Chapter 4
Index Modulation Techniques for 5G and Beyond Wireless Systems

Manish Mandloi, Arijit Datta, and Vimal Bhatia

Abstract Index modulation (IM) is one of the emerging techniques for enabling beyond 5G (B5G) wireless communications. It has the potential to meet the stringent energy efficiency (EE) and spectral efficiency (SE) requirements of B5G systems with better error rate performance over the conventional techniques. IM relaxes the need for activating all the resources at the transmitter to transmit the information, thereby allowing low-complexity transmitter architecture designs. The key idea behind IM is to encode the information in the indices of the available resources at the transmitter such as antenna, sub-carriers in orthogonal frequency division multiplexing, time-slots, and radio frequency (RF) mirrors. Massive-MIMO is another such promising technique which provides unprecedented growth in both EE and SE for B5G wireless systems. Spatial multiplexed massive-MIMO is shown to achieve the unbelievable capacity gains over the conventional MIMO systems. However, achieving such gains requires dedicated signal processing resources for each antenna which increase the cost, area, and power-requirement at the transmitter. Interestingly, through IM in massive-MIMO, exceptionally high EE and SE can be achieved with minimal use of the available resources. Recently, multi-dimensional IM (MIM), wherein multiple resources are indexed simultaneously during transmission to enhance the SE further, has attracted researchers and experts from both academia and industry. In this chapter, we discuss different IM and MIM techniques, their representations, and advantages in B5G communications. In particular, we discuss spatial modulation, generalized spatial modulation, media-based modulation, and their possible combi-

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nations as MIM in detail. We also shed the light on the maximum-likelihood detection of information symbols in such systems.

Keywords Index modulation · Massive-MIMO · Radio frequency mirrors · Maximum-likelihood detection · Bit error rate · Spectral efficiency

4.1 Introduction

The exponential increase in the number of mobile subscribers across the globe with advanced data thirsty applications at each user terminal demands fully connected, reliable, and high data rate wireless services (Boccardi 2014). Over the past two decades, the wireless community has seen an upshift of two generations over the second generation (2G) wireless standards to overcome the data rate requirements with an increased number of mobile users serviced simultaneously. With each generation shift (i.e., from 2G to 3G and from 3G to 4G), the overall spectral efficiency is enhanced almost 1000 times. The next generation of wireless systems (5G) are expected to roll out in the market by end 2020 with three-dimensional objectives identified by the international telecommunication union (ITU): (1) enhanced mobile broadband (eMBB), (2) massive machine type communication, and (3) ultra-reliable low latency communication (uRLLC) (Andrews 2014; Boccardi 2014). It is anticipated that the successful implementation of 5G networks will provide the wireless service between any-thing, any-time, and any-where. However, to achieve the key objectives of 5G and beyond wireless systems is a challenging task. To meet the fiber rate communication with high quality of service (QoS), wireless researchers and engineers have come up with multiple physical layer (PHY layer) concepts such as massive multiple-input multiple-output (MIMO) (Lu et al. 2014; Rusek 2013), non-orthogonal multiple access (NOMA) (Dai 2018; Ding 2017), and index modulation (IM) (Basar 2016; Wen et al. 2017). Moreover, research efforts are being put in place to utilize these concepts efficiently in wireless systems in order to achieve enhanced spectral efficiency (SE) and energy efficiency (EE).

Massive-MIMO is one of the promising techniques for achieving high SE and EE in wireless systems (Lu et al. 2014). In massive-MIMO, the large antenna array is used at the base station (BS) which serves comparatively less (few tens) number of users. This results in a substantial processing gain which provides enhanced performance gain over the conventional MIMO systems (Rusek 2013). In spite of its several advantages, the practical feasibility of massive-MIMO is challenging due to the fact that each transmit antenna at the base station as well as at multi-antenna users requires dedicated signal processing resources such as RF chains, power amplifiers, and other circuitry. This increases the power consumption and architectural complexity of the transmitter. Furthermore, reliable detection of spatially multiplexed information streams at the receiver is another crucial factor due to inter-channel interference (interference between multiple streams transmitted from the antennas of the same user/BS) for realizing uRLLC (Yang and Hanzo 2015).

On the other hand, NOMA (Ding 2017) is considered as another such technique which enhances the SE of wireless systems by relaxing the orthogonality of resources for multiple access (termed as orthogonal multiple access (OMA)). In contrast to OMA, NOMA shares the same resources, such as time and frequency for transmitting independent information streams to multiple users simultaneously. NOMA can be broadly classified as code domain (CD) NOMA and power domain (PD) NOMA (Dai 2018). Among these, PD-NOMA is interestingly explored by the researchers for its potential applications in B5G systems. In PD-NOMA, the information of multiple users is superimposed at the transmitter with different power gains which depend on the channel condition of each user. However, at the receiver end, users employ successive interference cancellation (SIC) to decode their information which is a complex process and is severely affected by error propagation (Dai 2018; Ding 2017).

Recently, IM techniques (Basar 2016; Wen et al. 2017) are getting increased attention from both academia and industry as a promising solution for spectrally efficient, low-power, and low-complexity architecture designs. IM relaxes the need for dedicated signal processing resources in wireless systems by encoding the extra information across the resources such as antenna, sub-carriers in OFDM, time-slots, and parasitic elements (radio frequency (RF) mirrors) available at the transmitter. Based on the indexing of different resources, IM techniques can be classified as:

- Spatial modulation (SM);
- Generalized spatial modulation (GSM);
- Space shift keying (SSK);
- OFDM sub-carrier index modulation (OFDM-IM);
- Media-based modulation (MBM).

In IM, extra information bits are encoded across the indices of the available resources at the transmitter along with transmitting information bits using the conventional modulation, i.e., through a symbol selected from the modulation alphabet (Basar 2016; Wen et al. 2017). Basically, there are two types of mappings involved in IM, namely index mapping and symbol mapping. Through index mapping, a part of incoming bits is allocated for activating the resources which yield activation pattern whereas the other part of the incoming bits is used for selecting a constellation point from the modulation alphabet as depicted in Fig. 4.1.

The concept of IM is first introduced in the name of *spatial modulation* in (Di Renzo et al. 2011; Mesleh 2008). In SM, extra information bits are encoded across the index of one active antenna element which is used for transmission of information by selecting a symbol from the conventional modulation alphabet. The increase in SE due to index mapping in SM depends on the total number of combinations of one active antenna. It turns out that, in SM the increase in SE is logarithmic with respect to the number of transmit antennas (discussed in detail later in the chapter). Although SM has limited SE due to only one active antenna, some of its key advantages include the complete elimination of inter-channel interference, requirement of only one radio frequency (RF) chain, and no constraints on the number of the receive antennas. The generalization of SM termed as GSM is proposed in Younis et al.

