CHAPTER X

Index Modulation: A Promising Technique for 5G and Beyond Wireless Networks

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Abstract

The increasing demand for higher data rates, better quality of service, fully mobile and connected wireless networks have led the researchers to seek new solutions beyond 4G wireless systems. It is anticipated that 5G wireless networks, which are expected to be introduced around 2020, will achieve ten times higher spectral and energy efficiency than current 4G wireless networks and will support data rates up to 10 Gbps for low mobility users. These ambitious goals set for 5G wireless networks require comprehensive changes in the design of different layers for next generation communications systems. Within this perspective, massive multiple-input multiple-output (MIMO) systems, more flexible waveforms such as generalized frequency division multiplexing (GFDM) and filter bank multi-carrier (FBMC) modulation, advanced relaying technologies, and millimeter-wave communications have been considered as some of the strong candidates for the physical layer design of 5G wireless networks. In this chapter, we investigate the potential and implementation of index modulation (IM) techniques for next generation MIMO and multi-carrier communications systems. In a specific manner, we focus on two promising forms of IM: spatial modulation (SM) and orthogonal frequency division multiplexing with IM (OFDM-IM), which have attracted significant attention from the wireless community in

the past few years. Furthermore, we review some of the recent as well as promising advances in IM technologies and discuss possible future research directions for IM-based schemes towards spectrum- and energy-efficient 5G and beyond wireless networks.

X.1 Introduction

After more than 20 years of research and development, the achievable data rates of today's cellular wireless communication systems are several thousands of times faster compared to earlier 2G wireless systems. However, unprecedented levels of spectral and energy efficiency are expected from 5G wireless networks to achieve ubiquitous communications between anybody, anything, and anytime[1]. In order to reach the challenging objectives of 5G wireless networks, the researchers have envisioned novel physical layer (PHY) concepts such as massive multiple-input multiple-output (MIMO) systems and non-orthogonal multi-carrier communications schemes like generalized frequency division multiplexing (GFDM) and filter bank multi-carrier (FBMC) modulation. However, the wireless community is still working relentlessly to come up with new and more effective PHY solutions towards 5G wireless networks. There has been a growing interest on index modulation (IM) techniques over the past few years. IM is a novel digital modulation scheme that is shown to achieve high spectral and energy efficiency by considering the indices of the building blocks of the considered communication systems to transmit information bits in addition to the ordinary modulation schemes. Two interesting as well as promising forms of the IM concept are *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.

SM techniques have attracted tremendous attention over the past few years after the inspiring works of Mesleh *et al.*[2] and Jeganathan *et al.*[3], which introduced new directions for MIMO communications. Despite the fact that having strong and well-established competitors such as vertical Bell Labs layered space-time (V-BLAST) and space-time coding (STC) systems[4], SM schemes have been regarded as possible candidates for next generation small/large-scale and single/multi-user MIMO systems. Meanwhile, several researchers have explored the potential of the IM concept for the subcarriers of OFDM systems in the past three years after its widespread introduction[5] and it has been shown that the OFDM-IM scheme offers attractive advantages over classical OFDM, which is an integral part of many current wireless communications standards and also being considered as a strong waveform candidate for 5G wireless networks.

In this chapter, we present the basic principles of these two promising IM schemes, SM and OFDM-IM, and review some of the recent, interesting as well as promising achievements in IM technologies. Furthermore, we discuss the possible implementation scenarios of IM techniques for next generation wireless networks and outline possible future research directions. Particularly, we investigate the recently proposed generalized, enhanced, and quadrature SM schemes and the application of SM techniques for massive multi-user MIMO (MU-MIMO) and relaying networks. Additionally, we review the recent advances in OFDM-IM technologies, such as generalized, MIMO, and dual-mode OFDM-IM schemes, and provide possible implementation scenarios.

The remainder of this chapter is organized as follows. In Section X.2, we describe the SM concept and discuss its advantages/disadvantages for next-generation wireless networks. In Section X.3, we review the most recent as well as interesting advances in SM technologies. In Section X.4, we present the OFDM-IM scheme and discuss its advantages over classical OFDM.

Finally, in Section X.5, we review the most recent developments in OFDM-IM technologies. Section X.6 concludes the chapter.

X.2 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 a MIMO system in addition to the conventional *M*-ary signal constellations. 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. 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 as seen from Fig. 1, 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 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 (I) of the active transmit antenna that performs the transmission of the corresponding modulated signal (s). Consequently, the transmission vector of SM, with dimensions $n_T \times 1$, becomes

$$\begin{bmatrix} 0 & \cdots & 0 & s & 0 & \cdots & 0 \end{bmatrix}^T \tag{2}$$

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

The receiver of the SM scheme has two major tasks to accomplish: detection of the active transmit antenna for the demodulation of the index selecting 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 make a joint search over all transmit antennas and constellation symbols to perform these two tasks[6]. In other words, the ML detector of the SM scheme independently implements a classical single-input multiple-output (SIMO) ML detector for all transmit antennas to find the activated transmit antenna by comparing the corresponding minimum decision metrics $(m_1, m_2, \ldots, m_{n_T})$. 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, second, it finds the data symbol transmitted over this antenna[7,8]. 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, its error performance is considerable worse than the ML detector, which makes its implementation problematic for critical applications.

SM systems provide attractive advantages over classical MIMO systems, which are extensively covered in the literature[9,10,11]. The main advantages of SM over classical MIMO systems can be summarized as follows:

- Simple transceiver design: Since only a single transmit antenna is activated, a single radio frequency (RF) chain can handle the transmission for the SM scheme. Meanwhile, inter-antenna synchronization (IAS) and inter-channel interference (ICI) are completely eliminated, and the decoding complexity of the receiver, in terms of total number of real multiplications performed, grows linearly with the constellation size and number of transmit antennas.

- Operation with flexible MIMO systems: SM does not restrict the number of receive antennas as the V-BLAST scheme, which requires $n_R > n_T$ to operate with minimum mean square error (MMSE) and zero forcing (ZF) detectors.
- High spectral efficiency: Due to the use of antenna indices as an additional source of information, the spectral efficiency of SM is higher than that of single-input single-output (SISO) and orthogonal STC systems.
- High energy efficiency: The power consumed by the SM transmitter is independent from number of transmit antennas while information can be still transferred via these antennas. Therefore, SM appears as a green and energy-efficient MIMO technology.

As an example, SM scheme achieves $200(n_T - 1)/(2n_T + 1)\%$ reduction in ML detection complexity (in terms of total number of real multiplications) compared to V-BLAST for an $n_T \times n_R$ MIMO system operating at a fixed spectral efficiency. This significant reduction is achieved by the activation of a single transmit antenna in SM. Additionally, the sparse structure of SM transmission vectors allows the implementation of several near/sub-optimal low-complexity detection methods for SM systems such as matched filter-based detection[12] and compressed sensing-based detection[13]. 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[14].

While the SM scheme has the aforementioned appealing advantages, it also has some disadvantages. The spectral efficiency of SM increases logarithmically with n_T, while the spectral efficiency of V-BLAST increases linearly with n_T. Therefore, higher number of transmit antennas are required for SM to reach the same spectral efficiency as that of V-BLAST. 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. Since SM transfers the information using only the spatial domain, plain SM cannot provide transmit diversity as STC systems.

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 communications systems[1].

X.3 Recent Advances in SM

The first studies on SM concept date back to the beginning of this century, in which the researchers used different terminologies. However, after the inspiring works of Mesleh *et al.*[2] and Jeganathan *et al.*[3] , numerous papers on SM have been published, in which the experts focus on generalized, spectrum- and energy-efficient SM systems[15,16,17], low-complexity detector types[8,12,13,18,19,20], block/trellis coded SM systems with transmit/time diversity[21,22,23], link adaptation methods such as adaptive modulation[24], transmit antenna selection[25] and precoding[26], performance analysis for different type of fading channels[27,28] and channel estimation errors[29], information theoretical analyses[30], differential SM schemes with non-coherent detection[31], cooperative SM systems[32,33,34,35,36,37], and so on. Interested readers are referred to previous survey papers on SM[10,11,38] for a comprehensive overview of these studies.

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, cooperative SM schemes, and spectrum sharing-based SM schemes, which have the potential to provide efficient solutions towards 5G and beyond wireless networks.

X.3.1 Generalized, Enhanced, and Quadrature SM Schemes

As mentioned earlier, the major disadvantage of SM is its lower spectral efficiency compared to classical V-BLAST scheme for the same number of transmit antennas. Although a considerable number of information bits can still be transmitted by the indices of active transmit antennas, for higher order modulations and MIMO systems, SM suffers a significant loss in spectral efficiency with respect to V-BLAST due to its inactive transmit antennas.

