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Index Modulation Techniques for 5G Wireless Networks

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The author sheds light on the potential and implementation of IM techniques for MIMO and multi-carrier communications systems, which are expected to be two of the key technologies for 5G systems. Specifically, he focuses on two promising applications of IM: spatial modulation and orthogonal frequency-division multiplexing with IM, and discusses the recent advances and future research directions in IM technologies toward spectrum- and energy-efficient 5G wireless networks.

ABSTRACT

The ambitious goals set for 5G wireless networks, which are expected to be introduced around 2020, require dramatic changes in the design of different layers for next generation communications systems. Massive MIMO systems, filter bank multi-carrier modulation, relaying technologies, and millimeter-wave communications have been considered as some of the strong candidates for the physical layer design of 5G networks. In this article, we shed light on the potential and implementation of IM techniques for MIMO and multi-carrier communications systems, which are expected to be two of the key technologies for 5G systems. Specifically, we focus on two promising applications of IM: spatial modulation and orthogonal frequency-division multiplexing with IM, and discuss the recent advances and future research directions in IM technologies toward spectrum- and energy-efficient 5G wireless networks.

INTRODUCTION

Unprecedented levels of spectrum- and energy efficiency are expected from fifth generation (5G) wireless networks to achieve ubiquitous communications between anybody, anything, and anytime [1]. In order to reach the challenging objectives of 5G wireless networks, researchers have envisioned novel physical layer (PHY) concepts such as massive multiple-input multiple-output (MIMO) systems and non-orthogonal multi-carrier communications schemes. However, the wireless community is still working day and night to come up with new and more effective PHY solutions toward 5G networks. There has been a growing interest in index modulation (IM) techniques over the past few years. IM, in which the indices of the building blocks of the considered communications systems are used to convey additional information bits, is a novel digital modulation scheme with high spectral and energy efficiency. *Spatial modulation* (SM) and *orthogonal frequency-division multiplexing with IM* (OFDM-IM) schemes, where the corresponding index modulated building blocks are the transmit antennas of a MIMO system and the subcarriers of an OFDM system, respectively, appear as two interesting as well as promising applications of the IM concept.

After the pioneering work of Mesleh *et al*. [2], SM techniques have attracted significant attention over the past few years. Although having strong and well established competitors such as vertical Bell Labs layered space-time (V-BLAST) and space-time coding (STC) systems, SM schemes have been regarded as possible candidates for spectrum- and energy-efficient next generation MIMO systems. On the other hand, researchers have started to explore the potential of the IM concept for subcarriers of OFDM systems in recent times, and it has been shown that the OFDM-IM scheme [3] can provide attractive advantages over classical OFDM, which is an integral part of many current wireless standards.

The aim of this article is to present the basic principles of these two promising schemes, SM and OFDM-IM, which are still waiting to be explored by many experts, and review some of the recent interesting results in IM techniques. Furthermore, we discuss the implementation scenarios of IM techniques for next generation wireless networks and outline possible future research directions. Particularly, we shift our focus to generalized, enhanced, and quadrature IM schemes and the application of IM techniques for massive multi-user MIMO (MU-MIMO) and cooperative communications systems.

INDEX MODULATION FOR TRANSMIT ANTENNAS: SPATIAL MODULATION

SM is a novel way of transmitting information by means of the indices of the transmit antennas of an $n_T \times n_R$ MIMO system in addition to the conventional M-ary signal constellations, where n_T and n_R denote the number of transmit and receive antennas, respectively. In contrast to conventional MIMO schemes that rely on either spatial multiplexing to boost the data rate or spatial diversity to improve the error performance, the multiple transmit antennas of a MIMO system are used for a different purpose in an SM scheme. More specifically, there are two information carrying units in SM: indices of transmit antennas and M-ary constellation symbols. For each signaling interval, a total of

$$\log_2(n_T) + \log_2(M) \tag{1}$$

bits enter the transmitter of an SM system, where M is the size of the considered signal

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constellation such as M-ary phase shift keying (M-PSK) or M-ary quadrature amplitude modulation (M-QAM). The $\log_2(M)$ bits of the incoming bit sequence are used to modulate the phase and/or amplitude of a carrier signal traditionally, while the remaining $\log_2(n_T)$ bits of the incoming bit sequence are reserved for the selection of the index of the active transmit antenna that performs the transmission of the corresponding modulated signal. On the other hand, the optimum maximum likelihood (ML) detector of the SM scheme jointly searches for all possible transmit antennas and M-ary constellation symbols to decide on both the transmitted symbol and the index of the activated transmit antenna.

SM systems provide important advantages over classical MIMO systems, which are extensively covered in the literature [4, 5]. As an example, assuming an $n_T \times n_R$ MIMO system operating at a fixed spectral efficiency, SM achieves $200(n_T - 1)/(2n_T + 1)$ percent reduction in ML detection complexity (in terms of total number of real multiplications) compared to V-BLAST due to the activation of a single transmit antenna. Furthermore, the sparse structure of the transmission vectors allows the implementation of several near/sub-optimal low-complexity detection methods for SM systems such as matched filter based detection and compressed sensing based detection. In terms of the energy efficiency in megabits per Joule, improvements up to 46 percent compared to V-BLAST are reported for different types of base stations (BSs) equipped with multiple antennas.

