Design Guidelines for Spatial Modulation

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***Abstract*—A new class of low-complexity, yet energy-efficient Multiple-Input Multiple-Output (MIMO) transmission techniques, namely, the family of Spatial Modulation (SM) aided MIMOs (SM-MIMO), has emerged. These systems are capable of exploiting the spatial dimensions (i.e., the antenna indices) as an additional dimension invoked for transmitting information, apart from the traditional Amplitude and Phase Modulation (APM). SM is capable of efficiently operating in diverse MIMO configurations in the context of future communication systems. It constitutes a promising transmission candidate for large-scale MIMO design and for the indoor optical wireless communication while relying on a single-Radio Frequency (RF) chain. Moreover, SM may be also viewed as an entirely new hybrid modulation scheme, which is still in its infancy. This paper aims for providing a general survey of the SM design framework as well as of its intrinsic limits. In particular, we focus our attention on the associated transceiver design, on spatial constellation optimization, on link adaptation techniques, on distributed/cooperative protocol design issues, and on their meritorious variants.**

***Index Terms*—Cooperative communications, large-scale MIMO, link adaptation, space–time coding, spatial modulation.**

I. Introduction

MULTIPLE-INPUT multiple-output (MIMO) systems are capable of achieving a capacity gain and/or diversity gain, which is based on striking a beneficial trade-off, depending on the near-instantaneous channel conditions [1]–[4]. Hence they have been adopted in most of the recent communication standards, such as IEEE 802.11n, IEEE 802.16e, and 3GPP Long-Term Evolution (LTE) [5], [6]. In a wireless MIMO transmission system, the transmission technique employed plays an important role in determining the achievable system performance. Recently, the conventional spatial-domain MIMO transmission techniques have been extended to the time-domain, the frequency-domain as well as to their combinations [7], [8]. In order to efficiently exploit the associated grade of freedom offered by MIMO channels, a meritorious transmission technique should be designed to satisfy a diverse range of practical requirements and to strike an attractive tradeoff amongst the conflicting factors of the computational complexity imposed, the attainable bit error ratio (BER) and the achievable transmission rate [9], [10].

In the diverse family of MIMO techniques, the recently proposed spatial modulation (SM) [11] (which was referred to as Information-Guided Channel Hopping (IGCH) modulation in [12]) is particularly promising, since it is capable of exploiting the indices of the transmit antennas (TAs) as an additional dimension invoked for transmitting information, apart from the traditional Amplitude and Phase Modulation (APM) [13]. At a given Signal to Noise Ratio (SNR), the throughput of the SM-MIMO may potentially become higher than that of Space–Time Coding (STC) [14], but this is not necessarily its most prominent benefit, because in SM only a single TA is activated at any time instant. Hence SM is capable of dispensing with the requirement of multiple Radio Frequency (RF) chains, therefore relaxing the Inter-Antenna-Synchronization (IAS) specifications, whilst mitigating the Inter Antenna Interference (IAI) of conventional MIMO techniques [15]. Additionally, the single-RF design is capable of reducing the total power consumption. In fact, only a single power amplifier is needed for implementing SM-MIMO systems, which is typically responsible for the vast majority of power dissipation at the transmitter [16], [17]. Another advantage of SM is that it may be flexibly configured for diverse transmit and receive antenna constellations, especially for the challenging scenario of asymmetric/unbalanced MIMO systems, whose channel matrix is rank-deficient [15].

Due to the above-mentioned advantages, SM constitutes an attractive option for the emerging family of large-scale MIMO systems [18], [19]. As a further advance, the principle of SMs was also extended to indoor optical wireless communication in [20]–[23], which relies on optical transmissions for conveying information. Altogether, SM constitutes a promising low-complexity energy-efficient MIMO transmission technique, which relies on a low-cost transceiver and is capable of efficiently operating in diverse MIMO configurations in the context of future communication systems. Recently, the potential benefits of SM have been validated not only via simulations [11], [14] but also by experiments [24]–[26]. The benefits of SM-MIMOs aided wireless communications are summarized in Fig. 1. In the sequel, they are characterized in more detail.