One of the first attempts to not only increase the spectral efficiency of SM but also ease the constraint on 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[15], where the number of active transmit antennas is no longer fixed to unity. In the GSM scheme, the same data symbol is transmitted over the selected multiple active transmit antennas. Let us denote the number of active transmit antennas by n_A where $n_A < n_T$. Then, for the GSM scheme, $\left\lfloor \log_2 \binom{n_T}{n_A} \right\rfloor$ information bits can be conveyed in each signaling interval in addition to the $\log_2(M)$ bits transmitted by the *M*-ary data symbols, where $\lfloor . \rfloor$ is the floor operation and $\binom{\cdot}{\cdot}$ stands for the Binomial coefficient. Since $\log_2(n_T) \leq \left\lfloor \log_2 \binom{n_T}{n_A} \right\rfloor$ for $n_T = 2^n (n = 1, 2, \ldots)$, the spatial domain can be used in a more effective way by the GSM scheme. As an example, for $n_T = 8$, only three bits can be transmitted by the antenna indices in SM, while this can be doubled by GSM for $n_A = 4$. Later, the concept of GSM has been extended to multiple-active spatial modulation (MA-SM, also named as multi-stream SM) by transmitting different data symbols from the selected active transmit antennas to further boost the spectral efficiency[17]. Therefore, the spectral efficiency of the MA-SM scheme can be calculated as

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

bits per channel use (bpcu), which is considerably higher than that of SM. It should be noted that MA-SM provides an intermediate solution between two extreme schemes: SM and V-BLAST, which are the special cases of MA-SM for $n_A = 1$ and $n_A = n_T$, respectively.

As a strong alternative to SM, GSM techniques have attracted considerable attention in the past few years. It has been shown that compared to V-BLAST, GSM can achieve better throughput and/or error performance. Furthermore, percentage savings in the required number of transmit RF chains have been reported[39]. 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[40]. Ordered block MMSE[41], compressed sensing[42], and reactive tabu search-based[43] low-complexity detectors of GSM, which provide near-ML error performance, have been proposed.

Enhanced SM (ESM) is a recently proposed and promising form of SM[44]. 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. As an example, for two transmit antennas and four bpcu transmission, the ESM scheme transmits two bits by the joint selection of active transmit antennas and signal constellations, where one quadrature PSK (QPSK) and two binary PSK (BPSK) signal constellations (one ordinary and one rotated) can be used. For two-bit sequences $\{0,0\}$, $\{0,1\}$, $\{1,0\}$, and $\{1,1\}$, the ESM scheme uses the following transmission vectors, respectively: $\begin{bmatrix}\mathcal{S}_4 & 0\end{bmatrix}^{\mathrm{T}}$, $\begin{bmatrix}0 & \mathcal{S}_4\end{bmatrix}^{\mathrm{T}}$, $\begin{bmatrix}\mathcal{S}_2 & \mathcal{S}_2\end{bmatrix}^{\mathrm{T}}$, and $\begin{bmatrix}\mathcal{S}_2 e^{j\theta} & \mathcal{S}_2 e^{j\theta}\end{bmatrix}^{\mathrm{T}}$, where $\mathcal{S}_m, m = 2,4$ denotes M-PSK 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 that the first two transmission vectors of the ESM scheme correspond to the classical SM using QPSK with single activated transmit antenna, where the first and second transmit antenna is 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. The reason behind reducing the constellation size from four to two can be explained by the fact that same number of information bits (two bits for this case) must be carried with M-ary constellations independent from the number of active transmit antennas. Examples of the generalization of the ESM scheme for different number of transmit antennas and signal constellations are available in the literature[44].

Quadrature SM (QSM) is a modified version of classical SM, which is proposed to improve the spectral efficiency while maintaining the advantages of SM such as operation with single RF chain and ICI free transmission[45]. 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. As an example, for $n_T = 2$ and $M = 4$, in addition to the two bits mapped to the QPSK constellation, extra two bits can be transmitted in the spatial domain by using one of the following four transmission vectors: $\left[s_R + js_I \quad 0\right]^{\mathrm{T}}$, $\left[s_R \quad js_I\right]^{\mathrm{T}}$, $\left[js_I \quad s_R\right]^{\mathrm{T}}$, and $\left[0 \quad s_R + js_I\right]^{\mathrm{T}}$ for input bit sequences $\{0,0\}$, $\{0,1\}$, $\{1,0\}$, and $\{1,1\}$, respectively, where s_R and s_I denote the real and imaginary parts of $s = s_R + js_I \in \mathcal{S}_4$, respectively. It is interesting to note that the first and second element of these two-bit sequences indicates the transmission position of the real and imaginary part of s, respectively. 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) generated by a single RF chain are used during transmission.

In Table 1, transmission vectors of SM, ESM, and QSM schemes are given for 4 bpcu transmission and two transmit antennas, where we considered natural bit mapping for ease of presentation. We observe from Table 1 that both ESM and QSM schemes convey more bits by the spatial domain compared to conventional SM, which leads to not only improved spectral efficiency but also higher energy efficiency.

In Fig. 2, 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 SIMO, SM, ESM, and QSM schemes. In all considered configurations, we normalized the average total transmitted energy 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. 2, QSM suffers a worse minimum Euclidean distance, as a result a worse error performance, compared to ESM scheme for higher spectral efficiency values, while the ESM scheme requires a more complex and high-cost transmitter with two RF chains. Finally, the results of Fig. 2 also prove that the relative d_{min} advantage of IM schemes over classical SIMO scheme increases with increasing spectral efficiency, that is, IM techniques become more preferable for higher spectral efficiency values.

In the past two years, ESM and QSM schemes have attracted significant attention from the community and several follow-up studies have been performed by the researchers. 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[46]. MA-SM and ESM concepts have been recently combined to obtain better error performance with the design of new signal constellations[47]. 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[48]. In the meantime, the researchers have explored the error performance of QSM for different type of fading channels[49,50] and cooperative networks[51,52], under channel estimation errors[53] and cochannel interference[54]. Conventional QSM has been extended to the receiver side by the generalized pre-coding aided QSM scheme[55]. It has been recently shown that near-ML compressed sensing based detectors can provide significant reduction in ML detection complexity of the QSM scheme[56,57]. Furthermore, the novel dual IM concept of QSM has also triggered the research activities on the design of high-rate SM systems[58].

X.3.2 SM-Based Massive Multi-user MIMO Systems

Massive MIMO systems, in which the BSs are equipped with tens to hundreds of antennas, has been regarded as one of the potential key technologies for 5G wireless networks due to their attractive advantages such as very high spectral and energy efficiency. While the initial studies on MIMO systems generally focused on point-to-point links, where two users communicate with each other, practical MU-MIMO systems are gaining more attention compared to classical point-to-point MIMO setups with two communicating terminals. MU-MIMO systems can exploit the multiple antennas of a MIMO system to support multiple users concurrently.

Within this perspective, the extension of MIMO systems into massive scale provides unique as well as promising opportunities for SM systems. For massive MIMO setups, it becomes possible to transmit a significant number of information bits by the spatial domain even if the number of available RF chains is very limited due to space and cost limitations of the mobile terminals. Although the spectral efficiency of SM systems become considerably lower compared with that of traditional methods such as V-BLAST for massive MIMO systems, the use of IM concept for the transmit antennas of a massive MIMO system can provide effective implementation solutions thanks to the inherently available advantages of SM systems. Furthermore, SM is well-suited to unbalanced massive MIMO configurations, in which the number of receive antennas are fewer than the number of transmit antennas[59] and V-BLAST-based systems cannot operate with linear detection methods such as ZF and MMSE detection. As seen from Fig. 3, SM techniques can be considered for both uplink and downlink transmissions in massive MU-MIMO systems.

In Fig. 3(a), we consider a massive MU-MIMO system, where K users employ SM techniques for their uplink transmission. Additional information bits can be transmitted using SM without increasing the system complexity compared to user terminals with single antennas employing ordinary modulations. To further boost the spectral efficiency of the mobile users, GSM, ESM, and QSM techniques can be considered at the users instead of SM. 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. However, the detection complexity of this detector can be unfeasible in practical scenarios with several users. Consequently, low-complexity sub-optimal detection methods can be implemented as well by sacrificing the optimum error performance. On the other hand, SM techniques along with precoding methods can be considered at BS for the downlink transmission as shown in Fig. 3(b). In order to support high number of users, the massive antennas of BS can be split into subgroups of fewer antennas where SM techniques can be employed for each user[60]. To perform an interference-free transmission for the specific case of two users, the data of User 1 can be mapped into the antenna indices while the data of User 2 can be conveyed with *M*-ary signal constellations[61]. The implementation of SM variants discussed in Section X.3.1 can also be considered at the BS to transmit the data of different users.

X.3.3 Cooperative SM Systems

Cooperative communications, which allows the transmission of a user's data not only by its own antenna, but also by the active or passive nodes available in the network, has been one of the hot topics in the wireless communications field in the past decade. Initially, cooperative communication systems have been proposed 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. However, due to the recent technological advances, multiple antennas can be employed at mobile terminals, and cooperative communications systems can efficiently provide additional diversity gains and high data rates by improving coverage. Consequently, relaying technologies have been incorporated into Long Term

Evolution Advanced (LTE-A) standard for increasing coverage, data rate, and cell-edge performance[62].

Considering the attractive 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. Fortunately, SM-based cooperative communications 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 due to the recent technological advances. It has been shown by several studies that SM techniques can be efficiently implemented for decode-and-forward (DF) and amplify-and-forward (AF) relaying-based cooperative networks, dual- and multi-hop relay systems, distributed cooperation, and network coding systems that allow bi-directional communications.[32,33,34,35,36,37].