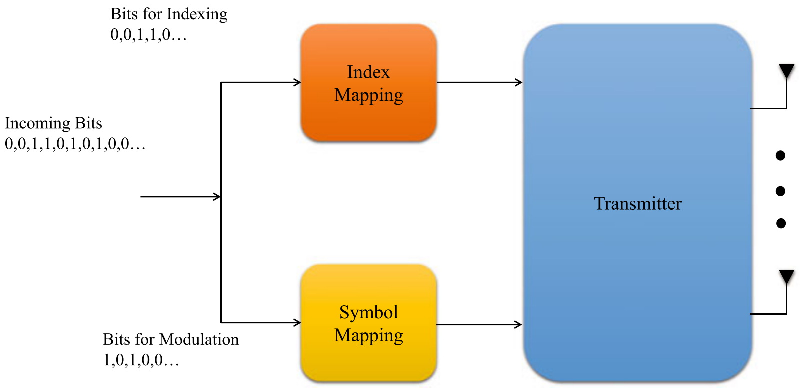

Fig. 4.1 Index and symbol mapping

(2010) where more than one antenna elements are active which helps in embedding more information bits. It is worth noting that the total number of combinations of active antennas increases in GSM which results in higher SE. Though GSM has higher SE over SM, it suffers from the inter-channel interference which is due to multiple active antennas. Reliable detection of information in SM and GSM is a challenging task due to embedded information in index as well as the transmitted symbols which involve significant complexity in detection. To avoid the complexity of detectors in SM and GSM, a simple modulation scheme called as SSK is proposed in Jeganathan et al. (2008, 2009). In SSK, only one antenna is active, which transmits the symbol 1 rather than transmitting a symbol from the modulation alphabet in contrast to SM and GSM. Therefore, SSK relaxes the need for detection of the transmitted symbol from the active antenna yielding a low-complexity detector design. OFDM-IM (Basar 2013, 2015; Ozturk 2016) is another technique where indexing is performed across the sub-carriers in an OFDM transmission system. In OFDM-IM, the combinations of active sub-carriers are large due to which not all the possible combinations are used for transmitting the information. On the other hand, MBM (Khandani 2013, 2014) is a recently proposed IM scheme where multiple RF mirrors are placed near the transmit antenna which creates different channel fade realizations for transmission of information. The indexing in MBM is performed across these channel fade realizations by activating the RF mirrors (Naresh and Chockalingam 2017). The key advantage of MBM is that it offers enhanced spectral efficiency over the other IM techniques such as SM, GSM, and SSK.

IM with massive-MIMO serves as a potential solution to provide better SE and EE in futuristic wireless systems. IM with massive-MIMO has the capability of enabling low-power and ultra-reliable communication which are key objectives of B5G wireless systems. Moreover, further research is being carried out over generalizing the IM concept by combining one or more IM techniques, which are termed as multi-dimensional IM (MIM) (Shamasundar 2017). In MIM, multiple IM concepts are integrated to transmit more information bits through multiple indexing as compared with the conventional IM. Therefore, based on the different possible combinations of IM techniques, MIM can be classified as:

- Space-time IM (ST-IM);
- Spatial modulated media-based modulation (SM-MBM);
- Generalized spatial modulated media-based modulation (GSM-MBM).

In all the aforementioned MIM schemes, indexing is performed across multiple resources simultaneously to encode additional information bits. In ST-IM, antenna and time-slots are indexed together which increase sparsity in the transmitted symbol vector. However, it lacks significantly in the spectral efficiency due to the use of multiple time-slots and activating only one of them. SM-MBM and GSM-MBM are the two most promising MIM techniques where antenna indexing and RF mirrors activity pattern are used for encoding the information. It provides a significant increase in both the SE and the sparsity in the transmitted symbol vector. However, in such MIM techniques, the complexity of the detector increases for achieving the target bit error rate performance. Although IM and MIM have several advantages over the conventional transmission scheme, symbol detection is one of the practical challenges in such systems. IM and MIM detection algorithms involve two key steps: i) detecting the indices used for transmission and ii) detecting the transmitted symbols (Gao et al. 2017; Narasimhan et al. 2015). Finally, the detected indices and symbols are combined to obtain the transmitted information bits through demapping as depicted in Fig. 4.2. To this end, there are several detection techniques proposed in the literature to detect the symbols reliably. In this chapter, we discuss ST-IM and SM-MBM schemes with their mathematical formulation and ML detection in detail.

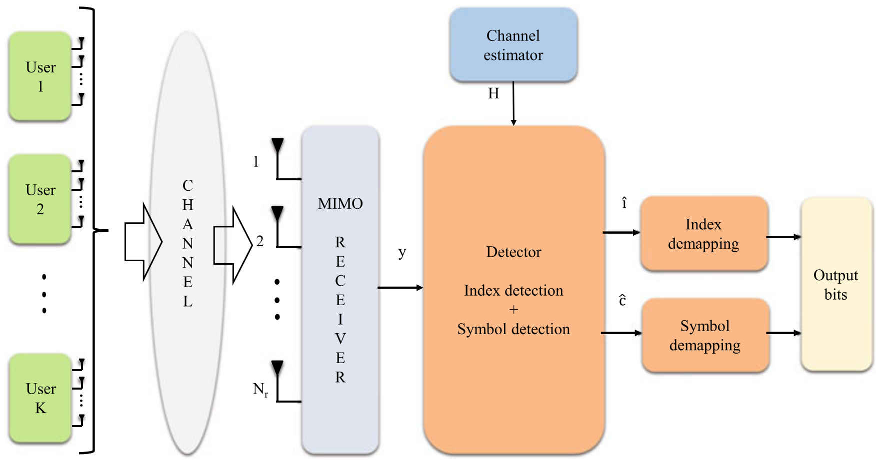

Fig. 4.2 Detector design and demapping

Notations Boldface uppercase and lowercase alphabets represent column vectors and matrices, respectively. $(.)^T$ and $()^{-1}$, respectively, denote transpose and inverse operations. $|\ .\ |$ is the cardinality of a set. $||\ .\ ||_2$ denotes L2-norm. The absolute value of an element is represented as $|\ .\ |$.

4.2 System Model

In this section, we briefly discuss the mathematical formulation of various terminologies in massive-MIMO system which is very much useful in developing the mathematical model for IM massive-MIMO systems in later sections of the chapter. We also discuss the optimal detection scheme in massive-MIMO systems which is termed as maximum-likelihood (ML) detection for detecting the transmitted information from the received symbol vector. Let us consider a massive-MIMO system with K users with each user having N_t transmit antennas, and a base station (BS) having N_r receive antennas to serve the users ($N_\mathrm{r} \times KN_t$) (Lu et al. 2014). We specifically consider the uplink scenario to introduce different IM and MIM schemes in the chapter. User i is assumed to transmit symbol vector $\mathbf{x}_i$ to the BS in each channel use. Each element $x_{(i,k)}$ of $\mathbf{x}_i$ for $k = 1, 2, \ldots, N_t$ is assumed to be taken from a modulation alphabet say $\mathcal{A}$ (e.g., $\mathcal{A} = \{-1 - 1i, -1 + 1i, 1 - 1i, 1 + 1i\}$ for 4-QAM). The wireless channel between the ith user and the BS is represented by $\mathbf{H}_i$ with dimension $N_r \times N_t$ as shown in Fig. 4.3. Note that the dimensions of the channel matrix may change during the discussion of different IM schemes due to different considerations in each scheme. With these assumptions and considerations, the received vector $\mathbf{y}$ can be written as

$$\mathbf{y} = \mathbf{H_1 x_1} + \mathbf{H_2 x_2} + \cdots + \mathbf{H_K x_K} + \mathbf{n}, \tag{4.1}$$

where $\mathbf{n}$ is the additive white Gaussian noise (AWGN) at the receiver, with each element having the Gaussian distribution with mean zero and variance σ^2, i.e., $\sim \mathcal{CN}(0, \sigma^2)$. Eq. (4.1) can also be written as

$$\mathbf{y} = \mathbf{Hx} + \mathbf{n}, \tag{4.2}$$

where $\mathbf{H} = [\mathbf{H}_1, \mathbf{H}_2, \ldots, \mathbf{H}_K]$ and $\mathbf{x} = \left[\mathbf{x}_1^T, \mathbf{x}_2^T, \ldots, \mathbf{x}_K^T\right]^T$ are the composite channel matrix and the transmitted symbol vector, respectively.