The wide-ranging simulation based and analytical studies disseminated in [27]–[34] have characterized some of the

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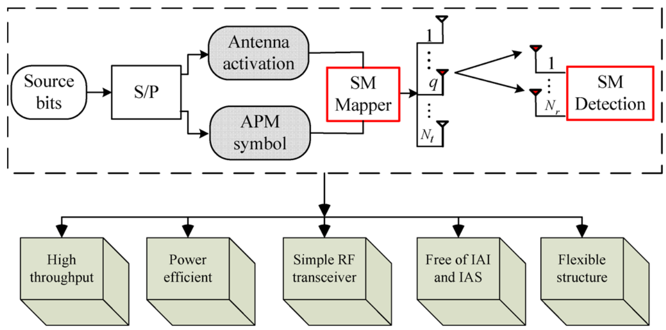

Fig. 1. Benefits of SM-MIMOs for wireless communications.

fundamental properties of SM related to the channel's correlation [27], [28]. Furthermore, the issues of achieving transmit diversity [29], the effects of power imbalance [30], the specific choice of the APM scheme used [31], the impact of the specific channel encountered [29], [32] as well as the effects of channel estimation errors [33], [34] were also characterized. It was found that the performance of SM-MIMOs is highly dependent on the specific type of the APM scheme used. For example, as a hybrid modulation scheme, which combines the classic APM constellation and the spatial-domain (SD) constellation, the SM's achievable performance depends both on the minimum Euclidean distance (ED) of the APM constellation employed, as well as the on absolute values of the modulated symbols [29]. Hence, a suitable APM scheme has to be carefully designed for exploiting the benefits of this hybrid modulation scheme.

On the other hand, it was also noted that the conventional open-loop SM schemes [11], [12] only offer receive-diversity gains. Hence there is also a paucity of SM-MIMO solutions on how to increase the system's robustness to time-varying channel conditions with the aid of either open or closed-loop transmit-symbol design techniques [14]. Additionally, unlike in conventional MIMO techniques, the transmit vectors of SM-MIMO schemes are sparsely populated, since they have mostly zero values [11]. This constraint makes SM rather different from classic Space Time Block Codes (STBC) [35] designed for achieving a diversity gain or from Spatial Division Multiplexing (SDM) [36] conceived for attaining a multiplexing gain as well as from the hybrid SDM-STBC schemes [37] aiming for striking a compromise. In order to increase the robustness of SM-MIMO systems, the classic time-variant parameter adaptation techniques [38], such as power allocation and precoding [39]–[41], which were proposed for conventional MIMO techniques may not be directly applied to SM schemes owing to their specific transmission mode.

In this treatise, we provide a general survey of the SM design framework as well as of its intrinsic limitations. We summarize the most recent research achievements and outline their potential applications, as well as their impediments, which have to be overcome before these MIMO technique may be used as mainstream solutions in practical systems. In particular, we focus our attention on the associated transceiver design, on spatial constellation optimization, on link adaptation techniques, on distributed/cooperative protocol design and on their meritorious variants.

The paper is organized as follows. Section II reviews the conventional SM technique and its relevant variants, emphasizing the flexible transceiver design techniques conceived for striking an attractive trade-off amongst the often conflicting system requirements. The spatial constellation optimization and the associated link adaptation techniques are presented in Sections III and IV, respectively. Section V surveys the family of relay aided SM schemes, which exploits the particular information transmission characteristics of SM and introduces the class of SM-related systems designed for dispersive channels. Finally, Section VI concludes the paper.

Although the list of the references is not exhaustive, the papers cited as well as the references therein can serve as a good starting point for further reading. In particular, there are several tutorial-style articles, [8], [14] and [15], which tend to have quite a different focus. To be specific, in [8], the authors have reviewed diverse MIMO arrangements and then focus on a new class of MIMOs based on the concept of space–time shift keying. In [14], the authors have evaluated the advantages and disadvantages of SM with respect to other popular MIMO schemes and summarized some early research achievements. Moreover, in [15], some of the co-authors of this treatise have provided a comprehensive survey of spatial modulation research, with an emphasis on a generalized transceiver scheme combining spatial modulation with spatial multiplexing and space–time block coding in order to increase either the spectral efficiency or the diversity gain. The price to pay for this flexibility is the need for multiple radio frequency chains. Moreover, in [15] the authors emphasized the energy efficiency of MIMO-based transmission schemes and the first SM-MIMO-based testbed results recorded both in realistic outdoor and indoor propagation environments were reported. Suffice to say that [15] was conceived for stimulating cross-disciplinary research across different communities, whilst this contribution is targeted at readers with a background in wireless communications, who might like to delve into SM-research.

Against this background, this contribution firstly provides a succinct description of the basic spatial modulation principle. To be specific, the SM techniques are classified and then the corresponding detection techniques are categorized with the aid of tables for explicit clarity. Moreover, this paper is more focused on illustrating those results that lead to new design guidelines, as exemplified by the constellation optimization issues of SM. Furthermore, there is a special emphasis on powerful adaptive modulation aided SM and on precoding aided SM. A range of performance metrics are introduced for optimizing spatial modulation, which rely either on the available long-term statistical or on the near-instantaneous knowledge about the channel.