In Fig. 4, four different cooperative SM transmission scenarios are considered, where S, R, and D respectively stand for the source, relay, and destination node. In Fig. 4(a), a dual-hop network is given, where the communications between S and D is accomplished over an intermediate R. In this dual-hop system, SM techniques can be implemented at S and/or R with DF- or AF-based relaying techniques. The scenario of Fig. 4(a) is generally observed in practical networks, where S and D cannot communicate directly due to distance or obstacles; as a result, DF-based dual-hop relaying has been also incorporated to LTE-A standards. In this relaying scenario, the energy and spectral efficiency of S can be improved by the use of IM techniques compared to the single-antenna case, while multiple RF chains are required at R and D for signal reception. However, considering the uplink transmission from S to D, this would not be a major design problem. In Fig. 4(b), a direct link from S to D is also considered and R can improve the quality of service of the transmission between S and D by employing different relaying methods such as incremental and selective relaying.

We consider the bi-directional (two-way) communications of S and D that is accomplished via R in Fig. 4(c). Without network coding, the overall transmission between S and D requires four transmission phases (from S to R, R to D, D to R, and R to S), which considerably reduce the spectral efficiency of the overall system. On the other hand, by using physical-layer network coding (PLNC), the two-way communications between S and D can be performed at two phases, where in the first transmission phase, S and D simultaneously transmit their signals to R with/without SM techniques. In the second transmission phase, R combines the signals received from S and D, and 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, a distributed cooperation scenario with N relay nodes ($R_1, \ldots, R_N$) is considered in Fig. 4(d). In the first transmission phase, S can use SM techniques to transfer its data to the relays. In the second transmission phase, one or more relays cooperate by forming a virtual SM/SSK system and the indices of the activated relays can be considered as an additional way to convey information. This allows the relays to cooperate even if they have single antennas $(n_R = 1)$ since their own indices carry information. Furthermore, to improve the spectral efficiency, opportunistic relay selection can be considered for the network topology of Fig. 4(d), where only the selected best relay takes part in transmission. For all different cooperation scenarios described above, the use of GSM/ESM/QSM techniques at S and/or R is also possible in order to improve the spectral/energy efficiency of the overall system.

X.3.4 Spectrum Sharing-Based SM Systems

Cognitive radio (CR) networks are capable of handling with the scarcity and inefficient use of the wireless spectrum by utilizing spectrum sharing. A typical CR network is consisted of two types of users: licensed and unlicensed users, which are also called as the primary users (PUs) and the secondary users (SUs), respectively. The secondary users (or cognitive radio users) are intelligent devices, which can sense the available spectrum as well as recognize the nearby environment in order to adjust their transmission parameters since these type users are allowed to use the same frequency band along with PUs under the condition of improving or at least, not degrading the performance of PUs[63]. Since both PUs and SUs use the available spectrum concurrently in CR networks, one of the major problems of these networks become the mutual interference generated by the users. Fortunately, SM techniques can be exploited effectively to overcome the interference problems of conventional CR networks,

SM techniques have been implemented for both underlay and overlay type CR networks in recent years[61,64,65,66,67,68,69,70]. In underlay networks, SUs can use the licensed spectrum band under an interference constraint to PUs. On the other hand, SUs assist the communications of PUs through cooperation in order to improve the performance of the primary network in overlay networks. Most of the spectrum sharing-based SM studies in the literature consider underlay networks, in which the secondary transmitters consider SM/SSK/QSM techniques in their transmission under an interference constraint[64,65,66,69,70]. In these studies, the authors investigated the error performance of IM-based CR networks in the presence of partial/full channel state information at the secondary transmitters and perfect/imperfect channel estimation at the secondary receivers. It has been shown that SM and its variants can provide efficient implementation scenarios for underlay networks.

The integration of SM into overlay networks has been also performed in some recent studies[61,67,68]. In order to mitigate the interference between PUs and SUs, the unique transmission properties of SM are considered. More specifically, the secondary transmitter exploits SM and considers the antenna indices to transmit its own data bits; on the other hand, it uses ordinary M-ary modulation to transmit PT's information with the purpose of supporting the communications of the primary network. It has been shown by computer simulations that SM-based systems can achieve better BER performance compared to conventional cooperative spectrum sharing systems using superposition coding.

X.4 Index Modulation for OFDM Subcarriers: OFDM with Index Modulation

Although the concept of IM is generally remembered by the SM scheme, it is also possible to implement IM techniques for communication systems different from MIMO systems. As an example, one can efficiently implement IM techniques for the massive subcarriers of an OFDM system. OFDM-IM is a novel multi-carrier transmission scheme that has been proposed by inspiring from the IM concept of SM[5]. Similar to the bit mapping of SM, the incoming bit stream is split into subcarrier index selection and M-ary constellation bits in the OFDM-IM scheme. Considering the index selection bits, only a subset of available subcarriers are activated, while the remaining inactive subcarriers set to zero and are not used in data transmission. However, the active subcarriers are modulated as in classical OFDM according to M-ary constellation bits. In other words, OFDM-IM scheme 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 determine the indices of the active subcarriers similar to SM-based schemes. However, considering the massive structure of OFDM frames, IM techniques can be implemented in a more flexible way for OFDM-IM schemes compared to SM-based schemes. On the other hand, keeping in mind the practical values of N_F, such as 128, 256, 512, 1024 or 2048 as in LTE-A standard, 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 128 active subcarriers out of $N_F = 256$ available subcarriers, one should consider 5.77×10^{75} 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 the implementation of 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

$$p_1 = \left\lfloor \log_2 \binom{N}{K} \right\rfloor \tag{4}$$

index selection bits, where typical N values could be 2, 4, 8, 16, and 32 with $1 \leq K < N$. It should be noted that classical OFDM becomes the 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.

The block diagrams of OFDM-IM scheme's transmitter and receiver structures are shown in Figs. 5(a) and 5(b), respectively. As seen from Fig. 5(a), for the transmission of each OFDM-IM frame, a total of

$$m = pG = \left(\left\lfloor \log_2 \binom{N}{K} \right\rfloor + K \log_2 M \right) G \tag{5}$$

bits enter the transmitter, where $p = p_1 + p_2$ and $p_2 = K \log_2 M$. In Fig. 5(a), $\mathbf{j}_g$ and $\mathbf{s}_g$ denote the vector of selected indices and *M*-ary data symbols with dimensions $K \times 1$, respectively. The operation of the OFDM-IM transmitter can be summarized as follows. First, OFDM-IM subblock creator obtains the OFDM-IM subblocks $\mathbf{x}_g, g = 1, \ldots, G$, with dimensions $N \times 1$ by considering $\mathbf{j}_g$ and $\mathbf{s}_g$. Afterwards, the OFDM-IM block creator obtains the main OFDM-IM frame $\mathbf{x}$ with dimensions $N_F \times 1$ 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. At the last step, inverse fast Fourier transform (IFFT), cyclic prefix (CP) insertion, and digital-to-analog (DAC) conversion procedures are performed for the transmission of the signals through the wireless channel as in classical OFDM systems.

The selection of active subcarriers appears as a challenging problem for OFDM-IM systems. For this purpose, two different index selection procedures are proposed for OFDM-IM depending on the size of the subblocks: reference look-up tables and combinatorial number theory method for lower and higher subblock sizes, respectively. Examples of these two methods are provided in Fig. 6. In the first example, two out of four subcarriers are selected as active by considering a reference look-up table with size four. In this case, two bits can determine the indices of the active subcarriers. In the second example, to select the indices of 16 active subcarriers out of 32 total subcarriers, the index selector processes 29 bits. First, these 29 bits are converted into a decimal number. Then, this decimal number is given to the combinatorial algorithm, which provides the required number of active indices.

The task of the OFDM-IM receiver is to determine the indices of the active subcarriers as well as the corresponding data symbols carried by these active subcarriers in conjunction with the index selection procedure used at the transmitter. After applying inverse operations (analog-to-digital (ADC) conversion, CP removal, FFT, and block deinterleaving), first, the received signals are separated since the detection of different subblocks can be carried out independently. Unfortunately, the optimal detection of OFDM-IM cannot be accomplished at the subcarrier level as in classical OFDM due to the index information, and the receiver must process the OFDM-IM subblocks for detection. The optimum but high-complexity ML detector performs a joint search by considering all possible subcarrier activation combinations and 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, 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 two 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.

It has been shown in the literature that OFDM-IM not only offers attractive advantages over classical OFDM but also it provides an interesting trade-off between error performance and spectral efficiency with its flexible system design. The major difference between classical OFDM and OFDM-IM schemes is the adjustable number of active subcarriers of the latter. In other words, the number of active subcarriers of OFDM-IM can be adjusted accordingly to reach the desired spectral efficiency and/or error performance. Furthermore, OFDM-IM can provide a better bit error rate (BER) performance than classical OFDM for low-to-mid spectral efficiency values 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. Finally, it has been proved that

OFDM-IM provides a better performance than classical OFDM in terms of ergodic achievable rate[63].

As a result, we conclude that due to its appealing advantages over OFDM and more flexible system design, OFDM-IM can be considered as a possible candidate for emerging high-speed wireless communications systems. Furthermore, OFDM-IM has the potential to be well-suited to machine-to-machine (M2M) communications systems of next generation wireless networks that require low power consumption.

X.5 Recent Advances in OFDM-IM

Subcarrier IM concept for OFDM has attracted significant attention from the wireless community in recent times since its widespread introduction in 2012-2013[5,71,72]. OFDM-IM techniques have been investigated in some up-to-date studies that deal with the capacity analysis[73] and error performance[74], the selection problem of the optimal number of active subcarriers[75,76], subcarrier level block interleaving for improved error performance[77], generalization[78], enhancement[79,80,81], and low-complexity detection of OFDM-IM[82], combination of OFDM-IM with coordinate interleaved orthogonal designs[83] and MIMO systems[84,85], and its adaptation to different wireless environments[86,87]. In this section, we focus on three recently proposed and promising forms of OFDM-IM: generalized OFDM-IM, MIMO-OFDM-IM, and dual-mode OFDM-IM systems.