Considering the advantages and disadvantages of SM systems, we may conclude that SM provides an interesting trade-off among complexity, energy/spectral efficiency, and error performance. Consequently, SM has been regarded as a possible candidate for spectrum- and energy-efficient next generation wireless communications systems [1].

RECENT ADVANCES IN SM

The first studies on the SM concept date back to the beginning of the 2000s in which researchers used different terminologies. However, after the inspiring work of [2], numerous papers on SM have been published in which the experts focus on generalized, spectrum- and energy-efficient SM systems, low-complexity detector types, block/trellis coded SM systems with transmit/time diversity, link adaptation methods such as adaptive modulation, transmit antenna selection and precoding, performance analysis for different fading channel types and channel estimation errors, information theoretical analyses, differential SM schemes with non-coherent detection, cooperative SM systems, and so on. For a comprehensive overview of these studies, interested readers are referred to survey papers [4, 5].

In this section, we review some of the recent as well as promising advances in SM technologies such as generalized, enhanced, and quadrature SM systems, massive MU-MIMO systems with SM, and cooperative SM schemes, which have the potential to provide efficient solutions toward 5G wireless networks.

GENERALIZED, ENHANCED, AND QUADRATURE SM SCHEMES

The generalized SM (GSM) scheme improves the spectral efficiency of SM by increasing the number of active transmit antennas [4]. In the GSM scheme, multiple antennas are selected as active to transmit the same data symbol. Denoting the number of active transmit antennas by n_A where $n_A < n_T$, $\lfloor \log_2 \binom{n_T}{n_A} \rfloor$ information bits can be transmitted for each signaling interval in addition to the $\log_2(M)$ bits transmitted by the M-ary data symbols, where $\lfloor \cdot \rfloor$ is the floor operation. Since $\log_2(n_T) \leq \lfloor \log_2 \binom{n_T}{n_A} \rfloor$ for $n_T = 2^n$ ($n = 1, 2, \ldots$), the spatial domain can be used more effectively by the GSM scheme. In [6], the concept of GSM has been extended to multiple-active spatial modulation (MA-SM), where different data symbols are transmitted from the selected transmit antennas to further boost spectral efficiency. Consequently, the spectral efficiency of the MA-SM scheme becomes $\lfloor \log_2 \binom{n_T}{n_A} \rfloor + n_A \log_2(M)$ bits per channel use (bpcu), which is considerably higher than that of SM.

Enhanced SM (ESM) is a recently proposed and promising variant of SM [7]. In the ESM scheme, the number of active transmit antennas can vary for each signaling interval, and the information is conveyed not only by the indices of active transmit antennas but also by the selected signal constellations used in transmission. In other words, the ESM scheme considers multiple signal constellations, and the information is transmitted by the combination of active transmit antennas and signal constellations.

Quadrature SM (QSM) [8] is yet another clever modification of classical SM to improve the spectral efficiency while maintaining its advantages such as operation with single RF chain and inter-channel interference (ICI) free transmission. In the QSM scheme, the real and imaginary parts of the complex M-ary data symbols are separately transmitted using the SM principle. For a MIMO system with n_T transmit antennas, the spectral efficiency of QSM becomes $2\log_2(n_T) + \log_2(M)$ bpcu by simultaneously applying the SM principle for in-phase and quadrature components of the complex data symbols. Even if the number of active transmit antennas can be one or two for the QSM scheme, a single RF chain is sufficient at the transmitter since only two carriers (cosine and sine) are used during transmission.

In Fig. 1, we compare the minimum squared Euclidean distance between the transmission vectors (d_{min}), which is an important design parameter for quasi-static Rayleigh fading channels to optimize the error performance of single-input multiple-output (SIMO), SM, ESM, and QSM schemes. In all considered configurations, the average total transmitted energy is normalized to unity to make fair comparisons. It is interesting to note that ESM and QSM schemes achieve the same d_{min} value for 4 and 6 bpcu transmissions. However, as seen from Fig. 1, QSM suffers a worse minimum Euclidean distance, and as a result worse error performance, compared to ESM for higher spectral efficiency values, while the ESM scheme requires a more complicated transmitter with two RF chains. Finally,

In contrast to conventional MIMO schemes that rely either on spatial multiplexing to boost the data rate or spatial diversity to improve the error performance, the multiple transmit antennas of a MIMO system are used for a different purpose in an SM scheme.

Although the spectral efficiency of SM systems cannot compete with that of traditional methods such as V-BLAST for massive MIMO systems, the use of the IM concept for the transmit antennas of a massive MIMO system can provide an easy as well as cheap implementation solution thanks to the inherently available advantages of SM systems.