II. Transceiver Design of SM-MIMO

A. The Transmitter Design of SM

In this section, we consider the $(N_t \times N_r)$-element SM-MIMO system, which relies on N_t transmit and N_r receive antennas, while communicating over frequency-flat Rayleigh fading channels. The conventional bit-to-symbol mapping rule

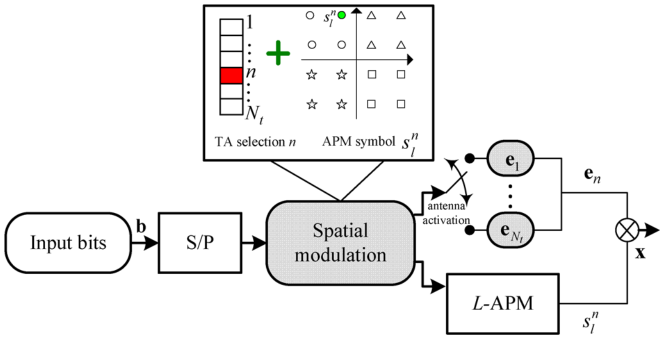

Fig. 2. SM bit-to-symbol mapping rule.

[11] of SM is portrayed in Fig. 2, which can be divided into three steps as follows:

Algorithm 1: Bit-to-symbol mapping principle of the SM transmitter of Fig. 2

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1) First, the information bit stream is divided into vectors containing $m_{\text{all}} = \log_2(L \cdot N_t)$ bits each.
2) Next, each vector is further split into two sub-vectors of $\log_2(N_t)$ and $\log_2(L)$ bits each. The bits in the first sub-vector are used for activating a unique TA for transmission, while the bits in the second sub-vector are mapped to an APM symbol s_l^n. Note that the TA activation process can be described by the N_t-dimensional standard basis vector $\mathbf{e}_n$ $(1 \leq n \leq N_t)$ (i.e., $\mathbf{e}_1 = [1, 0, \cdots, 0]^T$).
3) Finally, the transmitted symbol $\mathbf{x}$ is comprised of the APM symbol s_l^n emitted from the activated TA n. The resultant modulated symbol can be formulated as $\mathbf{x} = s_l^q \mathbf{e}_q \in \mathbb{C}^{N_t \times 1}$.

The corresponding vector-based signal received at the SM-MIMO receiver is given by

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} = \mathbf{h}_n s_l^n + \mathbf{n} \tag{1}$$

where $\mathbf{H}$ is an $(N_r \times N_t)$-element channel matrix, $\mathbf{h}_n$ is the nth column of $\mathbf{H}$ and the elements of the N_r-dimensional noise vector $\mathbf{n}$ are **complex** Gaussian random variables obeying $\mathcal{CN}(0, N_0)$.

B. Variants of the SM Principle

The first conference paper on SM was published in 2001 [45], but its extensive research was mainly fueled by the pioneering works of Haas *et al.* [42], Mesleh *et al.* [11], followed by Sugiura *et al.* [43], Yang *et al.* [12] and Jeganathan *et al.* [44]. Throughout its decade-long history, the SM concept has been termed in different ways and it was extended to different scenarios. A range of major contributions on the subject of SM and its related variants are listed in Table I. Specifically, the concept of SM was first touched upon in [45], where the distinct multipath components were exploited for detection. In [42], a novel Orthogonal Spatial-Division Multiplexing (OSDM) scheme was proposed, which utilizes the index of the TAs as a means of conveying additional source information. In [11], a beneficial framework was established for the bit-to-symbol mapping rule of SM. It was also demonstrated in [11] that SM may be capable of attaining a better performance than other conventional MIMO schemes, such as the Vertical Bell Laboratories Layered Space–Time (V-BLAST) and STBC [4], even without reducing the achievable data rate,. The above-mentioned IGCH technique was proposed in [12] for achieving a high throughput. Later, Space Shift Keying (SSK) [44] modulation was conceived for relying exclusively on the TA indices to convey information, whilst entirely dispensing with any classic Phase Shift Keying (PSK)/Quadrature Amplitude Modulation (QAM) signaling [13]. In a nutshell, all of the above-mentioned schemes activate only a single TA at any instant in order to maintain a low complexity, whilst mitigating to IAI and IAS specifications, as well as reducing to total power consumed.

Motivated by the above concepts, various generalized versions of SM were proposed. First, as a natural extension of SSK, the Generalized SSK (GSSK) scheme was proposed in [46], which activates multiple TAs for the sake of achieving an increased-rate data transmission. This extension has also been incorporated into the SM scheme and two classes of Generalized SM (GSM) schemes were obtained [47]–[49]. To be specific, in [47] a class of GSM arrangements was proposed for the sake of attaining increased transmit diversity gains, which uses all the active TAs for transmitting the same APM-modulated symbols. By contrast, in [48] and [49], another class of GSM arrangements was proposed for attaining an increased multiplexing gain, which uses the active transmit antennas to carry different information symbols during each time slot. Note that the above-mentioned generalized SM schemes of [46]–[49] allow us to activate several—rather than only a single antenna—at the transmitter for bit-to-symbol mapping, hence they are capable of overcoming a specific constraint of SM, namely that the number of TAs has to be a power of two. Moreover, SM was combined with the classic STBC scheme in [50] and with Trellis Coding (TC) in [51]–[53] in order to take advantage of the benefits of both.