X.5.1 Generalized OFDM-IM Schemes

Two generalized OFDM-IM structures have been proposed by modifying the original OFDM-IM scheme to obtain an improved spectral efficiency[78]. In the first scheme, which is named as the OFDM-GIM-I scheme, the number of active subcarriers are no longer fixed and it is also determined according to the information bits. As an example case of $N = 4, K = 2$ with quadrature PSK (QPSK) modulation $(M = 4)$, according to (5), $\left\lfloor \log_2 \binom{4}{2} \right\rfloor + 2\log_2(4) = 6$ bits can be transmitted per OFDM-IM subblock, that is, a total of $4 \times 4^2 = 64$ subblock realizations can be obtained. On the other hand, OFDM-GIM-IM scheme considers 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 all possible values of M-ary data symbols, a total of

$$\sum_{K=0}^{N} \binom{N}{K} M^K = \binom{4}{0}4^0 + \binom{4}{1}4^1 + \binom{4}{2}4^2 + \binom{4}{3}4^3 + \binom{4}{4}4^4 = 625 \quad (6)$$

possible subblock realizations can be obtained for which $\lfloor \log_2(625) \rfloor = 9$ bits can be transmitted per subblock. Consequently, compared to OFDM-IM, OFDM-GIM-I is capable of transmitting more number of bits per subblock.

The second generalized OFDM-IM scheme, which is called the OFDM-GIM-II scheme, improves the spectral efficiency further by applying IM independently for the in-phase and quadrature components of the complex data symbols analogous to QSM. In other words, a subcarrier can be active for one component, while being inactive simultaneously for the other component. For the case of $N = 8, K = 4$ with quadrature PSK (QPSK) modulation $(M = 4)$, according to (5), $\left\lfloor \log_2 \binom{8}{4} \right\rfloor + 4\log_2(4) = 14$ bits can be transmitted per OFDM-IM subblock. On the other hand, the OFDM-GIM-II scheme allows the transmission of $\left\lfloor \log_2 \left(\binom{8}{4} \left(\sqrt{4}\right)^4 \times \binom{8}{4} \left(\sqrt{4}\right)^4 \right) \right\rfloor = 20$ bits per subblock, which is 30% higher than that of

OFDM-IM.

X.5.2 From SISO-OFDM-IM to MIMO-OFDM-IM

In the first studies on OFDM-IM, the researchers generally investigated SISO configurations and performed comparisons with classical SISO-OFDM scheme. However, OFDM is generally implemented along with MIMO systems in current wireless communications standards to support high data rate applications, which require increased spectral efficiency. For this reason, MIMO transmission and OFDM-IM principles are combined to further boost the spectral and energy efficiency of the plain OFDM-IM scheme[84,85]. In the MIMO-OFDM-IM scheme, a V-BLAST type transmission strategy is adopted to obtain an increased spectral efficiency. More specifically, the transmitter of the MIMO-OFDM-IM scheme is obtained by the parallel-concatenation of multiple SISO-OFDM-IM transmitters (Fig. 5(a)). At the receiver of the MIMO-OFDM-IM scheme, the simultaneously transmitted OFDM-IM frames interfere with each other due to V-BLAST type parallel transmission; therefore, these frames are separated and demodulated using a novel low-complexity MMSE detection and LLR calculation-based detector. This detector 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. 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 FMBC, OFDM-IM is a more MIMO-friendly transmission technique and also provides improvements in BER performance over classical MIMO-OFDM.

In Fig. 7, we present the uncoded BER performance of MIMO-OFDM-IM

$(N = 4, K = 2, M = 2)$ and classical V-BLAST type MIMO-OFDM schemes $(M = 2)$ for three MIMO configurations: 2×2, 4×4, and 8×8. In all cases, we obtain the same spectral efficiency values for both schemes to perform fair comparisons. As seen from Fig. 7, considerable improvements in required signal-to-noise ratio (SNR) are obtained to reach a target BER value by the MIMO-OFDM-IM scheme compared to classical MIMO-OFDM.

Some other studies that combine OFDM-IM and MIMO transmission principles, have been also performed recently. Generalized space-frequency index modulation (GSFIM)[78] 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. However, the design of low complexity detector types is an open research problem for the GSFIM scheme. More recently, a space-frequency coded index modulation (SFC-IM) scheme is proposed to obtain diversity gains for MIMO-OFDM-IM[89]. Even more recently, low-complexity and near optimal detection algorithms, based on the sequential Monte Carlo theory, are proposed for emerging MIMO-OFDM-IM schemes[90].

X.5.3 Dual-Mode OFDM-IM Scheme

One of the main limitations of the plain OFDM-IM scheme is its limited spectral efficiency due to the inactive subcarriers, which do not carry information for IM purposes. 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 (5), 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. 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.

Dual mode OFDM-IM (DM-OFDM-IM) scheme provides a clever solution to overcome the spectral efficiency limitation of OFDM-IM by activating all subcarriers while still exploiting IM[81]. In DM-OFDM-IM scheme, all subcarriers are modulated and the index information is carried by the signal constellations assigned to 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-IM 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,

$$\tilde{m} = \tilde{p}G = \left(\left\lfloor \log_2 \binom{N}{K} \right\rfloor + K \log_2 M_1 + (N-K) \log_2 M_2 \right) G \tag{7}$$

bits can be transmitted, where $\tilde{p}$ is the number of bits per DM-OFDM-IM subblock and G is the number of DM-OFDM-IM 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 (7), that is, by not modulating the second group of subcarriers, the number of bits transmitted in a DM-OFDM-IM block becomes the same as that of OFDM-IM given in (5). It has been shown by computer simulations that DM-OFDM-IM scheme can achieve a better BER performance than other OFDM-IM variants by using a near-optimal LLR calculation-based detector. More recently, a generalized DM-OFDM-IM scheme is proposed[91]. 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.

X.6 Conclusions and Future Work

IM appears as a promising digital modulation concept for next generation wireless communications systems since IM techniques can offer low-complexity as well as spectrum- and energy-efficient solutions for emerging single/multi-carrier, massive single/multi-user MIMO, cooperative communications, and spectrum sharing systems. In this chapter, we have reviewed the basic principles, advantages/disadvantages, the most recent as well as promising developments, and possible implementation scenarios of SM and OFDM-IM systems, which are two highly popular forms of the IM concept. In Table 2, the pros and cons of the reviewed major IM schemes in terms of the spectral efficiency, ML detection complexity, and error performance are provided. We conclude from Table 2 that IM schemes can offer interesting trade-offs among the error performance, complexity, and spectral efficiency; consequently, they can be considered as possible candidates for 5G and beyond wireless communication networks. However, interesting and challenging research problems are still remaining to be investigated to further improve the efficiency of IM-based 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 (such as SM, GSM, ESM, QSM, and OFDM-IM) into massive MU-MIMO systems to be employed in 5G and beyond wireless networks and

the design of novel uplink/downlink transmission protocols

- The adaption of IM techniques to cooperative communications systems (such as dual/multi-hop, network-coded, multi-relay, and distributive networks) and spectrum sharing systems
- The investigation of the potential of IM techniques via practical implementation scenarios
- Exploration of new digital communications schemes for the application of IM techniques.

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Biography

Ertugrul Basar received his B.S. degree with high honors from Istanbul University, Turkey, in 2007, and his M.S. and Ph.D. degrees from Istanbul Technical University in 2009 and 2013, respectively. He spent the academic year 2011-2012 at the Department of Electrical Engineering, Princeton University, New Jersey. Currently, he is an assistant professor at Istanbul Technical University, Electronics and Communication Engineering Department, and a member of the Wireless Communication Research Group. He was the recipient of the Istanbul Technical University Best Ph.D. Thesis Award in 2014 and has won three Best Paper Awards including one from *IEEE International Conference on Communications (ICC 2016)*. He currently serves as an Associate Editor for IEEE COMMUNICATIONS LETTERS and IEEE ACCESS, a regular reviewer for various IEEE journals, and has served as a TPC member for several conferences. His primary research interests include MIMO systems, index modulation, cooperative communications, OFDM, and visible light communications. He is a senior member of IEEE and an inventor of two pending patents on index modulation schemes.