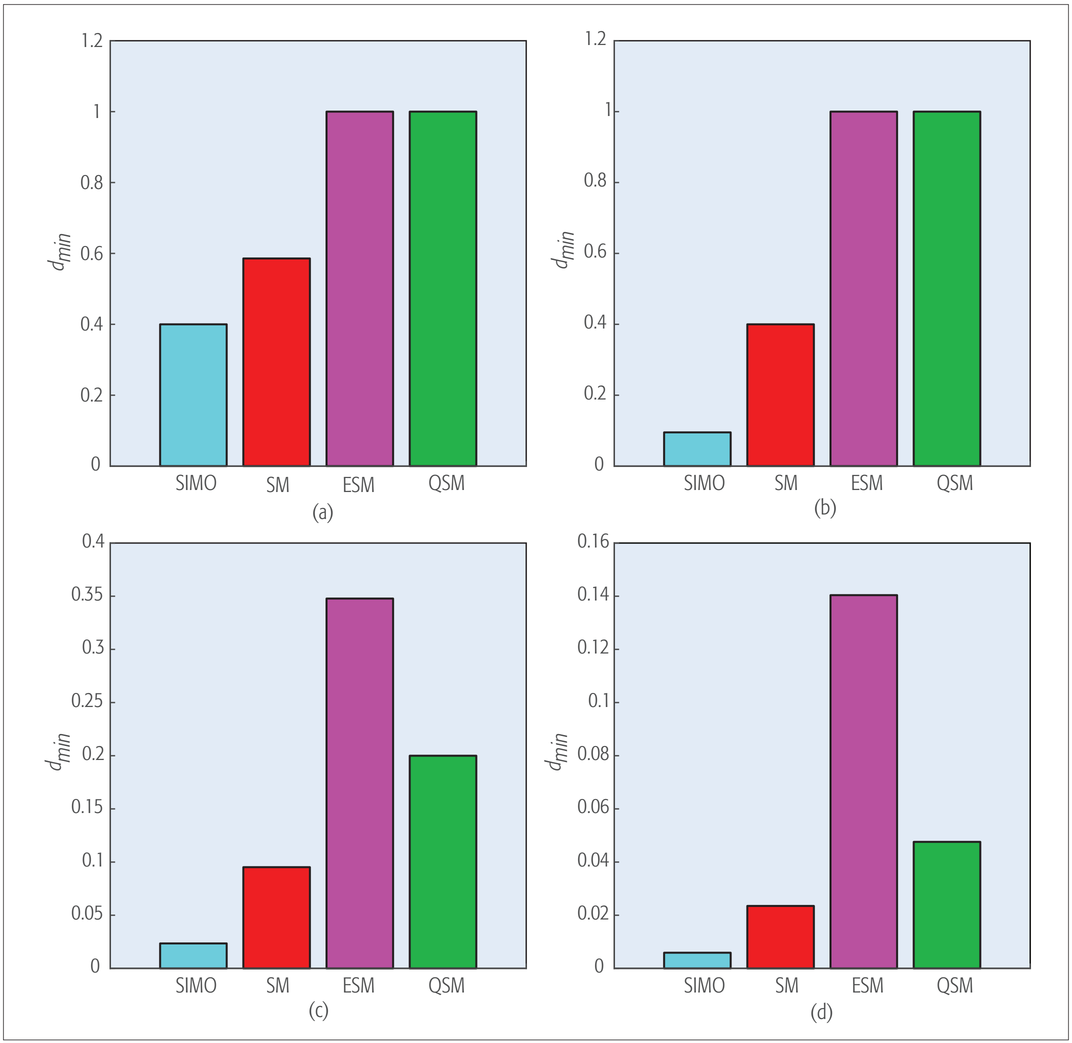

Figure 1. Minimum squared Euclidean distance (d_{min}) comparison of SIMO, SM, ESM, and QSM schemes for different configurations: a) 4 bpcu, $n_T = 2$. SIMO:16-QAM, SM:8-PSK, ESM:QPSK/BPSK, QSM:QPSK; b) 6 bpcu, $n_T = 4$. SIMO:64-QAM, SM:16-QAM, ESM:QPSK/BPSK, QSM:QPSK; c) 8 bpcu, $n_T = 4$. SIMO:256-QAM, SM:64-QAM, ESM:16-QAM/QPSK, QSM:16-QAM; d) 10 bpcu, $n_T = 4$. SIMO:1024-QAM, SM:256-QAM, ESM:64-QAM/8-QAM, QSM:64-QAM.

the results of Fig. 1 also prove that the relative d_{min} advantage of IM schemes over the classical SIMO scheme increases with increasing spectral efficiency, that is, IM techniques become more preferable for higher spectral efficiency values.

MASSIVE MULTI-USER MIMO SYSTEMS WITH SM

The massive MIMO concept, in which BSs have tens to hundreds of antennas, is considered as one of the potential key technologies for 5G wireless networks due to its appealing advantages such as very high spectral and energy efficiency. While the initial studies on MIMO systems generally focus on point-to-point links where two users communicate with each other, practical MU-MIMO systems are gaining more attention to exploit the multiple antennas of a MIMO system to support multiple users simultaneously.

The extension of MIMO systems into massive scale provides unique opportunities for SM systems since it becomes possible to transmit a higher number of information bits in the spatial domain with massive MIMO systems, even if the number of available RF chains is very limited. Although the spectral efficiency of SM systems cannot compete with that of traditional methods such as V-BLAST for massive MIMO systems, the use of the IM concept for the transmit antennas of a massive MIMO system can provide an easy as well as cheap implementation solution thanks to the inherently available advantages of SM systems [9].