4.2.1 Maximum-Likelihood Detection

The optimal detection of information from the received symbol vector can be obtained by performing an exhaustive search over all the possible combinations of the transmit symbol vectors (Rusek 2013). Since each element $x_{(i,k)}$ for $i = 1, 2, \ldots, K$ and $k =$

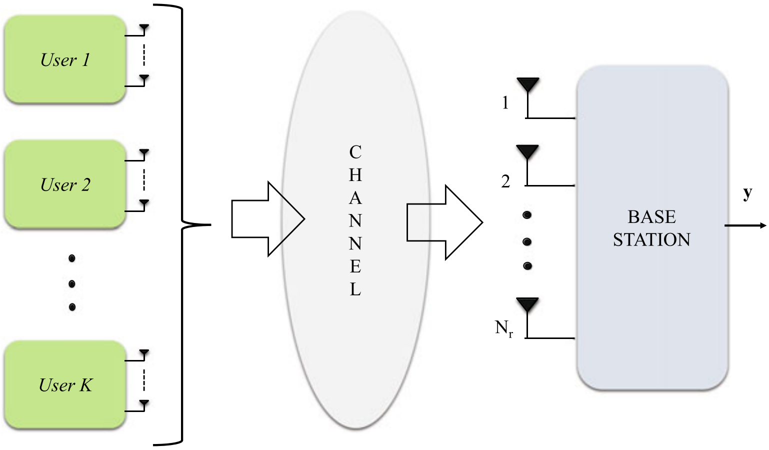

Fig. 4.3 Massive-MIMO system

$1, 2 \ldots, N_t$ is taken from a modulation alphabet of size $|\mathcal{A}|$, and therefore, the set of all the possible combinations of composite transmitted symbol vector $\mathbf{x}$ consists of $|\mathcal{A}|^{KN_t}$ symbol vectors. Thus, to obtain the best possible symbol vector, ML detector performs search over a set consisting of possible transmit $|\mathcal{A}|^{KN_t}$ vectors using the maximum-likelihood (ML) cost metric. The ML cost metric is given by

$$C_{\text{ML}} = \|\mathbf{y} - \mathbf{H}\mathbf{x}\|_2^2, \tag{4.3}$$

and the ML solution is given by

$$\widehat{\mathbf{x}}_{\text{ML}} = \arg \min_{\mathbf{x} \in \mathcal{A}^{KN_t}} \|\mathbf{y} - \mathbf{H}\mathbf{x}\|_2^2. \tag{4.4}$$

This can further be simplified as

$$\widehat{\mathbf{x}}_{\text{ML}} = \arg \min_{\mathbf{x}_i \in \mathcal{A}^{N_t}} \|\mathbf{y} - \sum_{i=1}^{K} \mathbf{H}_i \mathbf{x}_i\|_2^2, \tag{4.5}$$

$$= \arg \min_{x_{(i,j)} \in \mathcal{A}} \|\mathbf{y} - \sum_{i=1}^{K} \sum_{j=1}^{N_t} \mathbf{h}_{(i,j)} x_{(i,j)}\|_2^2 \tag{4.6}$$

However, it can be noted that the number of possible combinations is exponential in the number of users and the number of antennas at each user which makes the realization of ML detection computationally prohibitive.

4.3 Types of Index Modulation

In this section, we discuss the key concept behind SM, GSM, SSK, and MBM with the required mathematical formulation and block diagrams. We also provide the ML detection rule for each of the aforementioned IM schemes for optimal detection of the transmitted information. First, we discuss the SM scheme followed by the discussion on its generalized version, i.e., GSM scheme. Next, we discuss the SSK scheme which is a low-complexity modification of SM. Finally, we provide a brief introduction to the recently proposed MBM scheme.

4.3.1 Spatial Modulation

SM (Mesleh 2008), where indexing is performed across the antennas (i.e., spatial dimension), is the first IM scheme proposed in the literature. In SM, only one antenna out of the available antennas is active at a time which generates different single active antenna patterns termed as *antenna activation patterns* (Di Renzo et al. 2011). The information to be encoded is mapped on the antenna activity pattern by selecting one of the possible patterns based on the incoming information bits. As depicted in Fig. 4.4, the index mapper is connected to the antenna mapper which is used to activate the switch between the RF chain and the selected antenna for transmitting the processed information obtained from the symbol mapper for the ith user.

For simplicity, let us consider a transmitter with N_t antennas. Then, the total number of antenna activation patterns by selecting one antenna out of N_t available antennas equals to $\binom{N_t}{1}$. Therefore, the total number of bits which can be used for selecting one of these patterns is $\lfloor \log_2 \binom{N_t}{1} \rfloor$, where $\lfloor \cdot \rfloor$ is the flooring operation. After selecting the active antenna, a symbol is selected from the modulation alphabet by using $\log_2 |\mathcal{A}|$ bits for transmission through the active antenna. The SE of SM in terms

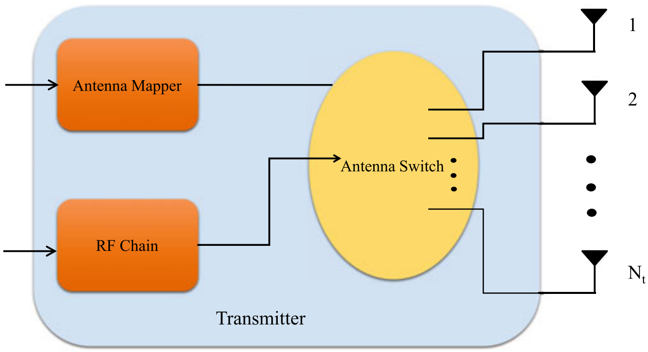

Fig. 4.4 Transmitter block diagram for SM

of bits per channel use (bpcu), i.e., the total number of bits that can be transmitted by a single user in the K user system is given by

$$\eta_{\mathrm{SM}} = \left(\underbrace{\left\lfloor \log_2 \binom{N_\mathrm{t}}{1} \right\rfloor}_{\text{Index mapping}} + \underbrace{\log_2 |\mathcal{A}|}_{\text{Symbol mapping}} \right) \quad \text{bpcu.} \tag{4.7}$$

