspired/related works for the interested readers. As seen from Table 6, OFDM-IM not only has been investigated from many different aspects and but also it has triggered the spread of IM from OFDM to other communication systems. It is important to note that most of these studies have performed during the past 1-2 years.

³The concept of OFDM-IM, as we know today, has come to life during the discussions between the authors of [8] for the application of the SM principle to the subcarriers of an OFDM system independently from the works of [346] and [350]–[352]. The initial design, which was named as OFDM with SM, was based on the activation of a single subcarrier among all available subcarriers, similar to the SM scheme, and a scheme with eight subcarriers is considered to transmit three additional bits with the index of the activated subcarrier. However, subblock partitioning method and corresponding mapping/demapping algorithms as well as low-complexity detectors were later developed to compete with classical OFDM in terms of spectral efficiency and detection complexity.

The initial attempts in the literature are focused on generalization and enhancement of the OFDM-IM scheme to further improve its error performance and/or spectral efficiency. Subcarrier level block interleaving is introduced in [340] to improve the error performance of OFDM-IM by benefiting from uncorrelated frequency-domain fading coefficients for the elements of OFDM-IM subblocks. The authors of [353] and [354] investigated the problem of the selection of the optimal number of active subcarriers as well as the optimal subcarrier grouping approach to improve the spectral and energy efficiency of OFDM-IM. The authors of [28] proposed the scheme of OFDM with generalized IM (OFDM-GIM) by changing the number of active subcarriers according to the information bits. The same authors also proposed applying IM independently and jointly to the IQ components of each subcarrier symbol in [355] and [356], respectively. The scheme of [355] is named as OFDM-I/Q-IM in [20] and its low-complexity ML detector is proposed along with the derivation of its exact coding gain (see Subsection VII.B for details). An improved constellation mapping algorithm is proposed for generalized OFDM-IM scheme in [357] to further improve the spectral efficiency at the cost of a negligible BER performance loss. In order to obtain additional diversity gains, OFDM-IM is combined with coordinate interleaving principle in [35] (see Subsection VII.C for details).

The authors of [31] proposed the scheme of dual-mode OFDM (DM-OFDM) in which the major disadvantage of OFDM-IM is removed by the activation of the inactive subcarriers of OFDM-IM to transmit modulated symbols selected from a secondary constellation that is distinguishable from the primary constellation used by the active subcarriers (see Subsection VII.D for details). Later, the same authors proposed the generalized DM-OFDM (GDM-OFDM) scheme in [37] by changing the number of subcarriers modulated by the same constellation alphabet according to the information bits of each OFDM subblock to further improve the spectral efficiency of DM-OFDM. Recently, in order to further increase the energy efficiency as well as the diversity gain of OFDM-IM, a CS-assisted signaling strategy is proposed for OFDM-IM systems in [358] by implementing conventional IM in a high-dimensional virtual digital domain and then exploiting CS for compressing high-dimensional IM symbols into low-dimensional frequency-domain subcarriers. The problem of unbalanced subcarrier activation is investigated in [359] and an equiprobable subcarrier activation method, which allows the activation of all subcarriers as equiprobably as possible, is proposed to improve the BER performance of plain OFDM-IM. Finally, the recent study of [40] proposed two enhanced OFDM-IM schemes, which are termed as OFDM with hybrid in-phase/quadrature index modulation (OFDM-HIQ-IM) and linear constellation precoded OFDM-I/Q-IM (LP-OFDM-I/Q-IM). The first scheme explores the IQ dimensions jointly for IM to transmit more number of IM bits in each subcarrier group, while the second scheme spreads information symbols across two adjacent active subcarriers

through linear constellation precoding to obtain additional diversity gains. It has been shown by theoretical analyses and computer simulations that OFDM-HIQ-IM and LP-OFDM-I/Q-IM schemes exhibit better BER performance compared to the existing OFDM-IM schemes as well as enable low-complexity detection.

In the past few years, the researchers have paid considerable attention to the performance analysis and optimization of OFDM-IM and investigated interesting practical issues. In [8] and [338], the error performance of OFDM-IM is investigated in the presence of channel estimation errors and under high mobility conditions, respectively. For the case of mobility, several interference unaware/aware detection methods are proposed for OFDM-IM. In [360], the authors combined N -continuous OFDM principle of [425] with IM and investigated the sidelobe suppression performance of this new system. It is shown in [360] that N -continuous OFDM-IM has excellent sidelobe suppression compared to plain OFDM-IM. In [367], PAPR and BER performances of OFDM-IM with ICI are investigated with computer simulations. The initial results of this study reported that OFDM-IM is able to reduce PAPR considerably and more robust to ICI compared to classical OFDM (see Subsections VIII-B and VIII-C for more details). On the other hand, the authors of [368] characterized the PAPR of the OFDM-IM scheme with the aid of a level-crossing rate analysis and showed that OFDM-IM and OFDM schemes exhibit similar PAPR performance for Gaussian input symbols. In the same study, minimum Euclidean distance upper bound of OFDM-IM is also derived and the beneficial operating interval (in terms of spectral efficiency) of OFDM-IM compared to classical OFDM is revealed. More recently, the authors of [369] proposed a highly-efficient PAPR reduction technique for OFDM-IM by utilizing the idle (inactive) subcarriers and convex programming.

In [370], the authors investigated the joint design problem of OFDM-IM and ICI self-cancellation methods, such as classical ICI cancellation and two-path cancellation schemes. The superiority of OFDM-IM over classical OFDM in the presence of ICI is shown by computer simulations. The authors of [371] calculated the signal-to-interference ratio of the SIM-OFDM scheme in Doppler spread environments. Recently, the problem of optimal tone spacing is investigated in [372] to minimize the effects of ICI and ISI under mobility and multi-path conditions. The authors showed that the optimal value of tone spacing can improve the performance of the OFDM-IM system. Even more recently, a linear processing-based ICI cancellation method is applied to OFDM-IM in [373] for rapidly time-varying channels. Finally, the recent studies of [374]–[376] investigated the error performance of OFDM-IM in the presence of CFO and reported improvements compared to classical OFDM.