Tables

Table 1: Transmission vectors ($\mathbf{x}^{\mathrm{T}}$) of SM, ESM, and QSM schemes for 4 bpcu and two transmit antennas ($n_T = 2$), the most significant bit is the one transmitted by the spatial domain for SM, the second most significant bit is the additional one bit transmitted by the spatial domain for ESM and QSM

Bits	*SM*	*ESM*	*QSM*	*Bits*	*SM*	*ESM*	*QSM*
0000	$\begin{bmatrix}1 & 0\end{bmatrix}$	$\begin{bmatrix}\frac{1+j}{\sqrt{2}} & 0\end{bmatrix}$	$\begin{bmatrix}\frac{1+j}{\sqrt{2}} & 0\end{bmatrix}$	1000	$\begin{bmatrix}0 & 1\end{bmatrix}$	$\begin{bmatrix}\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}\end{bmatrix}$	$\begin{bmatrix}\frac{j}{\sqrt{2}} & \frac{1}{\sqrt{2}}\end{bmatrix}$
0001	$\begin{bmatrix}\frac{1+j}{\sqrt{2}} & 0\end{bmatrix}$	$\begin{bmatrix}\frac{-1+j}{\sqrt{2}} & 0\end{bmatrix}$	$\begin{bmatrix}\frac{-1+j}{\sqrt{2}} & 0\end{bmatrix}$	1001	$\begin{bmatrix}0 & \frac{1+j}{\sqrt{2}}\end{bmatrix}$	$\begin{bmatrix}\frac{1}{\sqrt{2}} & \frac{-1}{\sqrt{2}}\end{bmatrix}$	$\begin{bmatrix}\frac{j}{\sqrt{2}} & \frac{-1}{\sqrt{2}}\end{bmatrix}$
0010	$\begin{bmatrix}j & 0\end{bmatrix}$	$\begin{bmatrix}\frac{-1-j}{\sqrt{2}} & 0\end{bmatrix}$	$\begin{bmatrix}\frac{-1-j}{\sqrt{2}} & 0\end{bmatrix}$	1010	$\begin{bmatrix}0 & j\end{bmatrix}$	$\begin{bmatrix}\frac{-1}{\sqrt{2}} & \frac{1}{\sqrt{2}}\end{bmatrix}$	$\begin{bmatrix}\frac{-j}{\sqrt{2}} & \frac{-1}{\sqrt{2}}\end{bmatrix}$
0011	$\begin{bmatrix}\frac{-1+j}{\sqrt{2}} & 0\end{bmatrix}$	$\begin{bmatrix}\frac{1-j}{\sqrt{2}} & 0\end{bmatrix}$	$\begin{bmatrix}\frac{1-j}{\sqrt{2}} & 0\end{bmatrix}$	1011	$\begin{bmatrix}0 & \frac{-1+j}{\sqrt{2}}\end{bmatrix}$	$\begin{bmatrix}\frac{-1}{\sqrt{2}} & \frac{-1}{\sqrt{2}}\end{bmatrix}$	$\begin{bmatrix}\frac{-j}{\sqrt{2}} & \frac{1}{\sqrt{2}}\end{bmatrix}$
0100	$\begin{bmatrix}-1 & 0\end{bmatrix}$	$\begin{bmatrix}0 & \frac{1+j}{\sqrt{2}}\end{bmatrix}$	$\begin{bmatrix}\frac{1}{\sqrt{2}} & \frac{j}{\sqrt{2}}\end{bmatrix}$	1100	$\begin{bmatrix}0 & -1\end{bmatrix}$	$\begin{bmatrix}\frac{j}{\sqrt{2}} & \frac{j}{\sqrt{2}}\end{bmatrix}$	$\begin{bmatrix}0 & \frac{1+j}{\sqrt{2}}\end{bmatrix}$
0101	$\begin{bmatrix}\frac{-1-j}{\sqrt{2}} & 0\end{bmatrix}$	$\begin{bmatrix}0 & \frac{-1+j}{\sqrt{2}}\end{bmatrix}$	$\begin{bmatrix}\frac{-1}{\sqrt{2}} & \frac{j}{\sqrt{2}}\end{bmatrix}$	1101	$\begin{bmatrix}0 & \frac{-1-j}{\sqrt{2}}\end{bmatrix}$	$\begin{bmatrix}\frac{j}{\sqrt{2}} & \frac{-j}{\sqrt{2}}\end{bmatrix}$	$\begin{bmatrix}0 & \frac{-1+j}{\sqrt{2}}\end{bmatrix}$
0110	$\begin{bmatrix}-j & 0\end{bmatrix}$	$\begin{bmatrix}0 & \frac{-1-j}{\sqrt{2}}\end{bmatrix}$	$\begin{bmatrix}\frac{-1}{\sqrt{2}} & \frac{-j}{\sqrt{2}}\end{bmatrix}$	1110	$\begin{bmatrix}0 & -j\end{bmatrix}$	$\begin{bmatrix}\frac{-j}{\sqrt{2}} & \frac{j}{\sqrt{2}}\end{bmatrix}$	$\begin{bmatrix}0 & \frac{-1-j}{\sqrt{2}}\end{bmatrix}$
0111	$\begin{bmatrix}\frac{1-j}{\sqrt{2}} & 0\end{bmatrix}$	$\begin{bmatrix}0 & \frac{1-j}{\sqrt{2}}\end{bmatrix}$	$\begin{bmatrix}\frac{1}{\sqrt{2}} & \frac{-j}{\sqrt{2}}\end{bmatrix}$	1111	$\begin{bmatrix}0 & \frac{1-j}{\sqrt{2}}\end{bmatrix}$	$\begin{bmatrix}\frac{-j}{\sqrt{2}} & \frac{-j}{\sqrt{2}}\end{bmatrix}$	$\begin{bmatrix}0 & \frac{1-j}{\sqrt{2}}\end{bmatrix}$

Table 2: Pros and cons of several index modulation schemes

	Scheme	*Spectral efficiency*	*ML detection complexity*	*Error performance*
Single-carrier communications 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 communications 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.

Figure Captions

Figure 1: Block diagram of the SM transceiver for an $n_T \times n_R$ MIMO system. s (or $\hat{s}$) and I (or $\hat{I}$) $\in \{1,2,\ldots,n_T\}$ denote the selected (or estimated) M-ary constellation symbol and transmit antenna index, respectively and $m_n, n = 1,2,\ldots,n_T$ is the minimum decision metric provided by the nth SIMO ML detector.

Figure 2: 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.

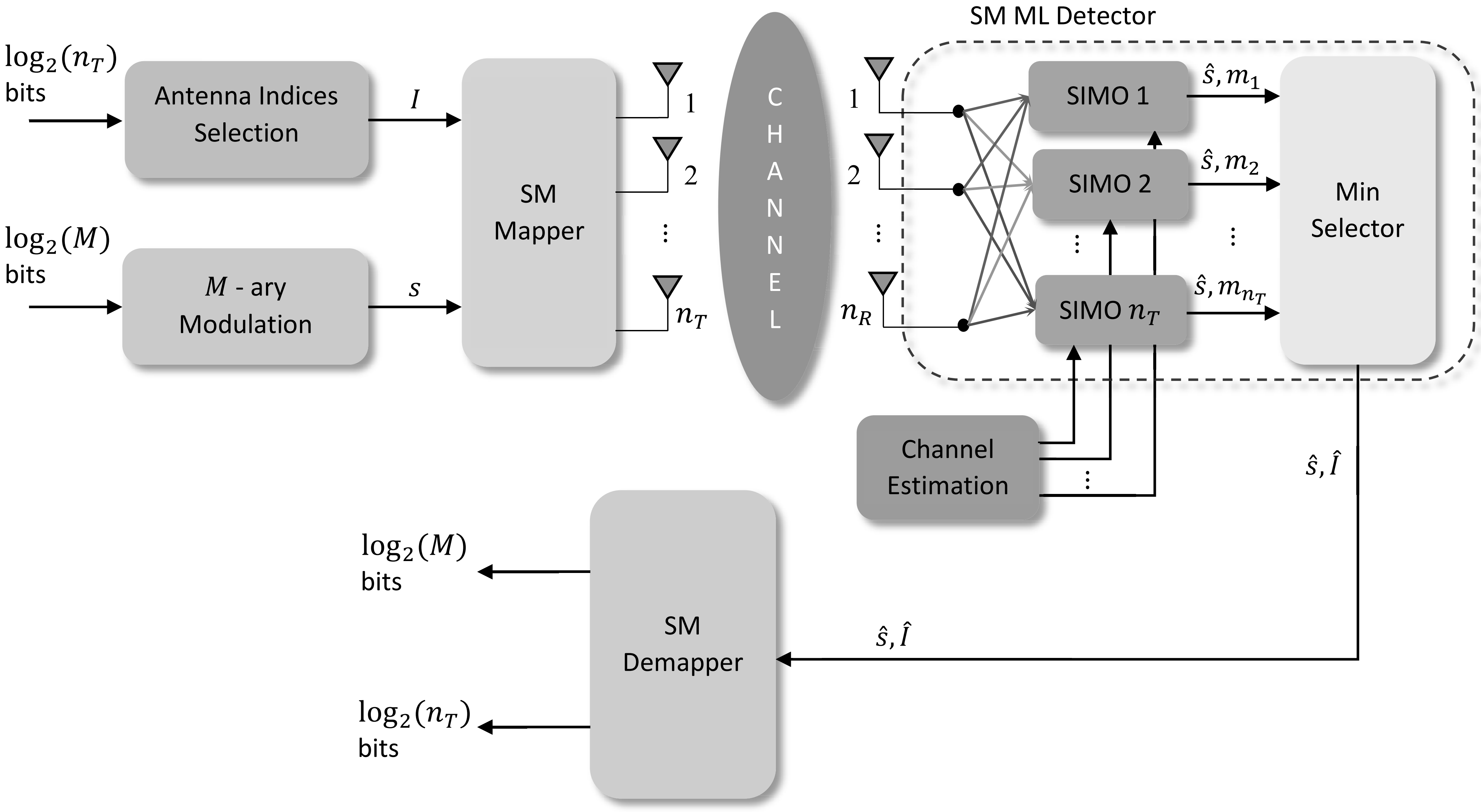
Figure 3: Massive MU-MIMO systems with SM
(a) An uplink transmission scenario where User k has n_T^k transmit antennas available for SM and the BS has $n_R \sim 10-100$ receive antennas.
(b) A downlink transmission scenario where User k has n_R^k receive antennas and the BS has $n_T \sim 10-100$ transmit antennas available for SM.