These η_{SM} bits can be conveyed through the symbol vector transmitted from the user, say ith user, which can be written as

$$\mathbf{x}_i = \left[0, 0, \cdots, \underbrace{x_{(i,k)}}_{\text{active antenna}}, \ldots, 0, 0 \right],$$

where kth antenna is active which transmits a symbol $x_{(i,k)} \in \mathcal{A}$. Similarly, each user maps the incoming information bits into a transmit vector for conveying the information to the BS. The symbol vector received at the BS can be written as

$$\mathbf{y} = \mathbf{H}_1\mathbf{x}_1 + \mathbf{H}_2\mathbf{x}_2 + \cdots + \mathbf{H}_K\mathbf{x}_K + \mathbf{n}$$

which is rewritten as

$$\mathbf{y} = \sum_{i=1}^{K} \mathbf{h}_{(i,k)}\mathbf{x}_{(i,k)} + \mathbf{n}, \quad \text{for } k = 1, 2, \ldots, N_\mathrm{t}, \tag{4.8}$$

where k differs for each i depending on the incoming information. For example, let us consider a system with single user having $N_\mathrm{t} = 4$ and using BPSK modulation, the set of all the possible transmit vector is given by

$$\mathbb{S}_{\mathrm{SM}} = \left\{ \underbrace{\begin{bmatrix} -1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} +1 \\ 0 \\ 0 \\ 0 \end{bmatrix}}_{k=1}, \underbrace{\begin{bmatrix} 0 \\ -1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ +1 \\ 0 \\ 0 \end{bmatrix}}_{k=2}, \underbrace{\begin{bmatrix} 0 \\ 0 \\ -1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ +1 \\ 0 \end{bmatrix}}_{k=3}, \underbrace{\begin{bmatrix} 0 \\ 0 \\ 0 \\ -1 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 0 \\ +1 \end{bmatrix}}_{k=4} \right\}$$

Therefore, by using $\mathbb{S}_{\mathrm{SM}}$ we can obtain $\eta_{\mathrm{SM}} = 3$ bpcu where 1 bit can be transmitted by using a symbol from BPSK and other 2 bits by using one activity pattern, i.e., $\lfloor \log_2 \binom{4}{1} \rfloor$.

4.3.1.1 ML Detection in SM

The ML solution in SM massive-MIMO can be obtained similar to that of the massive-MIMO system (discussed in Sect. 4.2.1). In SM, each user transmits a vector selected from $\mathbb{S}_{\text{SM}}$, the set of all the possible SM transmit vectors. Mathematically, the ML solution at the receiver to achieve the optimal detection can be written as

$$\widehat{\mathbf{x}}_{ML} = \arg \min_{\mathbf{x} \in \mathbb{S}_{\text{SM}}} \|\mathbf{y} - \mathbf{H}\mathbf{x}\|_2^2. \tag{4.9}$$

This can further be simplified as

$$\widehat{\mathbf{x}}_{\text{ML}} = \arg \min_{x_{(i,k)} \in \mathcal{A}, \mathbf{h}_{(i,k)} \in \mathbf{H}_i, \forall i} \|\mathbf{y} - \sum_{i=1}^{K} \mathbf{h}_{(i,k)} \mathbf{x}_{(i,k)}\|_2^2. \tag{4.10}$$

It can easily be observed from here that a joint search is performed over $x_{(i,k)} \in \mathcal{A}$ and $\mathbf{h}_{(i,k)} \in \mathbf{H}_i$.

4.3.2 Generalized Spatial Modulation

SM, which is simplest form of IM schemes, is limited in SE due to only one active antenna. Therefore, GSM, which is an spectrally efficient advancement of SM, proposes to activate multiple antennas for transmission of multiple data streams simultaneously (Younis et al. 2010). However, not all the antennas are active in GSM, which makes it different from spatial multiplexing-based MIMO transmission. The higher SE in GSM is achieved at the cost of increased architecture complexity, which is due to the requirement of dedicated RF chains for each of the active antenna as depicted in Fig. 4.5. In GSM, say N_a number of antennas are active out of all the available N_{t} antennas, and therefore, the total number of antenna activation patterns in GSM is $\binom{N_{\text{t}}}{N_{\text{a}}}$. The total number of bits which can be used for selecting one of these activation patterns is $\lfloor \log_2 \binom{N_{\text{t}}}{N_{\text{a}}} \rfloor$. Further, each of the N_{a} active antennas transmits a symbol selected from the modulation alphabet $\mathcal{A}$, which results in transmission of $N_{\text{a}} \log_2 |\mathcal{A}|$ information bits. Hence, the total number of information bits which can be conveyed form a single GSM user is

$$\eta_{\text{GSM}} = \left(\underbrace{\lfloor \log_2 \binom{N_{\text{t}}}{N_{\text{a}}} \rfloor}_{\text{Antenna Index Mapping}} + \underbrace{N_{\text{a}} \log_2 |\mathcal{A}|}_{\text{Symbol Mapping}} \right) \quad \text{bpcu}. \tag{4.11}$$

which is significantly higher than that of the SM scheme. The transmit vector in GSM consists of multiple non-zero entries and can be written as

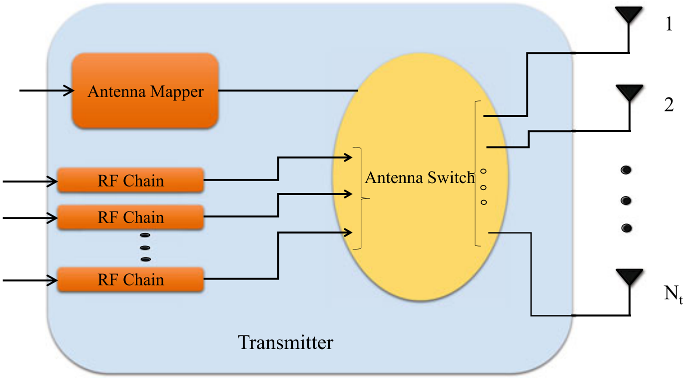

Fig. 4.5 Transmitter block diagram of GSM

$$\mathbf{x}_i = \left[0, \cdots, \underbrace{x_{i_1}}_{\text{active antenna 1}}, \ldots 0, \cdots, \underbrace{x_{i_2}}_{\text{active antenna 2}}, \ldots, 0, \ldots, \underbrace{x_{i_{N_\mathrm{a}}}}_{\text{active antenna } N_\mathrm{a}}, \ldots, 0 \right],$$

where each of the $x_{i_1}, x_{i_2}, \ldots, x_{i_{N_\mathrm{a}}}$ is selected from the modulation alphabet $\mathcal{A}$ and $i_1, i_2, \ldots, i_{N_\mathrm{a}}$ are the indices of the active antennas at the ith user. The received symbol vector at the BS can now be written as

$$\mathbf{y} = \sum_{i=1}^{K} \sum_{k=1}^{N_\mathrm{a}} \mathbf{h}_{i_k} \mathbf{x}_{i_k} + \mathbf{n}. \tag{4.12}$$