In Fig. 2a, a massive MU-MIMO system is considered where K users employ SM techniques for uplink transmission. Compared to user terminals with single antennas, additional information bits can be transmitted using SM without increasing the system complexity. GSM, ESM, and QSM techniques can be implemented at the users to further improve the spectral efficiency. At the BS, the optimal (ML) detector can be used at the expense of exponentially increasing decoding complexity (with respect to K) due to the inter-user interference. Low-complexity near-optimal detec-

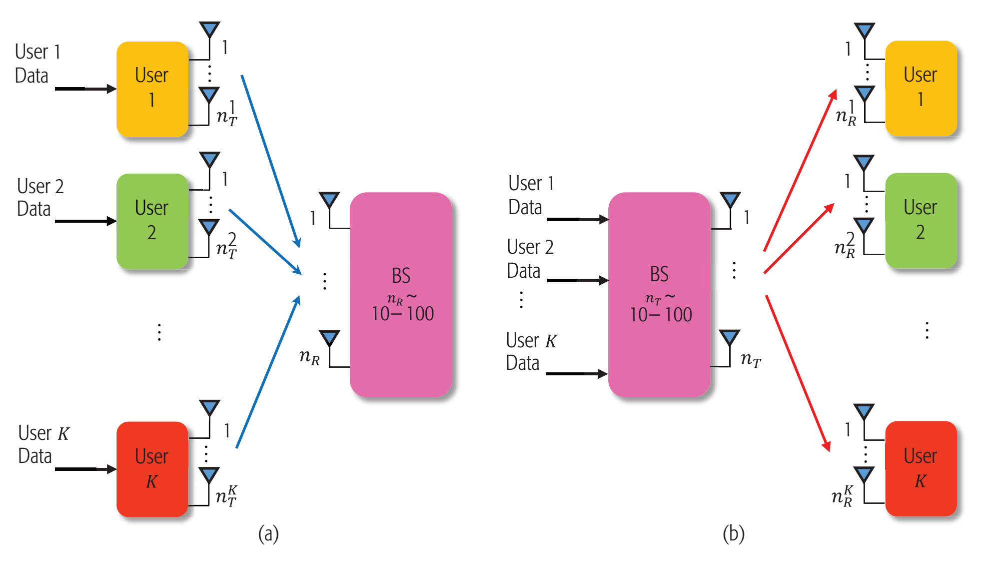

Figure 2. Massive MU-MIMO systems with SM: a) an uplink transmission scenario where User k has n_T^k transmit antennas available for SM and the BS has $n_R \sim$ 10–100 receive antennas; b) a downlink transmission scenario where User k has n_R^k receive antennas and the BS has $n_T \sim$ 10–100 transmit antennas available for SM.

Due to recent technological advances, more than one antenna can be employed at mobile and relay terminals, and 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.

tion methods can be implemented as well by sacrificing the optimum error performance. Alternatively, SM techniques can also be used at the BS for downlink transmission as shown in Fig. 2b. To support a high number of users, the massive antennas of a BS can be split into subgroups of fewer antennas where SM techniques can be employed for each user [10]. For the specific case of two users, the data of User 1 can be mapped into antenna indices, while the data of User 2 can be conveyed with M-ary signal constellations. GSM techniques can also be implemented at the BS to transmit the data of different users with either antenna indices and/or constellation symbols.

Cooperative SM Systems

Considering the effective solutions provided by SM techniques and cooperative communications systems, the combination of these two technologies naturally arises as a potential candidate for future wireless networks. Due to recent technological advances, more than one antenna can be employed at mobile and relay terminals, and 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 amplify-and-forward (AF) relaying-based cooperative networks, distributed cooperation, and network coding systems. Readers are referred to [4, 11] and the references therein for further information on cooperative SM systems.

In Fig. 3, we consider four different cooperative SM system configurations where S, R, and D stand for the source, relay, and destination node, respectively. In Fig. 3a, a dual-hop network is considered, where SM techniques can be implemented at S and R with DF- or AF-based relaying techniques. The scenario of Fig. 3a is generally observed in practical networks where S and D cannot communicate directly due to distance or obstacles. In this relaying scenario, SM techniques can improve the energy and spectral efficiency of S compared to the single antenna case. In Fig. 3b, a direct link from S to D exists, and R can cooperate by employing different relaying methods.

In Fig. 3c, we take into account the two-way communications of S and D, which is accomplished via R. Without network coding, the overall transmission between S and D requires four transmission phases, which considerably reduce the overall spectral efficiency. However, two-way communications between S and D can be accomplished at two phases with network coding where in the first transmission phase, S and D simultaneously transmit their signals to R using SM techniques. In the second transmission phase, R combines the signals received from S and D, then forwards this combined signal to S and D. The use of SM provides some opportunities for R such as transmitting one user's data with antenna indices and the other one's with constellation symbols. Finally, in Fig. 3d, we consider a distributed cooperation scenario with N relay nodes (R_1, … , R_N). In the first transmission phase, S can use SM techniques to transfer its data to relays. In the second transmission phase, one or more relays cooperate, and the indices of the activated relays can be considered as an additional way to convey information. This flexibility allows the relays to cooperate even if they have single antennas (n_R = 1). Furthermore, opportunistic relay selection is also an option for the network topology of Fig. 3d, where the adaptively selected best relay takes part in transmission. For all cooperation scenarios described above, S and/or R can use GSM/ESM/QSM techniques to further improve the spectral efficiency as well as to obtain more flexibility in the system design.

The IM concept can be considered for other communications systems apart from MIMO systems. For instance, IM techniques can be efficiently implemented for the subcarriers of an OFDM system. OFDM-IM is a novel multi-carrier transmission scheme that has been proposed with inspiration from the IM concept of SM.