The (ergodic) achievable rate of OFDM-IM is investigated in [361] and, in order to maximize the achievable rate of OFDM-IM, the optimal subcarrier activation strategy is designed (see Subsection VIII-D for details). The authors of [362] investigated subcarrier allocation (SA) problem for

OFDM-IM and two dynamic SA algorithms are proposed by utilizing CSI at the OFDM-IM transmitter. Considerable improvements are reported compared to ordinary OFDM-IM, which does not require CSI at the transmitter. A tight approximation for the BER of OFDM-IM is presented in [363] in the presence of imperfect and perfect detection of active indices. BER expressions for IM and ordinary modulation bits are also obtained in this study. A selective OFDM-IM scheme, which opportunistically activates a small subset of sub-carriers based on partial CSI and applies IM to these activated subcarriers, is proposed in [364]. Error propagation performance of this system is evaluated using moment generating function approach for various fading distributions. Finally, the author of [365] dealt with the effect of subcarrier activation ratio on the error performance of OFDM-IM and provided tools for the selection of suitable system parameters.

In order to reduce the cost of its practical implementation, low-complexity near/sub-optimal detection methods are also proposed for OFDM-IM. A new low-complexity greedy detection algorithm, which provides a close BER performance to the ML detector, is proposed for OFDM-IM in [377] and [378]. Similar to the LLR detector, this detector determines the active subcarriers first, and then, it estimates the corresponding data symbols. The main difference lies in the first step, namely the determination of the active subcarriers, where the LLR detector resorts to the LLR value whereas this detector calculates the subcarrier power. The author of [379] proposed a low-complexity OFDM-IM scheme by exploiting all possible SAPs for the transmission of data to remove the possibility of detecting an invalid SAP. A simple detector that identifies the active subcarriers as the ones with the highest power, is also proposed therein. Recently, the performance of OFDM-IM with the low-complexity detector of [377] is investigated in [380] for two-wave with diffuse power fading channels, which correspond to moderate, severe and worse than Rayleigh fading conditions that are foreseen for future D2D communication systems. Finally, the performance of OFDM-IM is investigated under a MRC diversity reception setup in [381].

The studies of [382]–[384] investigated the coded realization of OFDM-IM. More specifically, [382] considered the integration of OFDM-IM with convolutional, turbo and repetition codes using soft detection. The authors of [383] considered block Markov superposition transmission coding for OFDM-IM and reported improved error performance compared to classical OFDM for highly mobile environments. The performance of low density parity check (LDPC) coded OFDM-IM is studied for in-vehicle power line communications (PLC). The authors showed that OFDM-IM can effectively overcome the impulse noise occurring in-vehicle PLC and it can provide a good trade-off between the spectral and energy efficiency for these type of systems. Finally, in the most recent study of [385], a channel coding aided OFDM-IM with transmit diversity (OFDM-IM-TD) scheme is proposed to improve the BER performance of OFDM-IM. In this scheme, channel coding is employed for

ordinary modulation bits only, while the same set of active subcarriers are used for the clusters of subcarriers within a subblock to obtain transmit diversity. It has been shown that this scheme can provide better index error rate compared to CI-OFDM-IM.

Owing to the inherent advantages of OFDM-IM, the studies of [341] and [386]–[393] focused on the application of OFDM-IM to specific communication systems (see Subsection VIII.A for more details). For instance, the authors of [341] and [386]–[390] considered vehicular communication systems and reported promising results in terms of BER and maximum achievable rate. More recently, the studies of [391] and [392] showed that OFDM-IM is also well-suited for UWA communication systems. The authors also developed an ICI self-cancellation scheme for this particular implementation case. Finally, the authors of [393] explored the potential of OFDM-IM for low power, low cost and low data rate IoT devices.

The studies of [43], [45], [48], [52], [307], and [394]–[402] explored the potential of OFDM-IM for MIMO systems and reported promising results compared to traditional MIMO-OFDM schemes. Readers are referred to Subsection VII-E for the details.

The concept of OFDM-IM has been also considered for VLC. The first attempt was made in [56] by the optical OFDM-IM (O-OFDM-IM) scheme, which uses LEDs and PDs for transmission through OW channels. In this scheme, similar to OFDM-IM, IM techniques are implemented to complex OFDM frames first, and then, Hermitian symmetry is applied to obtain real-valued OFDM frames after IFFT operation. At the last step, the real-valued but bipolar OFDM frames are converted to unipolar by asymmetric clipping or DC biasing and transmitted through the optical multi-tap channel. It is shown by computer simulations that O-OFDM-IM appears as an alternative to classical optical OFDM solutions for VLC systems. An enhanced transmission scheme termed subcarrier index-power modulated optical OFDM (SIPM-O-OFDM) is proposed in [58] and [403]. In this scheme, the combination of subcarrier indices and subcarrier powers are used to convey information, i.e., the specific set of subcarriers operates at low and high power according to the information bits. Similar to the DM-OFDM scheme, all subcarriers are activated in SIPM-O-OFDM to obtain an increased capacity and promising results are reported compared to optical OFDM. In [404], the same research group introduced the concept of non-orthogonal multiple access (NOMA) [426] for SIPM-O-OFDM to more effectively use high power subcarriers and obtained a considerable capacity improvement compared to SIPM-O-OFDM. Finally, the scheme of SIPM-O-OFDM is generalized into its multi-level version in [405] to further improve the data rate of the system by using IM in a more effective way.

The recent interesting advances in OFDM-IM technologies have also triggered some new studies on FQAM [406]–[410], which can be considered as an extreme case of the OFDM-IM scheme with a single subblock and a single activated