For example, consider a multiple antenna system with $N_\mathrm{t} = 4$, $N_\mathrm{a} = 2$ and BPSK modulation, the set of all the possible transmit vectors can be given by

$$\mathbb{S}_{\mathrm{GSM}} = \left\{ \underbrace{\begin{bmatrix} -1 \\ -1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} -1 \\ +1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} +1 \\ -1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} +1 \\ +1 \\ 0 \\ 0 \end{bmatrix}, \ldots,}_{k=1,2} \underbrace{\begin{bmatrix} -1 \\ 0 \\ -1 \\ 0 \end{bmatrix}}_{k=1,3} \ldots, \underbrace{\begin{bmatrix} -1 \\ 0 \\ 0 \\ -1 \end{bmatrix}}_{k=1,4} \ldots, \underbrace{\begin{bmatrix} 0 \\ -1 \\ -1 \\ 0 \end{bmatrix}}_{k=2,3} \ldots, \underbrace{\begin{bmatrix} 0 \\ -1 \\ 0 \\ -1 \end{bmatrix}}_{k=2,4} \ldots, \underbrace{\begin{bmatrix} 0 \\ 0 \\ +1 \\ +1 \end{bmatrix}}_{k=3,4} \right\}$$

The total number of vectors in the set $\mathbb{S}_{\mathrm{GSM}}$ is $\binom{N_\mathrm{t}}{N_\mathrm{a}} \times |\mathcal{A}|^{N_\mathrm{a}} = 6 \times 2^2 = 24$ which can convey $\lfloor \log_2(24) \rfloor = 4$ bits of information. It is worth noting that not all the patterns are used here for transmission of information, and therefore, only 16 out of 24 patterns are used in this example. Also, spatial multiplexing and SM are the special cases of GSM with all active antennas and one active antenna, respectively. In spatial multiplexing, $N_\mathrm{a} = N_\mathrm{t}$ whereas in SM $N_\mathrm{a} = 1$.

4.3.2.1 ML Detection in GSM

Optimal detection in GSM can be performed by using the ML search over the set of all the possible combinations of the transmit vector. The ML solution for GSM scheme can be obtained as

$$\widehat{\mathbf{x}}_{\mathrm{ML}} = \arg \min_{x_{i_k} \in \mathcal{A}, \mathbf{h}_{i_k} \in \mathbf{H}_i, \forall i} \|\mathbf{y} - \sum_{i=1}^{K} \sum_{k=1}^{N_\mathrm{a}} \mathbf{h}_{i_k} \mathbf{x}_{i_k} \|_2^2. \tag{4.13}$$

In obtaining the ML solution, a joint search is performed over $x_{i_k} \in \mathcal{A}$ and $\mathbf{h}_{i_k} \in \mathbf{H}_i$ for all $i = 1, 2, \ldots, K$ and $k = 1, 2, \ldots, N_\mathrm{a}$. It can easily be observed that obtaining the ML solution in GSM is computationally expensive as compared to SM scheme.

4.3.3 Space Shift Keying and Generalized Space Shift Keying

SSK and GSSK are simplified forms of SM and GSM, respectively. In SSK, only one antenna is active which does not transmit the symbol from a conventional modulation alphabet (Jeganathan et al. 2009). The active antenna in SSK transmits only one type of symbol, i.e., 1 whereas all the other antennas remain off. If the number of antennas is N_t, then the total number of possible active antenna combinations are $\binom{N_\mathrm{t}}{1}$ which can convey $\lfloor \log_2 \binom{N_\mathrm{t}}{1} \rfloor$ bits at a time. On the other hand, in GSSK multiple antennas are active similar to GSM but these antennas only transmit 1 (Jeganathan et al. 2008). In GSSK, if N_a antennas are active, then the total number of active antenna combinations is $\binom{N_\mathrm{t}}{N_\mathrm{a}}$ and the total bits which can be conveyed by selection of an activity pattern is $\lfloor \log_2 \binom{N_\mathrm{t}}{N_\mathrm{a}} \rfloor$ bits at a time. The transmit symbol vector in SSK can be written as

$$\mathbf{x}_i = \left[0, 0, \cdots, \underbrace{1}_{\text{active antenna}}, \ldots, 0, 0 \right],$$

and the received symbol vector in SSK is given by

$$\mathbf{y}_{\mathrm{SSK}} = \sum_{i=1}^{K} \mathbf{h}_{i_k} + \mathbf{n}, \quad \text{for } k = 1, 2, \ldots, N_\mathrm{t}. \tag{4.14}$$

Similarly, the transmit vector in GSSK can be written as

$$\mathbf{x}_i = \left[0, \cdots, \underbrace{1}_{\text{active antenna 1}}, \ldots 0, \cdots, \underbrace{1}_{\text{active antenna 2}}, \ldots, 0, \cdots, \underbrace{1}_{\text{active antenna } N_\mathrm{a}}, \ldots, 0 \right],$$

and the received symbol vector is

$$\mathbf{y}_{\text{GSSK}} = \sum_{i=1}^{K} \sum_{k=1}^{N_{\text{a}}} \mathbf{h}_{i_k} + \mathbf{n}. \tag{4.15}$$

For example, if $N_{\text{t}} = 4$, then the set of all the possible transmit vector in SSK is

$$\mathbb{S}_{\text{SSK}} = \left\{ \underbrace{\begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}}_{k=1}, \underbrace{\begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}}_{k=2}, \underbrace{\begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}}_{k=3}, \underbrace{\begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}}_{k=4} \right\}$$

and the set of all the possible transmit vectors can be written as

$$\mathbb{S}_{\text{GSSK}} = \left\{ \underbrace{\begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \end{bmatrix}}_{k=1,2}, \underbrace{\begin{bmatrix} 1 \\ 0 \\ 1 \\ 0 \end{bmatrix}}_{k=1,3}, \underbrace{\begin{bmatrix} 1 \\ 0 \\ 0 \\ 1 \end{bmatrix}}_{k=1,4}, \underbrace{\begin{bmatrix} 0 \\ 1 \\ 1 \\ 0 \end{bmatrix}}_{k=2,3}, \underbrace{\begin{bmatrix} 0 \\ 1 \\ 0 \\ 1 \end{bmatrix}}_{k=2,4}, \underbrace{\begin{bmatrix} 0 \\ 0 \\ 1 \\ 1 \end{bmatrix}}_{k=3,4} \right\}$$

4.3.3.1 ML Detection in SSK and GSSK

It can be observed that the problem of detection in SSK and GSSK is simplified in the sense that there is no need to perform a search over the set $\mathcal{A}$. Therefore, the ML detection problem in SSK can be formulated as

$$\widehat{\mathbf{x}}_{\text{ML}} = \arg \min_{\mathbf{h}_{i_k} \in \mathbf{H}_i, \forall i} \|\mathbf{y} - \sum_{i=1}^{K} \mathbf{h}_{i_k} \|_2^2. \tag{4.16}$$

and that of in GSSK, ML solution can be obtained as

$$\widehat{\mathbf{x}}_{\text{ML}} = \arg \min_{\mathbf{h}_{i_k} \in \mathbf{H}_i, \forall i} \|\mathbf{y} - \sum_{i=1}^{K} \sum_{k=1}^{N_{\text{a}}} \mathbf{h}_{i_k} \|_2^2. \tag{4.17}$$

The ML search now reduces to search only over the set $\mathbf{H}$ in contrast to the SM and GSM where the search also involves set $\mathcal{A}$, which ultimately increases the computational complexity of detector at the receiver.