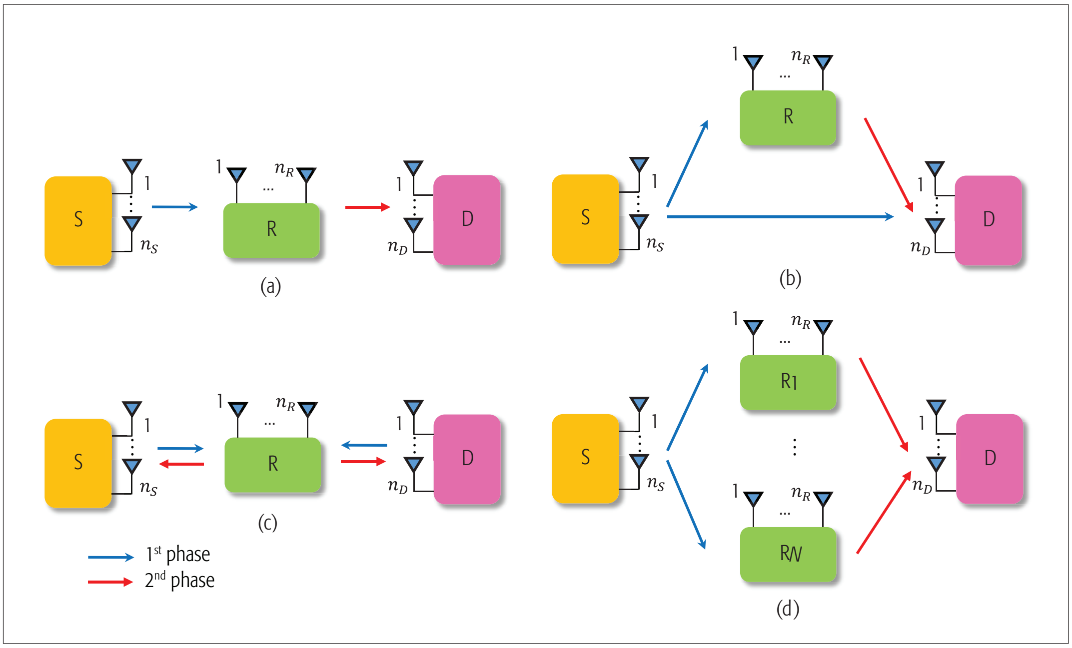

Figure 3. An overview of cooperative SM systems: a) dual-hop SM; b) cooperative SM; c) network-coded SM; d) multi-relay and distributed SM. n_S, n_R, and n_D denote the number of antennas for source (S), relay (R), and destination (D) nodes, respectively.

INDEX MODULATION FOR OFDM SUBCARRIERS: OFDM WITH INDEX MODULATION

The IM concept can be considered for other communications systems apart from MIMO systems. For instance, IM techniques can be efficiently implemented for the subcarriers of an OFDM system. OFDM-IM is a novel multi-carrier transmission scheme that has been proposed with inspiration from the IM concept of SM [3]. Similar to SM, in the OFDM-IM scheme, the incoming bitstream is split into index selection and M-ary constellation bits. According to the index selection bits, only a subset of available subcarriers are selected as active, while the remaining inactive subcarriers are not used and set to zero. On the other hand, the active subcarriers are modulated according to the M-ary constellation bits. In other words, the information is conveyed not only by the data symbols as in classical OFDM, but also by the indices of the active subcarriers, which are used for the transmission of the corresponding data symbols for the OFDM-IM scheme.

Considering an OFDM system with N_F subcarriers, one can directly select the indices of active subcarriers similar to the IM technique used for the transmit antennas of an MA-SM system. However, the massive OFDM frames can provide more flexibility for the employment of IM techniques for OFDM-IM schemes compared to SM schemes. On the other hand, keeping in mind that N_F can take very large values, such as 512,1024 or 2048 as in Long Term Evolution-Advanced (LTE-A) , there could be trillions of (actually more than a googol [10^{100}] in mathematical terms) possible combinations for active subcarriers if index selection is applied directly. As an example, assume that we want to select the indices of 256 active subcarriers out of $N_F = 512$ available subcarriers; then there could be 472.55×10^{150} possible combinations of active subcarriers, which turn the selection of active subcarriers into an almost impossible task. Therefore, for the implementation of OFDM-IM, the single and massive OFDM-IM block should be divided into G smaller and more manageable OFDM-IM subblocks, each containing N subcarriers to perform IM, where $N_F = G \times N$. For each subblock, K out of N available subcarriers can be selected as active according to the $p_1 = \lfloor \log_2 \binom{N}{K} \rfloor$ index selection bits where typical N values could be 2, 4, 8, 16, and 32 with $1 \leq K < N$. Please note that classical OFDM becomes a special case of OFDM-IM with $K = N$, that is, when all subcarriers are activated.