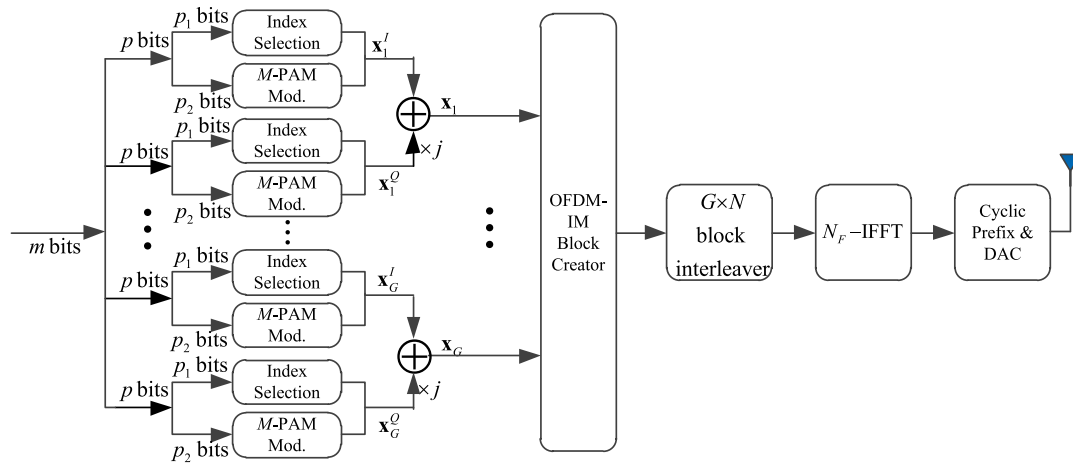


FIGURE 18. Block diagram of the OFDM-I/Q-IM transmitter.

subcarrier [349], and promising results are reported for the downlink of OFDMA cellular networks.

The encouraging potential of the OFDM-IM framework has inspired the researchers to integrate the IM concept into other communication systems. As an example, the authors of [18] proposed a code IM-spread spectrum (CIM-SS) scheme, which uses the spreading Walsh codes themselves to carry additional information, i.e., it considers the dimension of Walsh code indices for data mapping. It has been shown that the CIM-SS scheme provides a better performance than classical direct sequence SS scheme. More recently, the same authors introduced the generalized CIM-SS (GCIM-SS) scheme in [26] by employing multiple orthogonal Walsh codes at the transmitter. In [411], the authors combined CIM-SS scheme with differential chaos shift keying. Finally, the authors of [412] compared the energy efficiency, complexity and the BER performance of the SM and CIM schemes.

Another direction for the implementation of IM was precoder IM (PIM), which considered the indices of precoding matrices selected from a set of pre-determined pseudo-random phase precoding matrices [16], [413]. The authors also proposed a precoder index modulation SM (PIM-SM) scheme by combining PIM and SM principles to convey information by both antenna and precoding matrix indices. More recently, the capacity of PIM is investigated in [414] and a low-complexity message passing-based detection algorithm is proposed to overcome the exponential complexity of PIM detection. Subcarrier IM is considered for precoded OFDM to exploit a path diversity gain in [415] and [416]. A CS-based detector is proposed for this precoded OFDM-IM scheme in [415], while the case of highly correlated subcarriers is investigated in [416]. In [417] and [418], IM precoded OFDM is generalized to multiple-access systems and a scheme called sparse index multiple access is proposed as an alternative to MC-CDMA. Similarly, a CS-based low-complexity detector is proposed to detect the signals of multiple users.

Inspired by the OFDM-IM framework, IM techniques have been also implemented for other emerging multi-carrier and single-carrier systems. In [419], IM is applied to single-carrier interleaved frequency division multiple access (SC-IFDMA) systems and improvements are shown compared to conventional SC-IFDMA. In [54], the scheme of GFDM with IM (GFDM-IM) is proposed by combining GFDM, which is a promising non-orthogonal multi-carrier transmission scheme for 5G and beyond wireless networks, and IM. The authors reported improved BER performance compared to ordinary GFDM and OFDM-IM. The same authors also proposed SM-GFDM scheme in [420] to combine the advantages of GFDM to MIMO systems without increasing the system complexity. Recently, the authors of [46] considered IM for both space and time domains and proposed the scheme of space-time IM (STIM) for cyclic-prefixed single-carrier systems operating over frequency-selective fading channels. Finally, the studies of [50], [60], [62], and [64] respectively combined IM techniques with FBMC, discrete cosine transform based OFDM (DCT-OFDM), single-carrier frequency domain equalization (SC-FDE) and multi-carrier differential chaos shift keying systems (MC-DCSK), and proposed promising IM-based schemes (these four schemes are called FBMC-IM, DCT-OFDM-IM, SC-IM and carrier index DCSK (CI-DCSK), respectively) for future wireless communication systems compared to their traditional counterparts.

Remark: The most recent studies of [421]–[424] considered the radical use of IM techniques for channel division multiple access systems, active device identification in compressive random access systems, storing information in flash memories and parallel Gaussian channels, respectively.

B. OFDM IN-PHASE/QUADRATURE IM

OFDM-I/Q-IM is recently proposed in [20] and [355] to improve the spectral efficiency and BER performance of OFDM-IM, by applying IM independently on the IQ components of the OFDM signal.

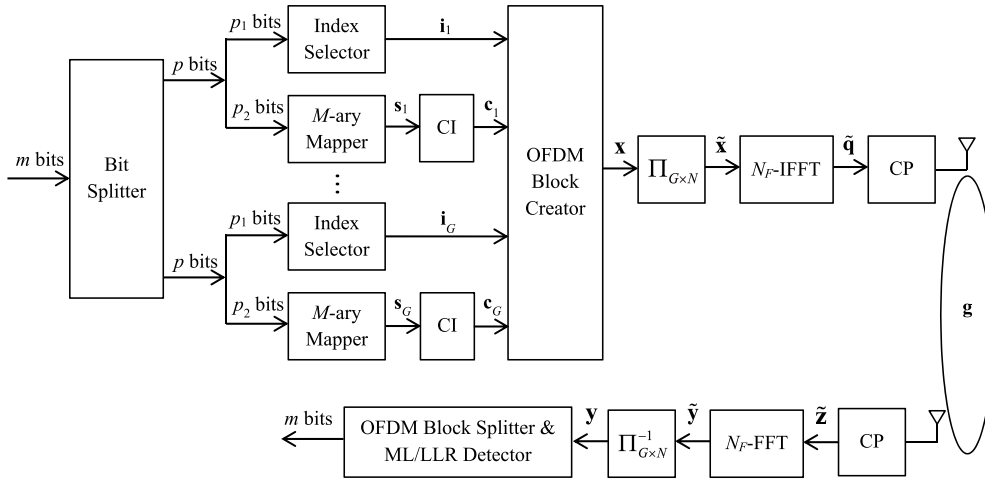


FIGURE 19. Transceiver Structure of the CI-OFDM-IM Scheme (Reproduced from [35] with permission).