Figure 4: An overview of cooperative SM systems where n_S, n_R and n_D denote the number of antennas for source (S), relay (R) and destination (D) nodes, respectively.
(a) Dual-hop SM
(b) Cooperative SM
(c) Network-coded SM
(d) Multi-relay and distributed SM.

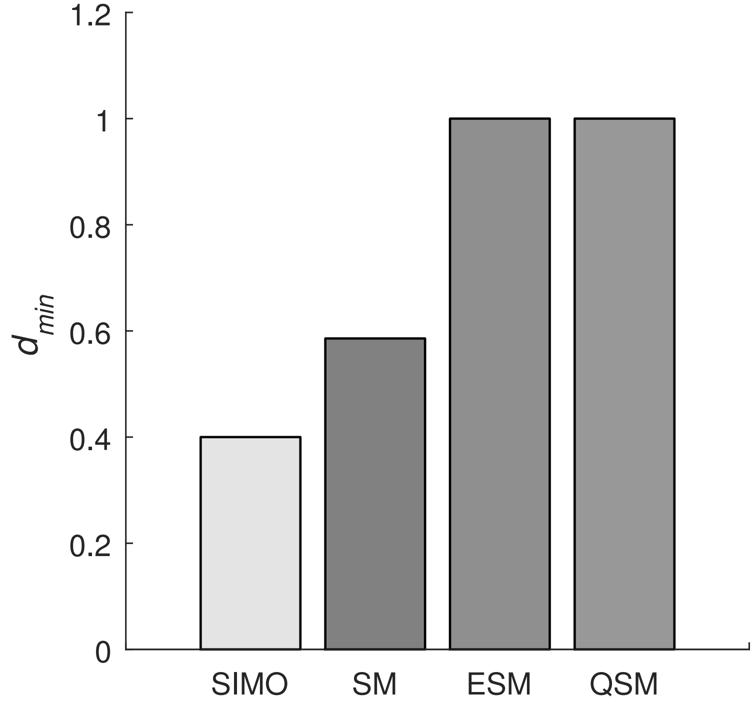
Figure 5: OFDM-IM system at a glance
(a) Transmitter structure
(b) Receiver structure

Figure 6: Two different index selection procedures for OFDM-IM

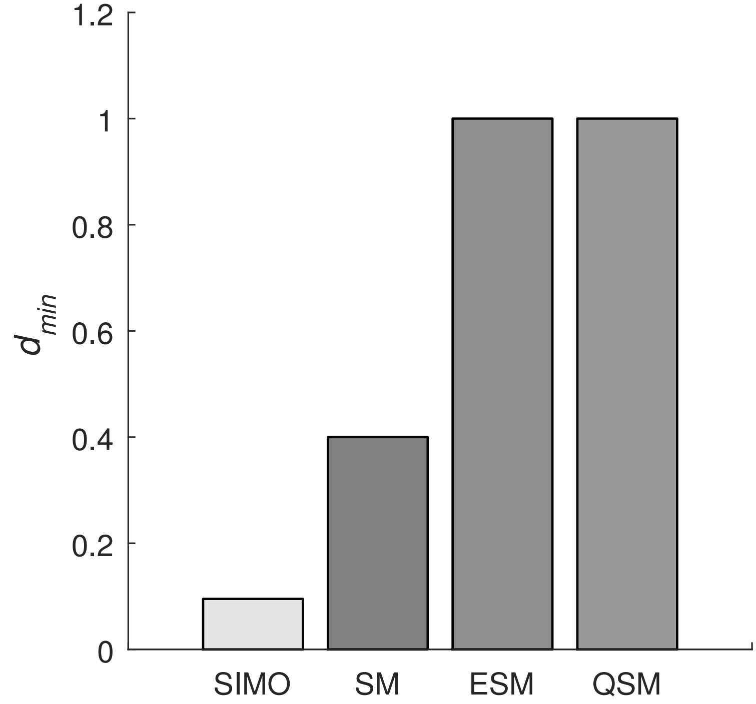
Figure 7: Uncoded BER performance of MIMO-OFDM-IM and classical MIMO-OFDM schemes for three $n_T \times n_R$ MIMO configurations: 2×2, 4×4, and 8×8. OFDM system parameters: $M = 2$ (BPSK), $N = 4, K = 2$, $N_F = 512$, CP length$=16$, frequency-selective Rayleigh fading channel with 10 taps, uniform power delay profile, successive MMSE detection. The 3% reduce in spectral efficiency compared to single-carrier case $(n_T \log_2 M)$ is due to CP.



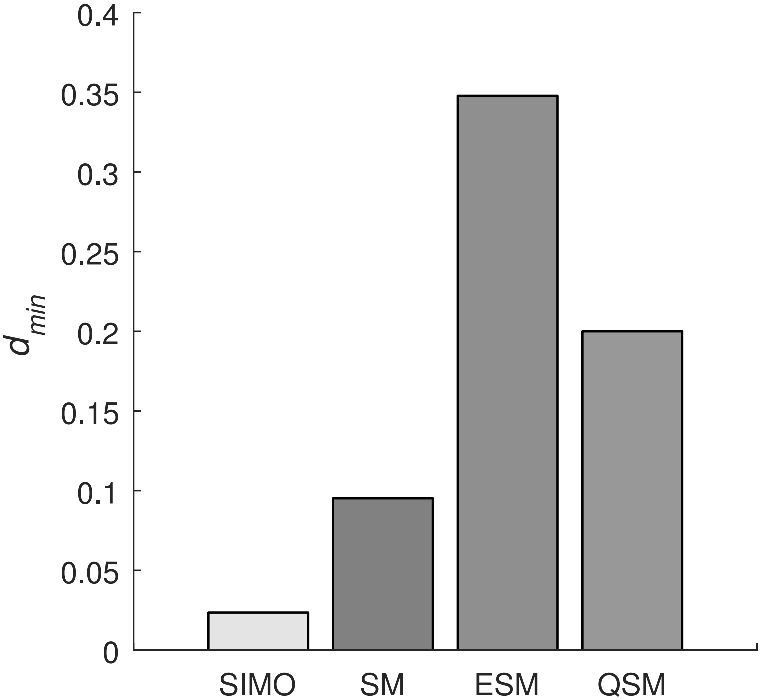
SM ML Detector
$\log_2(n_T)$ bits
Antenna Indices Selection
I
$\log_2(M)$ bits
M - ary Modulation
s
SM Mapper
1
2
n_T
CHANNEL
1
2
n_R
SIMO 1
SIMO 2
SIMO n_T
$\hat{s}, m_1$
$\hat{s}, m_2$
$\hat{s}, m_{n_T}$
Min Selector
Channel Estimation
$\hat{s}, \hat{I}$
$\log_2(M)$ bits
$\log_2(n_T)$ bits
SM Demapper
$\hat{s}, \hat{I}$