4.3.4 Media-Based Modulation

MBM is a recently proposed IM scheme where indexing is performed across the parasitic elements called as RF mirrors (Khandani 2013). These elements are placed near the transmit antennas. The ON/OFF switching of these RF mirrors generates different channel fade realizations at a far field in a rich scattering environment. The ON/OFF activity of the mirrors is chosen based on the incoming information bits. Once a switching pattern is selected for a particular antenna, the antenna then transmits a symbol selected from the modulation alphabet as depicted in Fig. 4.6 (Khandani 2014). Note that the key difference between other IM schemes discussed so far and MBM is that, in MBM all the antennas transmit information. If there are $m_{\rm rf}$ RF mirrors are placed near an antenna, then it generates $2^{m_{\rm rf}}$ ON/OFF switching patterns (Naresh and Chockalingam 2017). Therefore, to select a particular pattern requires $\lfloor \log_2 2^{m_{\rm rf}} \rfloor = m_{\rm rf}$ information bits which is linear with respect to the number of RF mirrors. This is in contrast to the logarithmic increase in information conveying capability of SM and GSM with respect to the total number of antennas. Other than $m_{\rm rf}$ bits, each antenna also transmits a symbol which convey additional $\log_2 |\mathcal{A}|$ information bits. Therefore, the total SE per antenna in terms of bpcu in MBM scheme is

$$\eta_{\rm MBM} = \left(\underbrace{m_{\rm rf}}_{\text{Index Mapping}} + \underbrace{\log_2 |\mathcal{A}|}_{\text{Symbol Mapping}} \right) \quad \text{bpcu.} \tag{4.18}$$

Let us consider a single antenna user with $m_{\rm rf} = 2$ as shown in Fig. 4.7. The set of possible ON/OFF activity patterns is $n_{\rm a} = \{(0, 0), (0, 1), (1, 0), (1, 1)\}$ where each of the activity pattern results in an independent channel realization $\mathbf{h}_1, \mathbf{h}_2, \mathbf{h}_3$ and $\mathbf{h}_4$, respectively. Based on the incoming information bits, one of these activity pattern is selected to transmit information bearing symbol selected from the modulation alphabet. Let us consider the composite channel matrix $\mathbf{H} = [\mathbf{h}_1, \mathbf{h}_2, \mathbf{h}_3, \mathbf{h}_4]$, then the composite transmit vector for a single antenna MBM transmitter is $\mathbb{S}_{\rm MBM} = \{[\alpha_i, 0, 0, 0], [0, \alpha_i, 0, 0], [0, 0, \alpha_i, 0], [0, 0, 0, \alpha_i]$. It is worth noting that the single antenna user transmits $\alpha_i \in \mathcal{A}$ only from the antenna, but for mathematical simplicity we consider the concept of composite channel and composite transmit vector.

For generalization of the transmit vector to the case of multiple users, let us consider single antenna users for simplicity. Each user consists of $m_{\rm rf}$ RF mirrors, $M = 2^{m_{\rm rf}}$ mirror activation patterns and use $\mathcal{A}$ modulation alphabet for transmission of a symbol. Let $\mathbf{h}_k^j$ denote the $N_r \times 1$ channel state vector corresponding to the jth MAP selected by the kth user for transmitting the $\alpha_k \in \mathbb{A}$, where $\mathbf{h}_k^j = [h_{1,k}^j, h_{2,k}^j, \ldots, h_{N_r,k}^j]^T$. Each $h_{i,k}^j$ is assumed to be independent and identically distribute (i.i.d.) complex Gaussian random variable with zero mean and unit variance, i.e., $\sim \mathcal{CN}(0, 1)$. Let us define the matrix $\mathbf{H}_k = [\mathbf{h}_k^1, \mathbf{h}_k^2, \ldots, \mathbf{h}_k^M]$ and the MBM signal set for a single user as

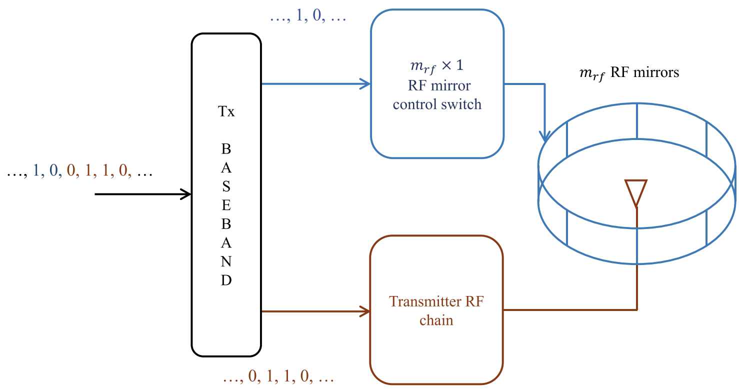

Fig. 4.6 Transmitter block diagram of MBM

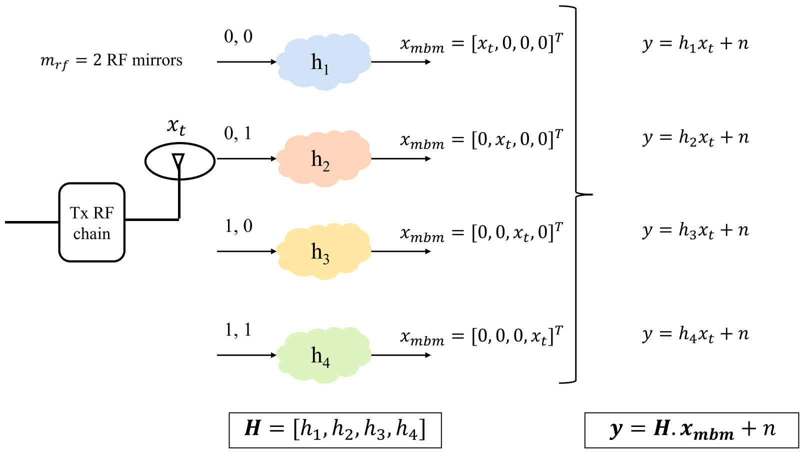

Fig. 4.7 Single antenna MBM system

$$\mathbb{S}_{\text{MBM}} = \{\mathbf{s}_{j,i} : j = 1, 2, \dots, M, i = 1, 2, \dots, |\mathbb{A}|\},$$
$$\text{s.t. } \mathbf{s}_{j,i} = [0, \dots, 0, \underbrace{\alpha_i}_{j\text{th coordinate}}, 0, \dots, 0]^T, \alpha_i \in \mathbb{A}, \tag{4.19}$$