The block diagram of the OFDM-I/Q-IM transmitter is illustrated in Fig. 18. OFDM-I/Q-IM divides the OFDM block with N_F subcarriers and M^2 -QAM constellation into G smaller subblocks, each containing $N = N_F/G$ subcarriers to perform IM independently in both IQ dimensions. For each subblock, $\lfloor \log_2 \binom{N}{K} \rfloor$ bits are used to activate K out of N subcarriers to carry the IQ components of K independent M^2 -QAM symbols, which can be implemented by a look-up table or the combinatorial method [8]. Unlike OFDM-IM, due to independent IM, the IQ components of an M^2 -QAM symbol in OFDM-I/Q-IM may be distributed into two different subcarriers. Under the same parameter setting of (N, K, M^2) ,

$$\log_2 \left[\binom{N}{K} \right] + K \log_2 M^2 \quad (9)$$

bits can be transmitted per subblock for OFDM-IM, while the amount increases to

$$2 \log_2 \left[\binom{N}{K} \right] + K \log_2 M^2 \quad (10)$$

for OFDM-I/Q-IM. Clearly, OFDM-I/Q-IM doubles the number of IM bits by extending the IM to include the IQ dimensions. After concatenating G OFDM-IM subblocks, a $G \times N$ block interleaver is employed to benefit from uncorrelated fading within the IM subblock.

The OFDM-I/Q-IM receiver needs to detect both the indices of the active subcarriers and the corresponding modulated symbols. The optimal ML detector, which performs a brute-force search over all possible SAPs and constellation points, has a high computational complexity. To achieve near-optimal performance with single-symbol decoding complexity, two low-complexity detectors, including the LLR detector [355] and the low-complexity ML detector [20], are proposed for OFDM-I/Q-IM. While both detectors exhibit approximately the same BER performance, they differ in the determination of the indices of the active subcarriers. Specifically, the LLR detector should compare the LLR values that

depend on the SNR, while the low-complexity ML detector should compare the ML metrics that are irrelevant to SNR.

The exact coding gains achieved by OFDM-I/Q-IM over classical OFDM and OFDM-IM have been theoretically analyzed in [20], which are shown to be contributed by two parts: one is the probability of each subcarrier to be selected as active, and the other is the ratio of the noise variances in the frequency domain. The coding gains achieved by OFDM-I/Q-IM over OFDM and OFDM-IM are reported as 6 dB and 2.5 dB, respectively, at the same spectral efficiency of 2 bps/Hz.

C. COORDINATE INTERLEAVED OFDM-IM

Coordinate interleaved OFDM-IM (CI-OFDM-IM) scheme is proposed in [35] to exploit the diversity potential of the plain OFDM-IM scheme by integrating the principle of CIODs [427] to OFDM-IM. CIODs are very powerful STBCs that allow single-symbol ML detection along with an increased spectral efficiency compared to ordinary orthogonal STBCs [428]–[430]. The main idea of CI-OFDM-IM is to distribute the real and imaginary parts of a complex data symbol over two active subcarriers of the OFDM-IM scheme to obtain additional diversity gain. With this purpose, the following generic 2×2 CIOD is considered:

$$\begin{bmatrix} s_{1,R} + js_{2,I} & 0 \\ 0 & s_{2,R} + js_{1,I} \end{bmatrix} \quad (11)$$

where the columns and the rows correspond to time slots and transmit antennas, respectively and, s_1 and s_2 are two complex data symbols drawn from a rotated M -QAM constellation. Block diagram of the CI-OFDM-IM transceiver is shown in Fig. 19. As seen from Fig. 19, the transmitter of the CI-OFDM-IM scheme is highly similar to that of OFDM-IM with a main bit splitting block along with index selector and M -ary mapper blocks for each OFDM-IM subblock g , where $g = 1, 2, \dots, G$ and G is the number of subblocks; however, it differs from the OFDM-IM scheme with the inclusion of the

CI block for each subblock, which processes the input data symbol vector (of subblock g) $\mathbf{s}_g = [s_1 s_2 \cdots s_K]^T$ to obtain the following interleaved data vector according to the CIOD principle of (11):

$$\mathbf{c}_g = \begin{bmatrix} s_{1,R} + js_{2,I} \\ s_{2,R} + js_{1,I} \\ s_{3,R} + js_{4,I} \\ s_{4,R} + js_{3,I} \\ \vdots \\ s_{K-1,R} + js_{K,I} \\ s_{K,R} + js_{K-1,I} \end{bmatrix} \quad (12)$$

Finally, the elements of \mathbf{c}_g are transmitted over the selected K active indices of subblock g , which are given by \mathbf{i}_g . In Table 7, we compare the subblock structures of OFDM-IM and CI-OFDM-IM schemes for a subblock size of $N = 4$ with $K = 2$. As seen from Table 7, the real and imaginary parts of two complex data symbols are separated and transmitted over two active subcarriers in CI-OFDM-IM. After the formation of the main OFDM block, block type subcarrier interleaving and classical OFDM procedures are applied before the transmission.

TABLE 7. Subblock structures of OFDM-IM and CI-OFDM-IM schemes for $N = 4$ and $K = 2$ (look-up table method).

IM bits	OFDM-IM Subblocks	CI-OFDM-IM Subblocks
[0 0]	$s_1 \ 0 \ s_2 \ 0$	$s_{1,R} + js_{2,I} \ 0 \ s_{2,R} + js_{1,I} \ 0$
[0 1]	$0 \ s_1 \ 0 \ s_2$	$0 \ s_{1,R} + js_{2,I} \ 0 \ s_{2,R} + js_{1,I}$
[1 0]	$s_1 \ 0 \ 0 \ s_2$	$s_{1,R} + js_{2,I} \ 0 \ 0 \ s_{2,R} + js_{1,I}$
[1 1]	$0 \ s_1 \ s_2 \ 0$	$0 \ s_{1,R} + js_{2,I} \ s_{2,R} + js_{1,I} \ 0$

Three types of detection algorithms are proposed for the CI-OFDM-IM scheme. The brute-force ML detector searches for all possible subblock realizations and has a complexity order of $\sim \mathcal{O}(M^K)$, while the reduced complexity ML detector benefits from the orthogonality (symbol-by-symbol decoding property) of CIODs and has a complexity order of $\sim \mathcal{O}(KM)$. However, both of these detectors become infeasible for increasing subblock sizes, as a result, an LLR calculation-based detector, which has a complexity order of $\sim \mathcal{O}(M^2)$, is proposed. The LLR detector considers all possible elements of the virtual M^2 -QAM constellation formed by $s_{1,R} + js_{2,I}$ for all possible s_1 and s_2 in order to calculate a probabilistic measure on the active status of each subcarrier.