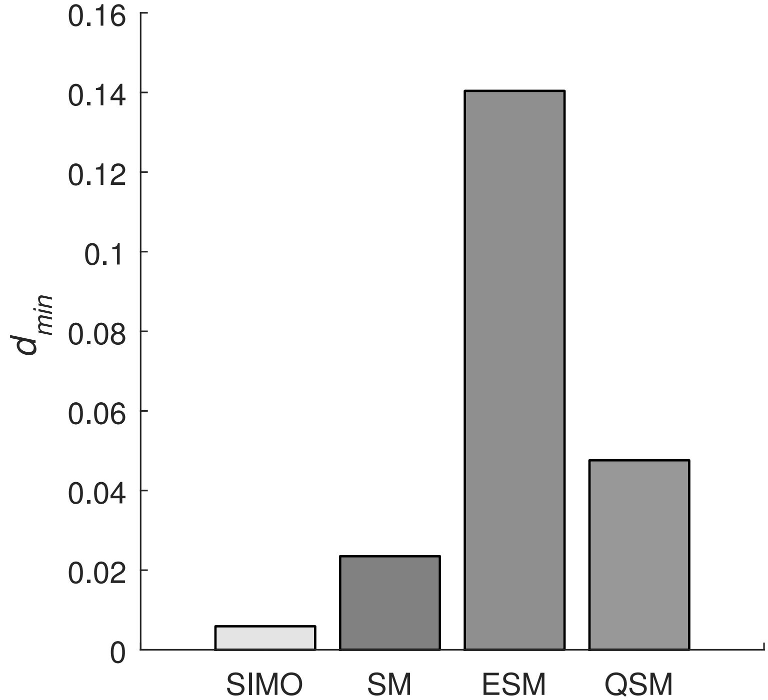
(a) 4 bpcu, $n_T = 2$



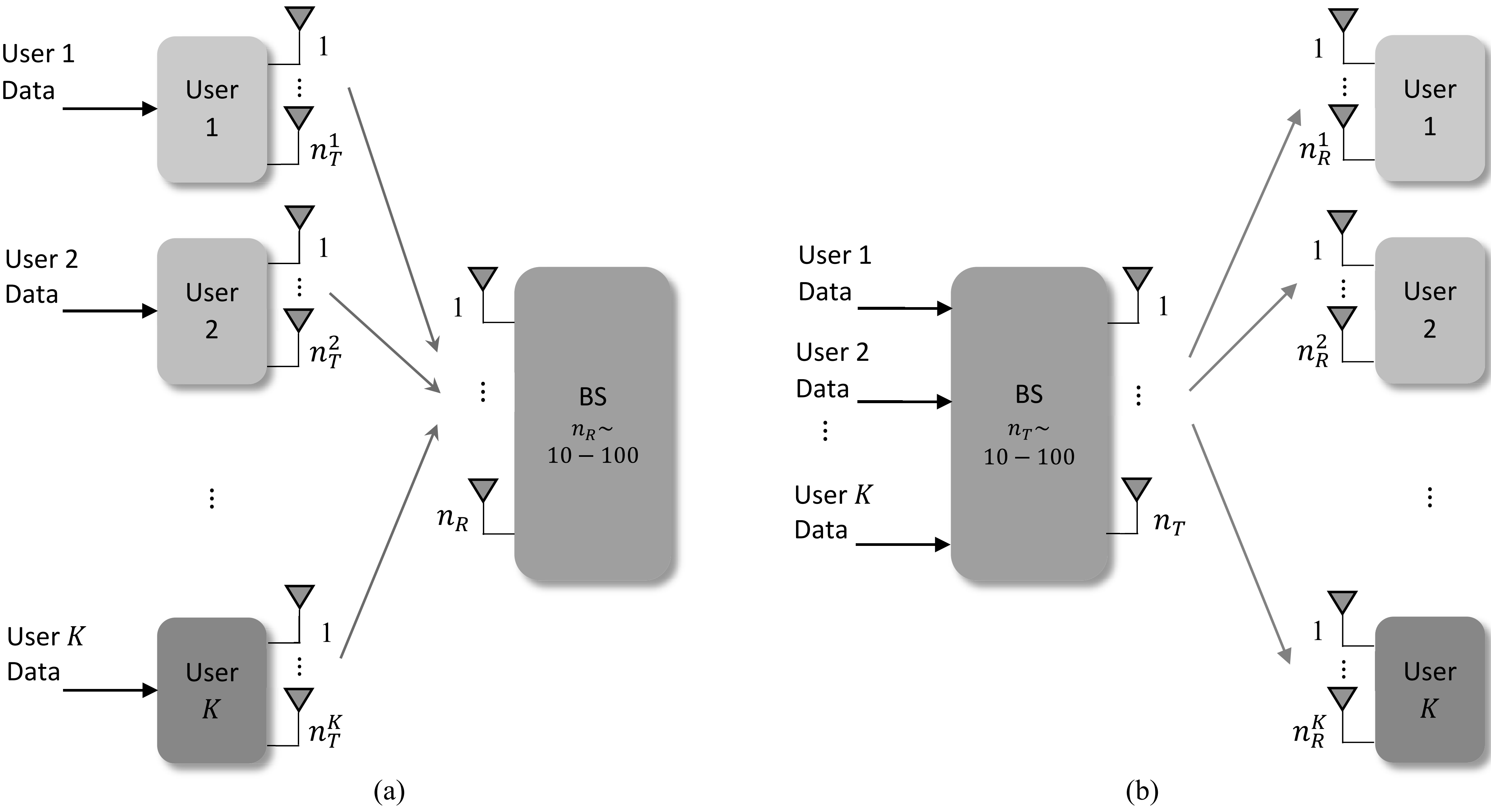
(b) 6 bpcu, $n_T = 4$



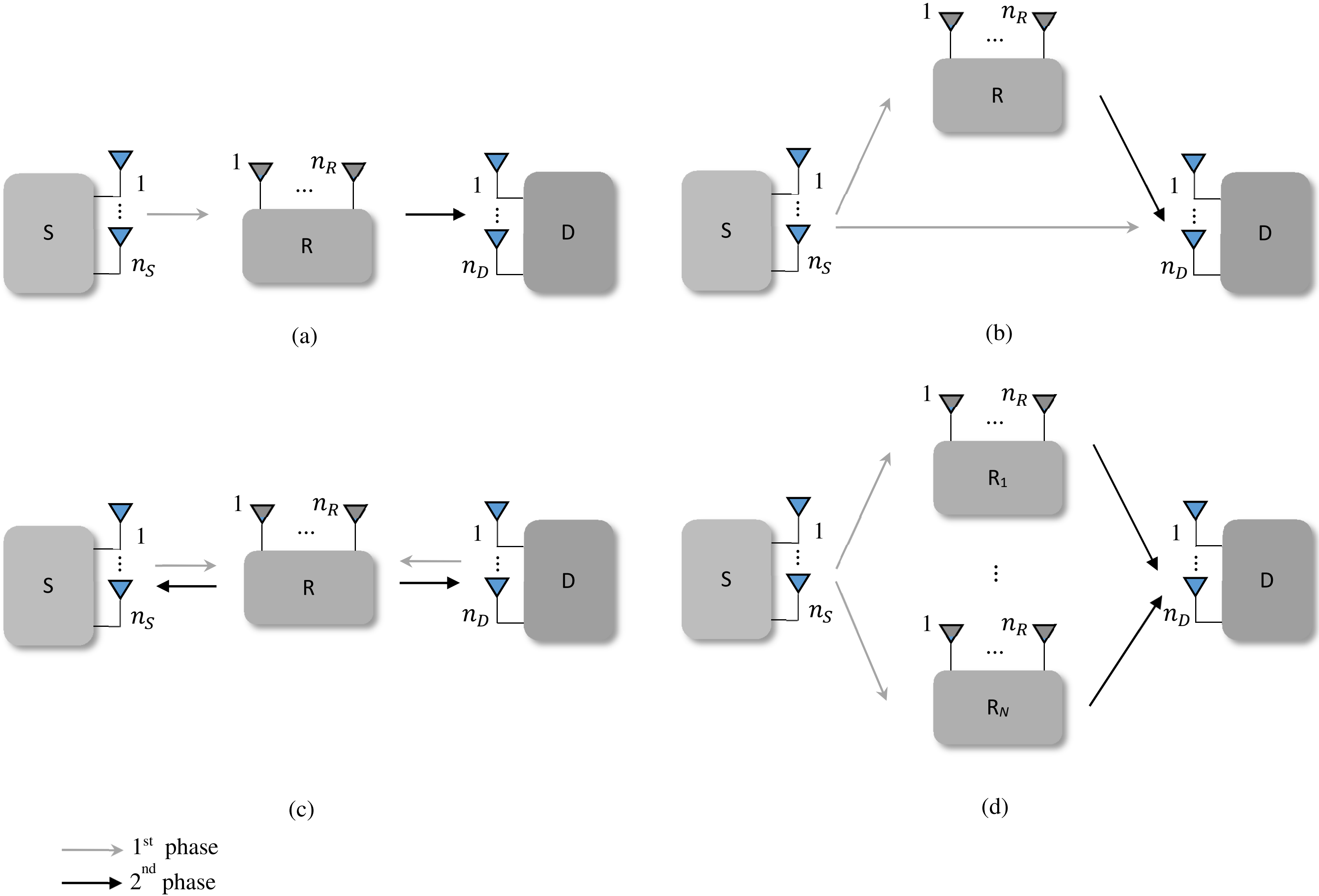
(c) 8 bpcu, $n_T = 4$

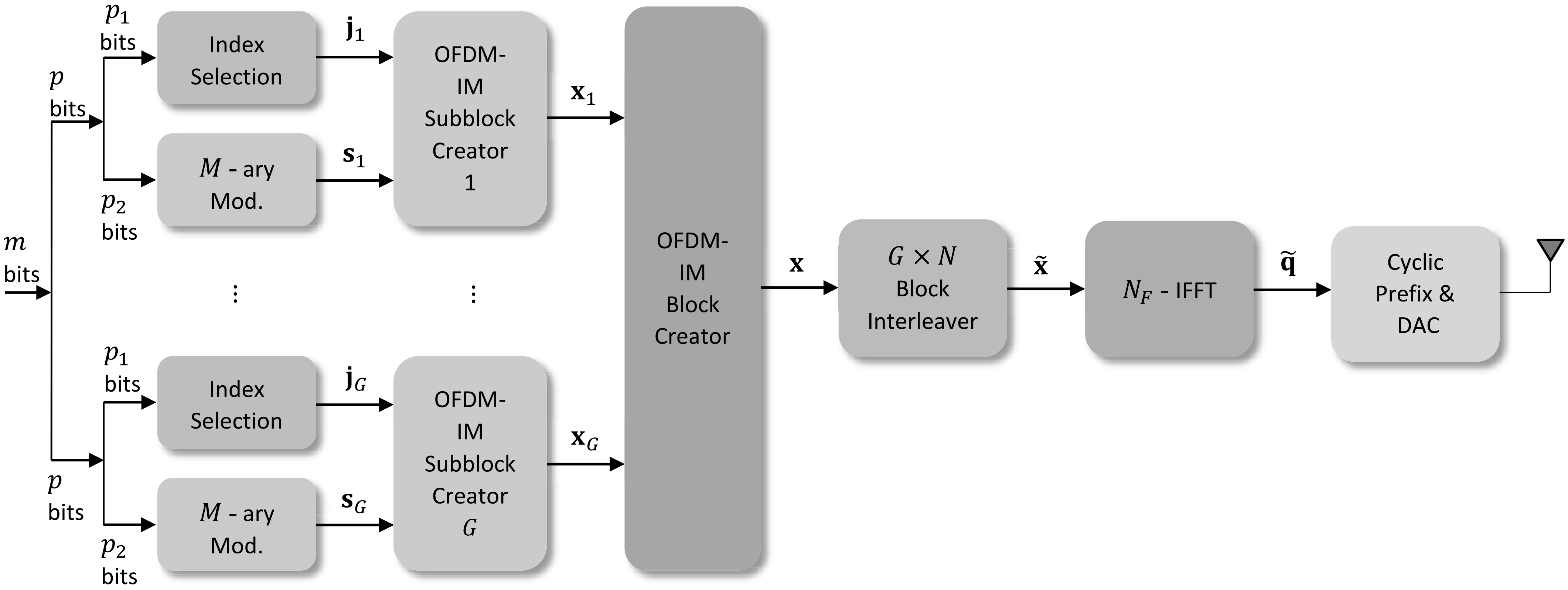


(d) 10 bpcu, $n_T = 4$



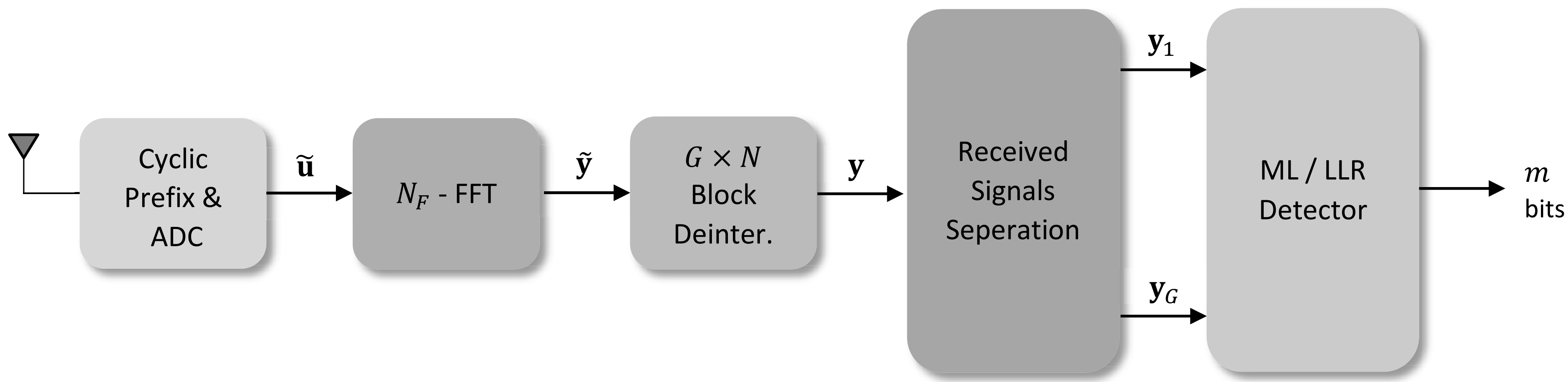
User 1
Data
User
1
1
n_T^1
User 2
Data
User
2
1
n_T^2
User K
Data
User
K
1
n_T^K
1
n_R
BS
$n_R \sim$
$10-100$
User 1
Data
User 2
Data
User K
Data
BS
$n_T \sim$
$10-100$
1
n_T
1
n_R^1
User
1
1
n_R^2
User
2
1
n_R^K
User
K
(a)
(b)


S
R
D
1
n_R
n_S
n_D
(a)
(b)
(c)
R₁
R$_N$
(d)
1st phase
2nd phase



m bits
p bits
p1 bits
p2 bits
Index Selection
M - ary Mod.
j1
s1
OFDM-IM Subblock Creator 1
x1
jG
sG
OFDM-IM Subblock Creator G
xG
OFDM-IM Block Creator
x
G × N Block Interleaver
x̃
N_F - IFFT
q̃
Cyclic Prefix & DAC

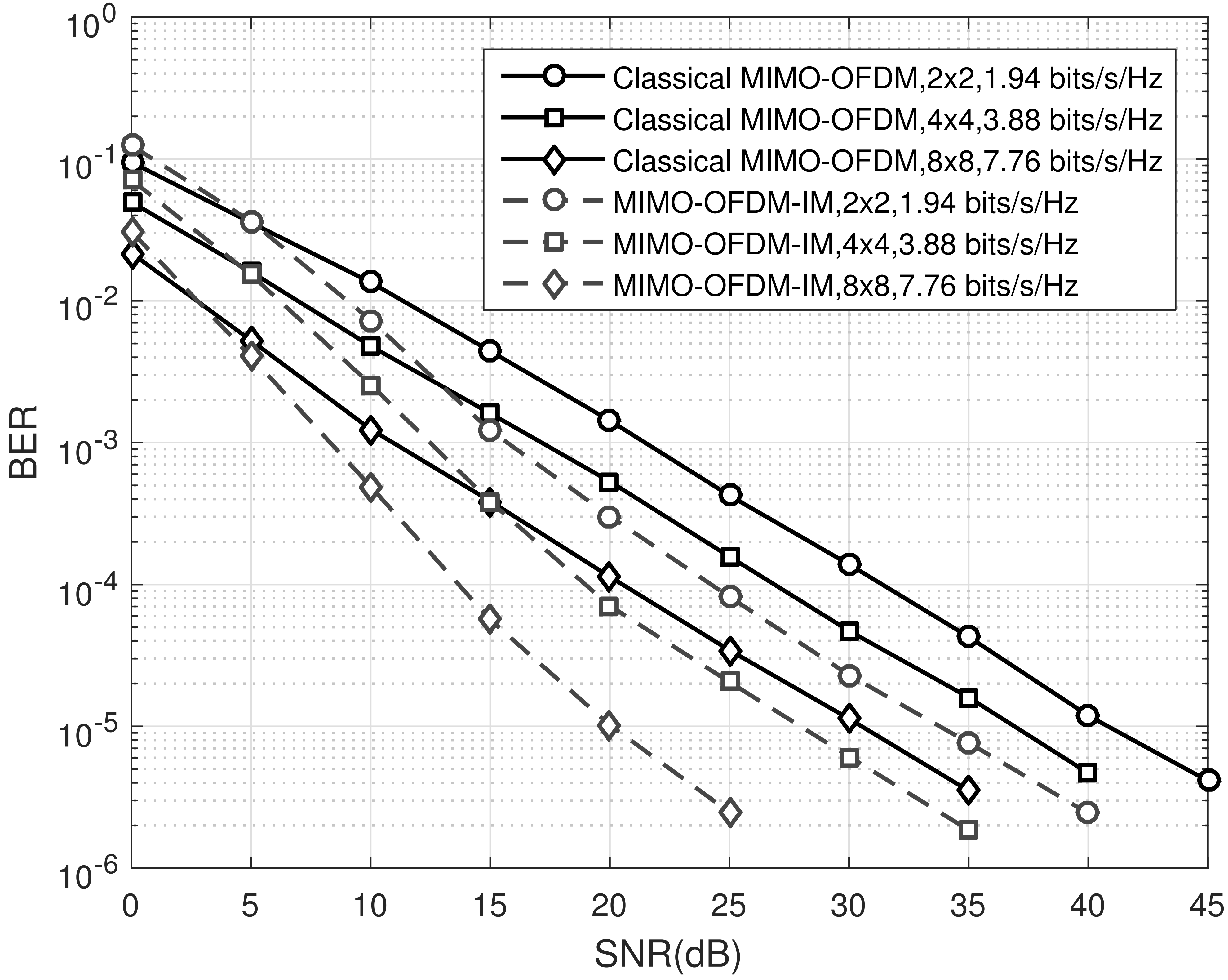
(a)



Cyclic Prefix & ADC
ũ
N_F - FFT
ỹ
G × N Block Deinter.