The block diagrams of OFDM-IM scheme's transmitter and receiver structures are illustrated in Figs. 4a and 4b, respectively. As seen from Fig. 4a, for each OFDM-IM frame, a total of

$$m = pG = \left(\left\lfloor \log_2 \binom{N}{K} \right\rfloor + K \log_2 M \right) G \qquad (2)$$

bits can be transmitted where $p = p_1 + p_2$ and $p_2 = K\log_2 M$. In Fig. 4a, $\mathbf{j}_g$ and $\mathbf{s}_g$ denote the vector of selected indices and M-ary data symbols with dimensions $K \times 1$, respectively. First, the OFDM-IM subblock creator forms the $N \times 1$ OFDM-IM subblocks $\mathbf{x}_g$, $g = 1, \ldots, G$; then the OFDM-IM block creator obtains the $N_F \times 1$ main OFDM-IM frame $\mathbf{x}$ by concatenating these G OFDM-IM subblocks. After this point, $G \times N$ block interleaving can be performed to ensure that the subcarriers of a subblock are affected by uncorrelated wireless fading channels. Finally, classical OFDM procedures such as inverse fast Fourier transform (IFFT), cyclic prefix (CP) insertion, and digital-to-analog conversion (DAC) are applied.

Two different index selection procedures are available for OFDM-IM: reference look-

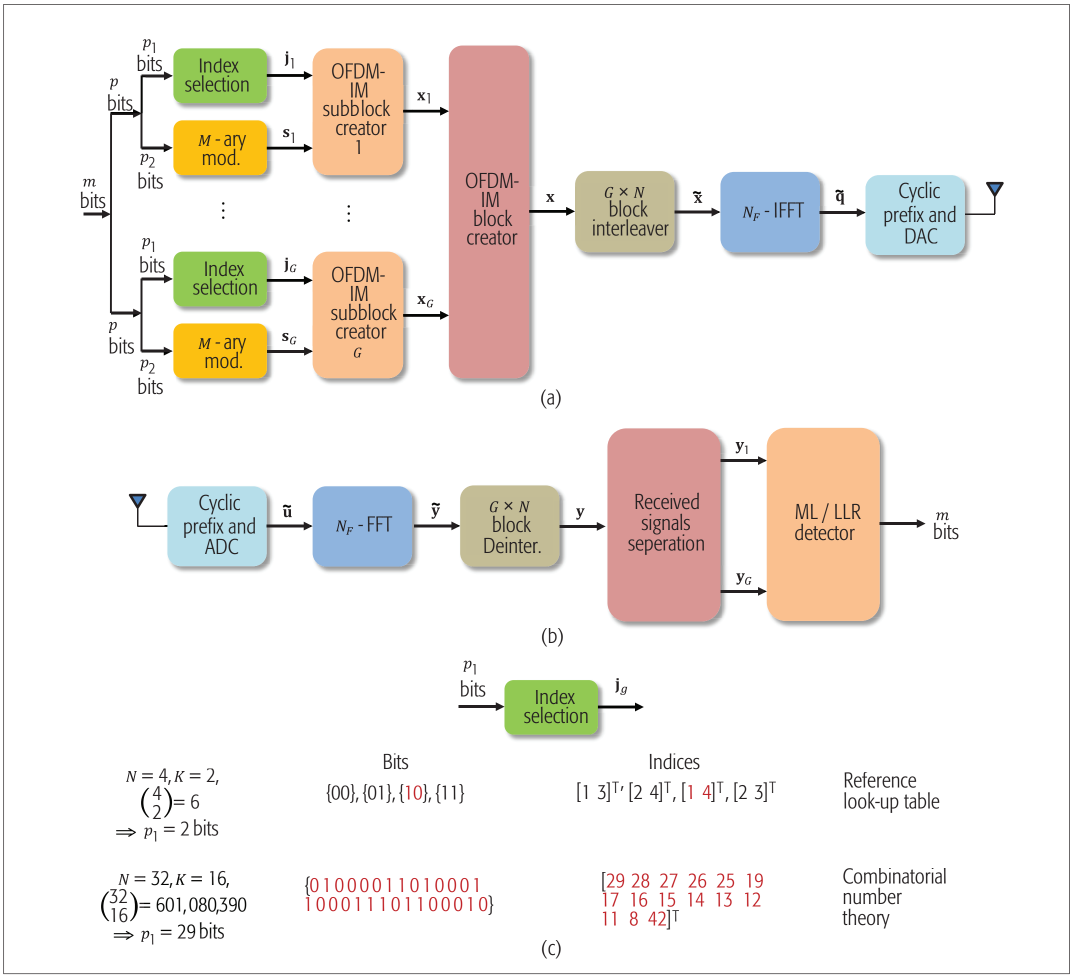

Figure 4. OFDM-IM system at a glance: a) transmitter structure; b) receiver structure; c) two different index selection procedures.

Due to its flexible system design with an adjustable number of active subcarriers and its attractive advantages over OFDM, OFDM-IM can be a possible candidate not only for high-speed wireless communications systems but also for M2M communications systems of 5G wireless networks which require low power consumption.

up tables for smaller N values and combinatorial number theory for higher N values, where examples of these two methods are provided in Fig. 4c. Similar to SM, the receiver of OFDM-IM has to determine the active subcarriers and the corresponding data symbols in accordance with the index selection procedure used at the transmitter. After applying inverse operations, first, the received signals are separated since the detection of different subblocks can be carried out independently. The optimum but high-complexity ML detector makes a joint search over possible subcarrier activation combinations and data symbols, while the low-complexity log-likelihood ratio (LLR) calculation-based near-optimal detector determines the indices of the active subcarriers first, and then detects the corresponding data symbols. The LLR detector calculates a probabilistic measure on the active status of a given subcarrier by considering the fact that the corresponding subcarrier can be either active (carrying an M-ary constellation symbol) or inactive. This detector is classified as near-optimal since it does not know the set of all possible subcarrier activation combinations.