D. DUAL-MODE OFDM

One of the main disadvantages of the plain OFDM-IM scheme is its limited spectral efficiency due to the inactive subcarriers used for IM, which do not carry information through ordinary modulation. As a result, the BER advantage of OFDM-IM over classical OFDM diminishes with increasing spectral efficiency values. This can be understood by clearly examining (8), which shows that the percentage of IM

bits reduces by increasing modulation orders. As an example, to achieve the same spectral efficiency as that of classical OFDM, one can set $K = N - 1$ and $N = M$, for which the percentage of IM bits compared to the total number of bits becomes $\frac{100}{M}\%$ and this limits the inherent advantages of OFDM-IM since the bits transmitted with IM have a higher order protection than ordinary modulation bits. In order to transmit a maximum number of bits with IM, one can select $K = N/2$; however, in this case, the spectral efficiency of OFDM-IM cannot compete with that of classical OFDM for the same modulation order in most cases.

The concept of DM-OFDM is a clever solution to overcome the spectral efficiency limitation of OFDM-IM by activating all subcarriers while still exploiting IM [31]. In DM-OFDM scheme, all subcarriers are modulated and the index information is carried by the signal constellations assigned to the subcarrier groups. Two distinguishable signal constellations, a primary and a secondary constellation, are determined to transmit the data symbols from the active and inactive subcarriers of the OFDM-IM scheme, respectively. In other words, OFDM-IM becomes the special case of DM-OFDM if the secondary constellation contains a single element that is zero. Denoting the sizes of the primary and secondary constellations with M_1 and M_2 , respectively, for each DM-OFDM block,

$$\begin{aligned} \tilde{m} &= \tilde{p}G \\ &= \left(\left\lceil \log_2 \binom{N}{K} \right\rceil + K \log_2 M_1 + (N - K) \log_2 M_2 \right) G \end{aligned} \quad (13)$$

TABLE 8. Subblock Structures of OFDM-IM and DM-OFDM schemes for $N = 4$ and $K = 2$.

IM bits	OFDM-IM Subblocks	DM-OFDM Subblocks
[0 0]	$s_1 \ 0 \ s_2 \ 0$	$s_1 \ \tilde{s}_1 \ s_2 \ \tilde{s}_2$
[0 1]	$0 \ s_1 \ 0 \ s_2$	$\tilde{s}_1 \ s_1 \ \tilde{s}_2 \ s_2$
[1 0]	$s_1 \ 0 \ 0 \ s_2$	$s_1 \ \tilde{s}_1 \ \tilde{s}_2 \ s_2$
[1 1]	$0 \ s_1 \ s_2 \ 0$	$\tilde{s}_1 \ s_1 \ s_2 \ \tilde{s}_2$

bits can be transmitted, where \tilde{p} is the number of bits per DM-OFDM subblock and G is the number of DM-OFDM subblocks, N is the number of subcarriers in a subblock similar to OFDM-IM with $N = N_F/G$ and K is the number of subcarriers modulated by considering the primary constellation. It should be noted that by letting $M_2 = 1$ in (13), that is, by not modulating the second group of subcarriers and leaving them empty, the number of bits transmitted in a DM-OFDM block becomes the same as that of OFDM-IM given in (8). In Table 8, subblock structures of OFDM-IM and DM-OFDM schemes are given for $N = 4$ and $K = 2$, where s_1 and s_2 are the elements of a primary constellation \mathcal{S} while \tilde{s}_1 and \tilde{s}_2 are the elements of a secondary constellation, which can be easily obtained by the rotation of the primary

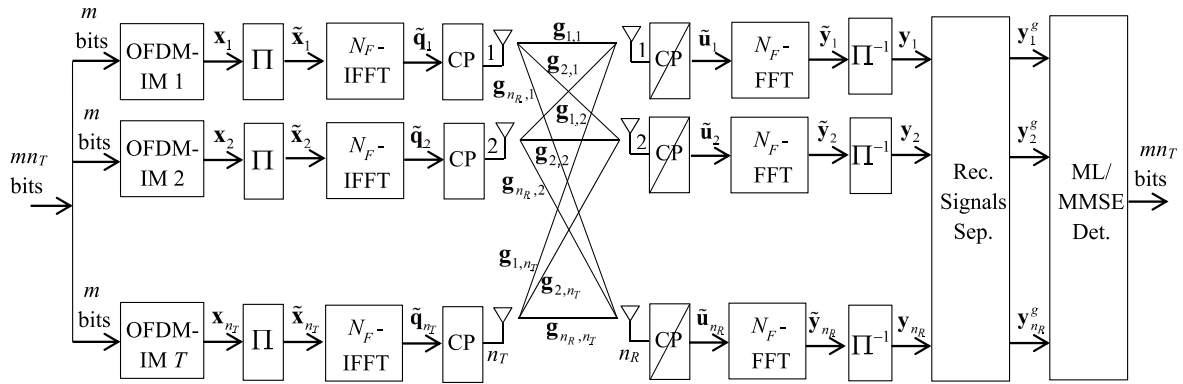


FIGURE 20. Transceiver structure of $n_T \times n_R$ MIMO-OFDM-IM scheme (Reproduced from [48] with permission).

constellation as $\mathcal{S}e^{j\theta}$. As seen from Table 8, DM-OFDM activates all of the available subcarriers and obtains an increase of $2 \log_2 M$ bits per subblock compared to OFDM-IM for the same constellation size ($M = M_1 = M_2$).

It has been shown by computer simulations that DM-OFDM scheme can achieve a better BER performance than other OFDM-IM variants by using a near-optimal LLR calculation-based detector. Recently, a generalized DM-OFDM (GDM-OFDM) scheme is proposed [37]. In this scheme, the number of subcarriers modulated by the primary and secondary constellations also changes according to the information bits to further improve the spectral efficiency with a marginal performance loss. A low-complexity LLR calculation-based detector is also proposed for this generalized DM-OFDM scheme and the trade-off it provides between the spectral efficiency and error performance has been demonstrated by computer simulations. Even more recently, the scheme of multiple-mode OFDM-IM (MM-OFDM-IM) is proposed in [42] by using the full permutation of modes to convey a higher number of IM bits.