y
Received Signals Seperation
y1
yG
ML / LLR Detector
m bits

(b)

	bits	*indices*	
$N = 4, K = 2,$ $\binom{4}{2} = 6$ $\Rightarrow p_1 = 2$ bits	$\{00\}, \{01\}, \{10\}, \{11\}$	$[1\ \ 3]^{\mathrm{T}}, [2\ \ 4]^{\mathrm{T}}, [1\ \ 4]^{\mathrm{T}}, [2\ \ 3]^{\mathrm{T}}$	Reference Look-up Table
$N = 32, K = 16,$ $\binom{32}{16} = 601,080,390$ $\Rightarrow p_1 = 29$ bits	$\{0\ 1\ 0\ 0\ 0\ 0\ 1\ 1\ 0\ 1\ 0\ 0\ 0\ 1\ 1\ 0\ 0\ 0\ 1\ 1\ 1\ 0\ 1\ 1\ 0\ 0\ 0\ 1\ 0\}$	$[29\ \ 28\ \ 27\ \ 26\ \ 25\ \ 19\ \ 17\ \ 16\ \ 15\ \ 14\ \ 13\ \ 12\ \ 11\ \ 8\ \ 4\ \ 2]^{\mathrm{T}}$	Combinatorial Number Theory



Classical MIMO-OFDM,2x2,1.94 bits/s/Hz
Classical MIMO-OFDM,4x4,3.88 bits/s/Hz
Classical MIMO-OFDM,8x8,7.76 bits/s/Hz
MIMO-OFDM-IM,2x2,1.94 bits/s/Hz
MIMO-OFDM-IM,4x4,3.88 bits/s/Hz
MIMO-OFDM-IM,8x8,7.76 bits/s/Hz
BER
SNR(dB)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
5
10
15
20
25
30
35
40
45