which means that $\mathbf{s}_{j,i}$ is an $M \times 1$ vector with only one nonzero entry $\alpha_i \in \mathbb{A}$ corresponding to the jth channel fade realization. For the kth user, let us denote $\mathbf{x}_k \in \mathbb{S}_{\text{MBM}}$, and therefore, the received vector at the BS can be written as

$$\mathbf{y} = \sum_{k=1}^{K} \mathbf{H}_k \mathbf{x}_k + \mathbf{n}, \tag{4.20}$$

where $\mathbf{n}$ is an $N_r \times 1$ additive white Gaussian noise (AWGN) vector with $\mathbf{n} \sim \mathcal{CN}(0, \sigma^2 \mathbf{I}_{N_r})$. Further, we can rewrite the received vector as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}, \tag{4.21}$$

where $\mathbf{H} = [\mathbf{H}_1 \quad \mathbf{H}_2 \quad \ldots \quad \mathbf{H}_K]$ is an $N_r \times KM$ multi-user MBM-MIMO channel matrix and $\mathbf{x} = [\mathbf{x}_1^T \quad \mathbf{x}_2^T \quad \ldots \quad \mathbf{x}_K^T]^T$ is $KM \times 1$ multi-user MBM-MIMO transmit symbol vector.

At receiver, the objective is to detect the ML solution given the received vector $\mathbf{y}$ and the channel state information $\mathbf{H}$ as

$$\hat{\mathbf{x}} = \arg \min_{\mathbf{x} \in \mathbb{S}_{\text{MBM}}^K} \|\mathbf{y} - \mathbf{H}\mathbf{x}\|_2^2. \tag{4.22}$$

However, finding ML solution requires an exhaustive search over the set of all the possible vectors, i.e., $\mathbb{S}_{\text{MBM}}^K$ which is computationally impractical in massive-MIMO systems.

4.4 Multi-dimensional Index Modulation

In this section, we discuss an improved IM scheme termed as MIM wherein multiple IM schemes are integrated to obtain higher SE. First, we discuss the space-time IM scheme which is the simplest form of MIM. Next, we extend this concept to the spatial MBM which achieves significantly high SE over other IM and MIM schemes.

4.4.1 Space-Time IM

In space-time IM, multiple resources are utilized for indexing such as time-slots and antennas at the transmitter apart from transmitting the symbol selected from the modulation alphabet (Shamasundar 2017). Let us consider T time-slots and N_t antennas are available for indexing. The total number time-slot activity patterns are $\binom{T}{1}$, and for each time-slot activity pattern, there are $\binom{N_\text{t}}{1}$ antenna activity patterns possible. Therefore, the total number of bits that can be conveyed by indexing across time-slots is $\lfloor \log_2 \binom{T}{1} \rfloor$ and that of across antenna is $\lfloor \log_2 \binom{N_\text{t}}{1} \rfloor$. The incoming information bits are divided into three part: One part is used for selecting the time-slot, second part is used for selecting an antenna, and the third part is used to select a symbol from $\mathcal{A}$ for transmission. The SE in space-time IM in terms of bpcu is

$$\eta_{\text{ST-IM}} = \lfloor \log_2 \binom{T}{1} \rfloor + \lfloor \log_2 \binom{N_\text{t}}{1} \rfloor + \log_2 |\mathcal{A}|. \tag{4.23}$$

For example, if $T = 2$, $N_\mathrm{t} = 4$ and BPSK modulation is considered, then the set of possible transmit vector is

$$\mathbb{S}_{\text{ST-IM}} = \left\{ \left\{ \underbrace{\begin{bmatrix}-1\\0\end{bmatrix}}_{T=1}, \underbrace{\begin{bmatrix}0\\0\end{bmatrix}}_{T=2} \right\}, \left\{ \underbrace{\begin{bmatrix}+1\\0\end{bmatrix}}_{T=1}, \underbrace{\begin{bmatrix}0\\0\end{bmatrix}}_{T=2} \right\}, \left\{ \underbrace{\begin{bmatrix}0\\-1\end{bmatrix}}_{T=1}, \underbrace{\begin{bmatrix}0\\0\end{bmatrix}}_{T=2} \right\}, \left\{ \underbrace{\begin{bmatrix}0\\+1\end{bmatrix}}_{T=1}, \underbrace{\begin{bmatrix}0\\0\end{bmatrix}}_{T=2} \right\} \right\}$$
$$\left\{ \left\{ \underbrace{\begin{bmatrix}0\\0\end{bmatrix}}_{T=1}, \underbrace{\begin{bmatrix}-1\\0\end{bmatrix}}_{T=2} \right\}, \left\{ \underbrace{\begin{bmatrix}0\\0\end{bmatrix}}_{T=1}, \underbrace{\begin{bmatrix}+1\\0\end{bmatrix}}_{T=2} \right\}, \left\{ \underbrace{\begin{bmatrix}0\\0\end{bmatrix}}_{T=1}, \underbrace{\begin{bmatrix}0\\-1\end{bmatrix}}_{T=2} \right\}, \left\{ \underbrace{\begin{bmatrix}0\\0\end{bmatrix}}_{T=1}, \underbrace{\begin{bmatrix}0\\+1\end{bmatrix}}_{T=2} \right\} \right\} \tag{4.24}$$

The transmit symbol vector of ith user for ST-IM can be written as

$$\mathbf{x}_i^{(t)} = [0, \ldots, 0, x_i(k, \tau), 0, \ldots, 0], \tag{4.25}$$

where k is the active antenna index, $\tau \in \{1, 2, \ldots, T\}$, $x_i(k, \tau) \in \mathcal{A}$, i.e., $x_i(k, t) = 0$ for all $t \neq \tau$. With the assumption that the channel state information is block faded for T time-slots, then the received vector in ST-IM can be written as

$$\begin{aligned} \mathbf{y} &= \mathbf{H}_i \mathbf{x}_i^{(t)} + \mathbf{n} \\ &= \sum_{i=1}^{K} \mathbf{h}_{i,k} x_i(k, \tau) + \mathbf{n} \end{aligned} \tag{4.26}$$

Now, let us consider the composite transmit vector $\mathbf{x} = [\mathbf{x}_1^{(t)}, \mathbf{x}_2^{(t)}, \ldots, \mathbf{x}_K^{(t)}]$. The ML detector in ST-IM for obtaining the optimal solution can be formulated as

$$\hat{\mathbf{x}} = \arg \min_{\mathbf{x}_i^{(t)} \in \mathbb{S}_{\text{ST-IM}}^K} \|\mathbf{y} - \mathbf{H}_i \mathbf{x}_i^{(t)}\|_2^2, \tag{4.27}$$

$$= \arg \min_{x_i(k,\tau) \in \mathcal{A}} \|\mathbf{y} - \sum_{i=1}^{K} \mathbf{h}_{i,k} x_i(k, \tau)\|_2^2. \tag{4.28}$$

4.4.2 Spatial Modulated Media-Based Modulation

SM-MBM is a new MIM scheme where the concept of SM and MBM is integrated to obtain a higher SE over both SM and MBM (Shamasundar 2017). In SM-MBM, we consider multiple antenna transmitter with each antenna having multiple RF mirrors deployed nearby each antenna as depicted in Fig. 4.8.