E. OFDM-IM SOLUTIONS FOR MIMO SYSTEMS

MIMO friendliness has become one of the most important requirements of new generation waveform designs due to the continuously increasing demand for higher data rates as well as QoS. In other words, a competitive waveform must be easily adapted to MIMO setups while providing reliable error performance with a reasonable encoding/decoding complexity. The scheme of MIMO-OFDM-IM has been proposed in [48] by modifying the plain SISO-OFDM-IM framework to operate over MIMO frequency selective channels [431]. The transceiver structure of the MIMO-OFDM-IM scheme is shown in Fig. 20. As seen from Fig. 20, the transmitter of the MIMO-OFDM-IM scheme is obtained by parallel concatenation of n_T OFDM-IM transmitters. From this perspective, MIMO-OFDM-IM can be regarded as the combination of SMX (V-BLAST) and OFDM-IM schemes. Consequently, the spectral efficiency of MIMO-OFDM-IM becomes n_T times as that of plain OFDM-IM.

The transmitter of MIMO-OFDM-IM accepts mn_T bits at the input, where m is the number of bits transmitted by an OFDM-IM block (frame). The resulting OFDM-IM blocks \mathbf{x}_t are then interleaved to obtain $\tilde{\mathbf{x}}_t$ for $t = 1, 2, \dots, n_T$ and transmitted after N_F -IFFT operation and CP insertion. At the receiver, the simultaneously transmitted OFDM-IM frames are separated by employing different type of detectors. First, CP removal is performed at each branch of the receiver followed by N_F -FFT and block deinterleaving. Then, the received signals \mathbf{y}_r , $r = 1, 2, \dots, n_R$ are separated considering the subblocks of the OFDM-IM blocks as \mathbf{y}_r^g for $r = 1, 2, \dots, n_R$ and $g = 1, 2, \dots, G$. The optimum but high complexity ML detector searches for all subblock realizations of n_T transmit antennas jointly. On the other hand, using a low-complexity MMSE detection and LLR calculation-based detector, which performs sequential MMSE filtering to perform the detection of OFDM-IM subblocks at each branch of the transmitter and considers the statistics of the MMSE filtered received signals to improve the error performance, demodulation of MIMO-OFDM-IM can be performed. It has been demonstrated via extensive computer simulations that MIMO-OFDM-IM can be a strong alternative to classical MIMO-OFDM due to its improved BER performance and flexible system design. It should be noted that unlike other waveforms such as GFDM or FBMC, OFDM-IM is a more MIMO-friendly transmission technique and also provides improvements in BER performance over classical MIMO-OFDM.

In Fig. 21, we provide the uncoded BER performance curves of MIMO-OFDM-IM and classical V-BLAST type MIMO-OFDM schemes for three different MIMO configurations (2×2 , 4×4 and 8×8), where the same spectral efficiency values are obtained for both schemes. As observed from Fig. 21, to reach a target BER value, significant signal-to-noise ratio (SNR) improvements can be obtained by the MIMO-OFDM-IM scheme compared to classical MIMO-OFDM.

It should be noted that the principle of MIMO-OFDM-IM is also introduced independently in [395] and the performance of the conventional MMSE detector is investigated

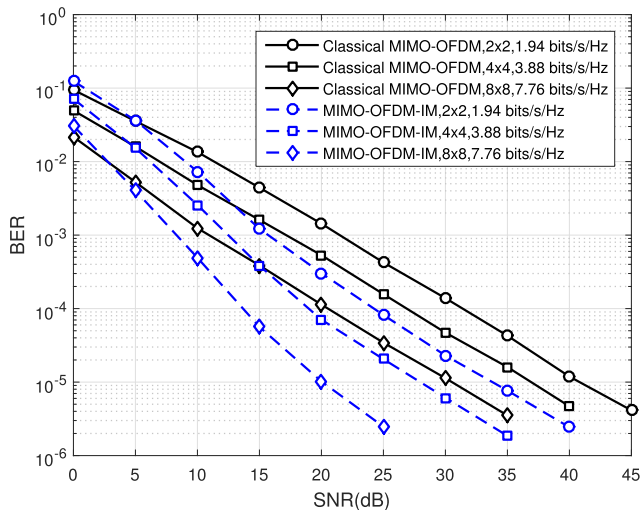


FIGURE 21. BER performance of MIMO-OFDM-IM and classical MIMO-OFDM schemes for three $n_T \times n_R$ MIMO configurations. OFDM system parameters: $M = 2$, $N = 4$, $K = 2$, $N_F = 512$, CP length = 16, frequency-selective Rayleigh fading channel with 10 taps, uniform power delay profile, successive MMSE detection (Reproduced from [48] with permission).

with computer simulations. In [307] and [394], the author shed light on the implementation and error performance analysis of MIMO-OFDM-IM scheme and proposed different type of detectors, i.e., ML, near-ML, simple MMSE and ordered successive interference cancellation-based MMSE detectors of MIMO-OFDM-IM are proposed, and their theoretical error performance is investigated. These two studies clearly demonstrated the interesting trade-off offered by MIMO-OFDM-IM between error performance and spectral efficiency. More recently, low-complexity and near optimal detection algorithms, based on the sequential Monte Carlo theory, are proposed for emerging MIMO-OFDM-IM schemes in [396] and [397].