It has been shown that OFDM-IM provides an interesting trade-off between error performance and spectral efficiency, and it offers some attractive advantages over classical OFDM. Unlike classical OFDM, the number of active subcarriers of an OFDM-IM scheme can be adjusted accordingly to reach the desired spectral efficiency and/or error performance. Furthermore, due to the information bits carried by IM, which have lower error probability compared to ordinary M-ary constellation bits, OFDM-IM can provide better bit error rate (BER) performance than classical OFDM for low-to-medium spectral efficiency values, while it exhibits comparable decoding complexity using the near-optimal LLR detector. Furthermore, it has been recently proved that OFDM-IM also outperforms classical OFDM in terms of ergodic achievable rate [12].

Consequently, we conclude that due to its flexible system design with adjustable number of active subcarriers and its attractive advantages over OFDM, OFDM-IM can be a possible candidate not only for high-speed wireless communications systems but also for machine-to-machine (M2M) communications systems of 5G wireless networks, which require low power consumption.

RECENT ADVANCES IN OFDM-IM

The subcarrier IM concept for OFDM has recently attracted significant attention from researchers, and has been investigated in some up-to-date studies that deal with the error performance and capacity analysis, generalization, enhancement, and optimization of OFDM-IM, and its adaptation to different wireless environ-

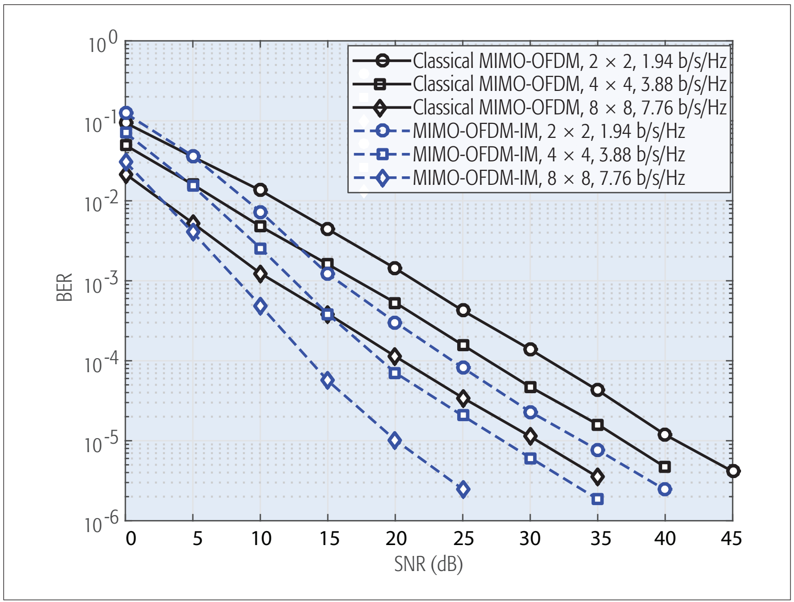

Figure 5. Uncoded BER performance of MIMO-OFDM-IM and classical MIMO-OFDM schemes for three $n_T \times n_R$ MIMO configurations. OFDM system parameters: $M = 2$, $N = 4$, $K = 2$, $N_F = 512$, CP length = 16, frequency-selective Rayleigh fading channel with 10 taps, uniform power delay profile, successive MMSE detection (Reproduced from [13] with permission).

ments. Interested readers are referred to [13, references therein] for an overview of these studies. In this section, we focus on two recently proposed and promising forms of OFDM-IM: generalized OFDM-IM and MIMO-OFDM-IM systems.

GENERALIZED OFDM-IM SCHEMES

Two generalized OFDM-IM structures (OFDM-GIM-I and OFDM-GIM-II) have been recently proposed by modifying the original OFDM-IM scheme [14]. In the OFDM-GIM-I scheme, the number of active subcarriers is no longer fixed, and it is also determined according to the information bits. Considering the case of $N = 4$, $K = 2$ with binary PSK (BPSK) modulation ($M = 2$), according to Eq. 2, (OFDM), $\lfloor \log_2\binom{4}{2} \rfloor + 2\log_2(M) = 4$ bits can be transmitted per OFDM-IM subblock, that is, a total of $4 \times 2^2 = 16$ subblock realizations can be obtained. On the other hand, considering all activation patterns ($K \in \{0, 1, 2, 3, 4\}$), which means that the number of active subcarriers can take values from zero (all subcarriers are inactive, $K = 0$) to four (all subcarriers are active, $K = 4$), as well as considering all possible values of M-ary data symbols, a total of $\Sigma_{K=0}^{N} \binom{N}{K} M^K = 81$ possible subblock realizations can be obtained for which $\lfloor \log_2(81) \rfloor = 6$ bits can be transmitted per OFDM-GIM-I subblock. As a result, the OFDM-GIM-I scheme can provide more flexibility for the selection of active subcarriers and can transmit more bits per subblock compared to OFDM-IM.