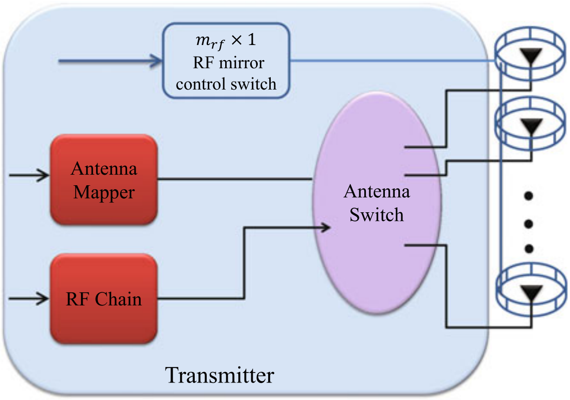

Fig. 4.8 SM-MBM transmitter block diagram

In SM-MBM, the information is conveyed by using antenna activation pattern, mirror activation pattern, and the symbol transmitted selected from the modulation alphabet. The total number of information bits that can be conveyed by using antenna activation pattern and mirror activation pattern is $\lfloor \log_2 \binom{N_t}{1} \rfloor + m_{rf}$. Additionally, $\log_2 |\mathcal{A}|$ bits are also conveyed using a symbol selected from the modulation alphabet $\mathcal{A}$. This results in the total SE of SM-MBM scheme as

$$\eta_{\text{SM-MBM}} = \left(\underbrace{\lfloor \log_2 \binom{N_t}{1} \rfloor}_{\text{Antenna index mapping}} + \underbrace{m_{rf}}_{\text{RF mirror index mapping}} + \underbrace{\log_2 |\mathcal{A}|}_{\text{Symbol mapping}} \right) \quad \text{bpcu.} \tag{4.29}$$

The transmit symbol vector $\mathbf{x}_i$ from the ith user can be written as $\left[0, \cdots, 0, x_{(i,k,p)}, 0, \ldots, 0\right]$, where $x_{i,k,p} \in \mathcal{A}$ is the information symbol from the kth antenna and pth mirror activation pattern. It is worth noting that $k \in \{1, 2, \ldots, N_t\}$ and $p \in \{1, 2, \ldots, 2^{m_{rf}}\}$, and therefore, the size of the symbol vector $\mathbf{x}_i$ is $2^{m_{rf}} \times N_t$ with only one nonzero entry. Similarly, the channel matrix $\mathbf{H}_i$ consists of $2^{m_{rf}} \times N_t$ columns with each column of size $N_r \times 1$. The received vector in SM-MBM system can be written as

$$\begin{aligned} \mathbf{y} &= \sum_{i=1}^{K} \mathbf{H}_i \mathbf{x}_i + \mathbf{n}, \\ &= \sum_{i=1}^{K} \mathbf{h}_{(i,k,p)} x_{(i,k,p)} + \mathbf{n}. \end{aligned} \tag{4.30}$$

Table 4.1 IM and MIM schemes with their SE

IM and MIM schemes	Indexing	SE (bpcu)
SM	Antenna	$\eta_{\mathrm{SM}} = \left(\underbrace{\lfloor \log_2 \binom{N_{\mathrm{t}}}{1} \rfloor}_{\text{Antenna index mapping}} + \underbrace{\log_2 \lvert \mathcal{A} \rvert}_{\text{Symbol mapping}} \right)$
GSM	Antenna	$\eta_{\mathrm{GSM}} = \left(\underbrace{\lfloor \log_2 \binom{N_{\mathrm{t}}}{N_{\mathrm{a}}} \rfloor}_{\text{Antenna index mapping}} + \underbrace{N_{\mathrm{a}} \log_2 \lvert \mathcal{A} \rvert}_{\text{Symbol mapping}} \right)$
SSK	Antenna	$\eta_{\mathrm{SSK}} = \left(\underbrace{\lfloor \log_2 \binom{N_{\mathrm{t}}}{1} \rfloor}_{\text{Antenna index mapping}} \right)$
GSSK	Antenna	$\eta_{\mathrm{SSK}} = \left(\underbrace{\lfloor \log_2 \binom{N_{\mathrm{t}}}{N_{\mathrm{a}}} \rfloor}_{\text{Antenna index mapping}} \right)$
MBM	RF mirrors	$\eta_{\mathrm{MBM}} = \left(\underbrace{m_{\mathrm{rf}}}_{\text{RF mirror index mapping}} + \underbrace{\log_2 \lvert \mathcal{A} \rvert}_{\text{Symbol mapping}} \right)$ bpcu
SM-MBM	Antenna and RF mirrors	$\eta_{\mathrm{SM\text{-}MBM}} = \left(\underbrace{\lfloor \log_2 \binom{N_{\mathrm{t}}}{1} \rfloor}_{\text{Antenna index mapping}} + \underbrace{m_{\mathrm{rf}}}_{\text{RF mirror index mapping}} + \underbrace{\log_2 \lvert \mathcal{A} \rvert}_{\text{Symbol mapping}} \right)$ bpcu

Next, to detect the transmitted information symbol optimally, we introduce the ML detection for SM-MBM which can be written as

$$\hat{\mathbf{x}} = \arg \min_{\mathbf{x}_i \in \mathbb{S}^K_{\text{SM-MBM}}} \|\mathbf{y} - \mathbf{H}_i \mathbf{x}_i\|_2^2, \tag{4.31}$$

$$= \arg \min_{x_{(i,k,p)} \in \mathcal{A}} \|\mathbf{y} - \sum_{i=1}^{K} \mathbf{h}_{(i,k,p)} x_{(i,k,p)}\|_2^2, \tag{4.32}$$

where $\mathbb{S}^K_{\text{SM-MBM}}$ is the set of all the possible composite transmit vectors from the K users jointly.

This completes our discussion on different IM and MIM schemes in detail. All the schemes are listed in Table 4.1 with their SE in terms of bpcu.

4.5 Conclusion

In this chapter, we introduced different IM schemes as a low-complexity solution for B5G wireless systems. In particular, first, we discussed SM, GSM, SSK, and MBM schemes with their mathematical formulation in detail. We also discussed the ML solution for each of these IM techniques. Through discussion, it is revealed that SSK is the simplest IM scheme and require low-complexity receiver design for detection of information symbols. SM and GSM involve the transmission of additional information through a symbol selected from the modulation alphabet which increases its SE at the cost of increased detection complexity and requirement of dedicated RF chain(s). On the other hand, MBM, which is a new IM scheme, has improved SE over SSK, SM, and GSM due to linear increase in SE with respect to the number in RF mirrors. Next, we discussed multi-dimensional IM schemes which involve combination of two or more IM schemes to convey the information from transmitter to the receiver thereby enhancing the SE further. IM and MIM are the emerging scheme with significant advantages in terms of inter-channel interference, reliability, and saving in resources. However, there is a lot of research scope to develop low-complexity receiver architectures for detection and demapping of the transmitted information in IM and MIM. As a future work, application of IM and MIM in the downlink of NOMA systems is an interesting work which could replace the complex successive interference cancellation operation at the user end without affecting the SE.

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