Some other studies that combine OFDM-IM and MIMO transmission principles, have been also performed in recent times. Generalized space-frequency index modulation (GSFIM) [52] combines OFDM-IM concept with GSM principle by exploiting both spatial and frequency (subcarrier) domains for IM. It has been shown that GSFIM scheme can also provide improvements over MIMO-OFDM in terms of achievable data rate and BER performance with ML detection for lower constellations such as BPSK and QPSK. The low complexity detection problem of high-dimensional GSFIM schemes is investigated in [398] and a detection algorithm based on multistage message passing is proposed. More recently, a space-frequency coded index modulation (SFC-IM) scheme is proposed to obtain a diversity gain for MIMO-OFDM-IM [399]. By combining space-frequency coding with MIMO-OFDM-IM, the authors obtained a transmit diversity order of two and a linear-complexity ML receiver is also constructed for this new scheme. In [400], the authors investigated multiuser detection of the massive MIMO-OFDM-IM system with imperfect CSI considering

low-complexity generalized approximate message passing algorithm for uplink transmission. It has been shown by the authors that the massive MIMO-OFDM-IM system can improve the energy efficiency without sacrificing the spectral efficiency and error performance compared to classical massive MIMO-OFDM scheme. In [401], the same authors considered uplink MU implementation of MIMO-OFDM-IM and showed that improvements can be obtained in PAPR, energy efficiency and BER performance in comparison to classical MU-OFDM system. In [402], the performance of MIMO-OFDM-IM is investigated for rapidly time-varying (very high mobility) channels. The authors considered a circular shift-based activation pattern to avoid inter-antenna interference and ICI simultaneously. Recently, a scheme called multi-space-frequency STSK (MSF-STSK) is proposed in [43] by combining GSM, OFDM-IM and STSK principles for mmWave communications. Even more recently, a novel MIMO-GFDM system, which combines GFDM with space and frequency IM (SFIM), is proposed in [45]. In this GFDM-SFIM scheme, dual-mode IM principle of [31] is integrated to SM-based MIMO-GFDM systems to further improve their BER performance.

VIII. PRACTICAL ISSUES FOR OFDM-IM

In this section, we investigate practical implementation issues for OFDM-IM and demonstrate its possible application areas. More specifically, we focus our attention into vehicular and UWA communications systems and investigate important issues such as ICI, PAPR and achievable rate, which are of critical importance for practical implementation scenarios.

A. APPLICATIONS TO VEHICULAR AND UNDERWATER ACOUSTIC COMMUNICATIONS

The concept of activating partial subcarriers during the transmission of an OFDM symbol endows OFDM-IM and its variants with potential of adaptation to high mobility scenarios, such as V2X and UWA communications, since the power of the Doppler induced ICI, which scales with the number of active subcarriers, will be significantly reduced.

The first attempt on applying OFDM-IM to V2X communications was made in [341], where great benefits of OFDM-IM with interleaved grouping in terms of BER and achievable rate performance are revealed via analytical and simulated comparisons with classical OFDM and OFDM-IM with localized grouping. OFDM-I/Q-IM has been also tested over V2X channels in [389]. Thanks to the increased number of IM bits, OFDM-I/Q-IM can operate with a smaller group of subcarriers and modulation order compared with OFDM-IM at the same spectral efficiency, and therefore, it even boosts the BER performance. The authors of [386] investigated the performance of OFDM-IM with all SAPs encoded in a V2X scenario and demonstrated that OFDM-IM can be considered as a strong candidate for the transmission technique of the vehicular communications standard.

The first application of OFDM-IM to UWA communications was reported in [391]. Noticing that the power leakage

from the active subcarriers to the inactive ones because of ICI significantly increases the possibility of erroneous detection of subcarrier states, the authors of [391] proposed a solution by integrating the well-known ICI self-cancellation techniques into the OFDM-IM framework. With a simple modification, OFDM-IM is shown to be very effective in ICI mitigation by both computer simulations and sea experiments. The integration idea of [391] is generalized in [392], where both the one-path and two-path implementations are demonstrated. In addition, a hybrid OFDM-IM system with improved spectral efficiency, which introduces an additional bit to indicate the OFDM-IM mode or the classical OFDM mode, is proposed.

B. INTER-CARRIER INTERFERENCE

Conventional OFDM is sensitive to ICI due to CFO caused by the Doppler shift and local oscillators' mismatch between the transceiver. In the current literature, OFDM-IM is considered to offer robustness to ICI [367]. In [366], OFDM-IM is firstly considered in optical communications due to its tolerance to ICI caused by the nonlinearity in the fiber. In [371], the signal-to-interference ratio of OFDM-IM is analyzed and compared to OFDM in presence of CFO. Furthermore, the BER performance of OFDM-IM with CFO is analyzed in [374], to theoretically prove the performance advantage of OFDM-IM in case of ICI. Specifically, it is shown in [374] that interleaved OFDM-IM can achieve much lower error floor in case of different CFO values compared to traditional OFDM. In addition, the optimal subcarrier spacing for minimizing the effects of ICI is investigated in [372], which gave another way for system design to further restrain the influence of ICI.

In spite of its advantages in ICI resistance, OFDM-IM can be combined with ICI cancellation schemes to further improve the system performance. For example, ICI self-constellation schemes are explored for OFDM-IM in [370] and [375], for offering considerable performance gain in the case of CFO. Recently, linear processing-based ICI cancellation method [373] and Discrete Wavelet Transform (DWT)-based OFDM-IM [376] are developed for the scene of high mobility channels, respectively.

C. PEAK-TO-AVERAGE POWER RATIO

Until now, the high PAPR of the transmit signal has remained an open problem for OFDM-based transmission systems. Thanks to the sparsity of the active subcarriers, we may construct ideal transmit waveform with lower PAPR for the OFDM-IM system. According to current studies in this issue, the most important factor, which affects the PAPR, is the ratio of active subcarriers in the OFDM-IM system. On the one hand, when the number of active subcarriers is relatively high, OFDM-IM will exhibit similar PAPR as conventional OFDM, as studied in [368]. This conclusion is similar to the former studies in [432], which analyzed the PAPR of the OFDMA system. On the other hand, with the decreasing number of active subcarriers, the PAPR of OFDM-IM

systems will be effectively reduced compared to traditional OFDM, as described in [351], [352], and [367]. Specifically, the analysis for the PAPR distribution in case of sparse active subcarriers is given in the former studies as [433]. In general, following the theoretical proof of [433], we could construct optimized transmit signals with lower PAPR for OFDM-IM, by increasing the sparsity of the active subcarriers though a careful design.

Furthermore, substantial research efforts have been invested in reducing the PAPR of conventional OFDM as summarized in [434]. In OFDM-IM, the introduction of unique idle subcarriers will give an additional degree of freedom to minimize the PAPR of the transmit signals. For example, the combination of active constellation extension (ACE) [435] and idle subcarriers is developed in [369], to obtain a better tradeoff between PAPR and BER performance for OFDM-IM.