The OFDM-GIM-II scheme aims to further improve the spectral efficiency by applying IM independently for in-phase and quadrature components of the complex data symbols similar to the QSM scheme. In other words, a subcarrier can be active for one component, while it can simultaneously be inactive for the other component. Considering the case of $N = 16$, $K = 10$ with quadrature PSK (QPSK) modulation ($M = 4$), according to Eq. 2, $\lfloor \log_2\binom{16}{10} \rfloor + 10\log_2(M) = 32$ bits can be transmitted per OFDM-IM subblock. On the other hand, the OFDM-GIM-II scheme allows the transmission of

$$\left\lfloor \log_2\left(\binom{16}{10}\left(\sqrt{M}\right)^K \times \binom{16}{10}\left(\sqrt{M}\right)^K\right)\right\rfloor$$

= 44 bits per subblock, which is 37.5 percent higher than that of OFDM-IM. Please note that the in-phase and quadrature components of a complex M-QAM symbol are the elements of a $\sqrt{M}$-ary pulse amplitude modulation (PAM) constellation, where a total of

$$\binom{N}{K} \times \left(\sqrt{M}\right)^K$$

realizations are possible per component.

FROM SISO-OFDM-IM TO MIMO-OFDM-IM

The first studies on OFDM-IM generally focused on point-to-point single-input single-output (SISO) systems, which can be unsuitable for some applications due to their limited spectral efficiency. More recently, MIMO transmission and OFDM-IM principles are combined to further boost the spectral and energy efficiency of the OFDM-IM scheme [13]. Specifically, the transmitter of the MIMO-OFDM-IM scheme consists of parallel concatenated SISO-OFDM-IM transmitters (Fig. 4a) to operate over $n_T \times n_R$ MIMO frequency selective fading channels. At the receiver of the MIMO-OFDM-IM scheme, the simultaneously transmitted OFDM-IM frames are separated and demodulated using low-complexity minimum mean square error (MMSE) detection and an LLR calculation-based detector that considers the statistics of the MMSE filtered received signals. It has been shown via extensive computer simulations that due to its improved error performance and flexible system design, MIMO-OFDM-IM can be a strong alternative to classical MIMO-OFDM, which has been included in many current wireless standards.

In Fig. 5, the uncoded BER performance curves of the MIMO-OFDM-IM and classical V-BLAST type MIMO-OFDM schemes are given for three MIMO configurations where the same spectral efficiency values are obtained for both schemes. As observed from Fig. 5, significant signal-to-noise ratio (SNR) improvements can be obtained by the MIMO-OFDM-IM scheme compared to classical MIMO-OFDM to reach a target BER value. On the other hand, the generalization of MIMO-OFDM-IM for massive MU-MIMO systems remains an interesting research problem toward 5G wireless networks.

Another recently proposed IM scheme, which is called generalized space-frequency index modulation (GSFIM)[15], combines the OFDM-IM concept with the GSM principle by exploiting both spatial and frequency (subcarrier) domains for IM. It has been shown that GSFIM can also provide improvements over MIMO-OFDM in terms of achievable data rate and BER performance with ML detection for BPSK and QPSK constellations. However, the design of low-complexity detector types is an open research problem for the GSFIM scheme.

CONCLUSIONS AND FUTURE WORK

IM is an up and coming concept for spectrum- and energy-efficient next generation wireless communications systems to be employed in 5G wireless networks. IM techniques can offer low-complexity as well as spectrum- and energy-efficient solutions toward the single/multi-carrier, massive MU-MIMO, and cooperative communications systems to be employed in 5G wireless networks. In this article, we have reviewed the basic principles, advantages, recent advances, and application areas of SM and OFDM-IM systems, which are two popular applications of the IM concept. In Table 1, the pros and cons of the reviewed IM schemes in terms of spectral efficiency, ML detection complexity, and error performance are provided. We conclude from Table 1 that IM schemes can be considered as possible candidates for 5G wireless networks due to the interesting trade-offs they offer among error performance, complexity, and spectral efficiency, while there are still interesting as well as challenging research problems that 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 IM schemes with higher spectral and/or energy efficiency, lower transceiver complexity, and better error performance
- The integration of IM techniques (e.g., SM, GSM, ESM, QSM, and OFDM-IM) into massive MU-MIMO systems to be employed in 5G wireless networks and the design of novel uplink/downlink transmission protocols
- The adaption of IM techniques to cooperative communications systems (e.g., dual/multihop, network-coded, multi-relay, and distributive networks)
- The investigation of the potential of IM techniques via practical implementation scenarios

	Scheme	Spectral efficiency	ML detection complexity	Error performance
Single carrier communication systems	SIMO	Low	Low	Low
	SM	Moderate	Low*	Moderate
	GSM	Moderate	Moderate*	Moderate
	MA-SM	High	Moderate*	Moderate
	ESM	High	Low	High
	QSM	High	Low	High
	V-BLAST	High	High*	Moderate
Multi-carrier communication systems	OFDM	Low	Low	Low
	OFDM-IM	Low	Moderate*	Moderate
	OFDM-GIM-I	Moderate	High*	Moderate
	OFDM-GIM-II	Moderate	High*	Moderate
	MIMO-OFDM-IM	High	High*	High
	GSFIM	High	High	Moderate
	V-BLAST-OFDM	High	Moderate*	Moderate

*Lower-complexity near/sub-optimal detection is also possible.

Table 1. Pros and cons of several index modulation schemes.

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