D. ACHIEVABLE RATE

In [361], assuming slowly varying Rayleigh fading channels, the achievable rates of OFDM-IM systems under both finite constellation input and Gaussian input are analyzed. It is revealed that grouping the subcarriers in an interleaved manner harvests more frequency diversity gain than in a localized manner for OFDM-IM and the superiority of OFDM-IM over classical OFDM is significant for small M , while becoming less apparent and even diminishing as M grows, where M is the cardinality of the signal constellation. Moreover, there exists an optimal non-zero number of inactive subcarriers, typically 1 or 2, in the sense of maximizing the achievable rate for a given SNR. On the effects of the modulation type, it is found that QAM is always more favorable than PSK in terms of the achievable rate, whereas the superiority of OFDM-IM over classical OFDM is greater for PSK than for QAM. With Gaussian input, differently, the achievable rate of OFDM-IM monotonically increases upon decreasing the number of inactive subcarriers, and it is upper bounded by that of classical OFDM.

Under finite constellation input, the achievable rates of OFDM-IM and classical OFDM systems over V2X channels are evaluated and compared in [341]. Unlike the phenomena in slowly varying Rayleigh fading channels, classical OFDM outperforms OFDM-IM with localized grouping, while OFDM-IM with interleaved grouping maintains the superiority over classical OFDM at high SNR. In [368], the overall achievable rate of OFDM-IM systems under Gaussian input is divided into two parts, corresponding to the classic APSK symbols and subcarrier IM symbols, respectively. Focusing on the second part only, it is observed that OFDM-IM with fewer activated subcarriers outperforms that with more activated subcarriers, when they converge to the same throughput at high SNR.

IX. CONCLUSIONS AND FUTURE WORKS

The wireless community is a few steps away from the implementation of 5G wireless networks, which are expected

to provide ubiquitous communication capabilities. In this article, we have provided a new vision for the PHY configuration of 5G and beyond wireless networks by taking a different approach than the traditional solutions widely considered in previous communication systems of the past half century. This vision has been created by IM, which considers new dimensions, such as the indices of transmit antennas of a MIMO system, subcarriers of an OFDM system or RF mirrors of an RA, for the transmission of digital information through on/off keying of the building blocks of the considered communication systems. IM is an up and coming digital modulation concept that has a great potential for next-generation wireless communication systems due to spectrum/energy-efficient as well as low-complexity solutions it offers for emerging single/multi-carrier, massive single/multi-user MIMO, cooperative communication, M2M, V2X, D2D, UWA, OW communication, FD and spectrum sharing systems. Although plain IM schemes may have the difficulty to compete with traditional methods such as V-BLAST or STC in terms of spectral efficiency or reliability, IM-based schemes have an undeniable potential for future wireless networks due to their more flexible system structure and other potential advantages such as energy efficiency and low-complexity.

In this article, we have reviewed the basic principles, advantages/disadvantages, the most recent and promising developments and possible implementation scenarios of SM, CM (MBM/RA) and OFDM-IM systems, which come forward as three promising forms of the IM concept. With a comprehensive review, we have demonstrated that IM schemes can offer interesting trade-offs in terms of error performance, complexity and spectral efficiency; as a result, we conclude that they can be considered as possible candidates for next-generation (5G and beyond) wireless communication networks. Among these three promising IM forms, SM and OFDM-IM can be implemented with a low-cost transceiver structure, while CM may require a more complicated transmitter due to the employment of RAs. However, it can achieve the same spectral efficiency as that of SM by using considerably lower number of transmit antennas. On the other hand, OFDM-IM is an emerging multi-carrier transmission scheme and it can be also combined with SM and its variants.

However, there are still interesting as well as challenging research problems need to be solved in order to further improve the efficiency of IM schemes. These research challenges can be summarized as follows:

- The design of novel generalized/enhanced/differential IM schemes with higher spectral and/or energy efficiency, lower transceiver complexity and better error performance.
- The optimization and integration of IM techniques to cooperative, massive MU-MIMO, FD, spectrum sharing, visible light, M2M, V2X, D2D communication systems to be employed in 5G and beyond wireless networks and the design of novel uplink/downlink/point-to-point transmission protocols.

- Exploration of totally new digital communication schemes for the application of IM techniques.
- The investigation of the potential of IM techniques via practical implementation testbeds and under real-world conditions.

More specifically, QSM and ESM schemes have attracted the attention of the community in the past two years by exploiting the spatial domain IM in a more effective way than the previous SM-based schemes. Differential IM schemes have also shown a great potential for non-coherent communication systems. We believe that there are still challenging research problems to solve for the generalization and optimization of these SM variants as well as for the design of low-complexity receiver structures. Regarding applications and practical issues for SM, although several studies have appeared in the area of cooperative networks, there are still many research directions to follow for FD/CR networks, massive MU-MIMO and OW systems. RA-based CM is a relatively new variant of IM and therefore, it provides a completely new dimension for the exploration of new IM-based schemes. Although early attempts have been made to combine CM with SM variants and space-time coding, interesting research problems such as enhancement and generalization of CM schemes, suboptimal detection methods, analyses for channel estimation errors, correlated channel states as well as MIMO fading channels remain to be investigated. For the case of multi-carrier communications, several promising OFDM-IM variants have been proposed in the past two years and this trend is continuing as of today. Considering that the design of novel waveforms for 5G and beyond wireless networks has been a very hot topic in the past several years, IM provides a new degrees of freedom for not only OFDM schemes, but also for other waveforms such as GFDM and FBMC. Furthermore, IM-based schemes have the flexibility that is required for vast 5G applications and can be further explored for potential applications. We believe that more effective OFDM-IM variants, in terms of spectral efficiency and/or error performance, can be explored for not only SISO/SIMO systems but also for MIMO systems. IM can be also considered for totally new digital communication systems that rely on traditional methods for data transmission.

In light of the comprehensive literature review provided by this article on IM technologies, we conclude that the concept of IM can be considered for almost every communication system that has the ability to map information bits to the on/off status of their transmission entities such as antennas, subcarriers, modulation types, time slots, precoding/spreading matrices, antenna characteristics and so on. It is interesting to note that IM techniques can be also used in storage and multiple access schemes. The question of “what is next?” could be answered very soon.

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