Recently, Space–Time Shift Keying (STSK) [43] and its generalized form, namely GSTSK [54] was further extended by applying SSK/SM to both the space and to the time dimensions upon combining SSK/SM with space–time block codes, which resulted in an improved diversity versus multiplexing tradeoff. In contrast to the TA-index of conventional SM, in STSK [43], the specific indices of the pre-designed space–time dispersion matrices were exploited for conveying additional data. To be specific, one out of N_t dispersion matrices was activated rather than simply activating one out of N_t TAs in order to disperse a PSK/QAM symbol in STSK, where a beneficial diversity gain may be achieved as a merit of the simultaneous transmissions from the multiple TAs. As a further advance, the STSK concept was extended to the frequency domain in [55] and [56] with the assistance of a Frequency-Shift Keying (FSK) modulator. To be specific, in [55] the Space–Frequency Shift Keying (SFSK) as well as the Space–Time–Frequency Shift Keying (STFSK) schemes were proposed, which have the added benefit of spreading the transmit signal across both the space and time

TABLE I
CONTRIBUTION TO SM SCHEME AND ITS RELATED VARIANTS

Year	Authors	Contributions
2001	Chau and Yu [45]	Introduced the concept of SM and exploited the distinct multipath fading characteristics for antenna index detection.
2002	Haas *et al.* [42]	Proposed an OSDM scheme, which uses Walsh-Hadamard codes and an antenna array for data multiplexing.
2004	Song *et al.* [62]	Proposed channel hopping modulation, which is applicable to an arbitrary number of TAs.
2006	Mesleh *et al.* [63]	Proposed an efficient MIMO scheme, namely SM, which maps multiple information bits into a single information symbol and to the index of a single TA transmitting antenna.
2008	Jeganathan *et al.* [46]	Conceived an SSK concept and its improved version of the SSK modulation, namely GSSK, which activates multiple TAs for data transmission.
	Yang *et al.* [12]	Introduced the IGCH technique based on the fact that the independent fading of multiple channel can be used as an additional information channel.
	Mesleh *et al.* [11]	Proposed a simple MRC-based receiver design for SM, which detects the TA index and APM separately.
2009	Abu-alhiga *et al.* [58]	Designed a power-efficient SIM scheme, which maps a stream of bits into the indices of the available subcarriers in an on-off keying fashion.
	Jeganathan *et al.* [44]	Presented the framework of SSK, which is a low-complexity version of SM concept and exclusively employs the TA indices for data transmission.
2010	Di Renzo *et al.* [30]	Introduced an opportunistic power allocation scheme for SSK modulation, which exploits CSI for performance improvement
	Mesleh *et al.* [51]	Proposed a trellis coded SM (TC-SM) scheme, where the Trellis Coded Modulation is applied to SM to improve its performance in correlated channels.
	Serafimovski *et al.* [64]	Introduced a Fractional Bit Encoded (FBE)-SM scheme, which allows the transmitter to be equipped with an arbitrary number of TAs.
	Fu *et al.* [47]	Proposed high-rate generalized SM, which uses multiple active TAs to encode information bits.
	Younis *et al.* [48]	Proposed a GSM scheme, which sends the same symbol from more than one transmit antenna at a time.
	Sugiura *et al.* [43]	A novel STSK modulation scheme is proposed, which constitutes a generalized shift keying architecture utilizing both the space as well as time dimensions and hence includes the SM and SSK schemes as special cases.
	Renzo *et al.* [65]	Introduced the Time-Orthogonal Signal Design assisted SM (TOSD-SM) for offering transmit-diversity.
2011	Yang *et al.* [66]	Designed a Bit-Padding IGCH (BP-IGCH) scheme, which eliminates the limitation that the number of TAs has to be a power of two based on the IGCH concept.
	Başar *et al.* [50]	Combined SM and STBC to take advantage of the benefits of both, while avoiding their drawbacks.
	Sugiura *et al.* [54]	Proposed a novel Generalized STSK (G-STSK) architecture for striking a flexible tradeoff among diversity, throughput as well as complexity.
	Ngo *et al.* [55]	Proposed the SFSK modulation as well as the STFSK concept, which spreads the transmit signal across the space- and time- and frequency-domain.
	Qu *et al.* [67]	Conceived a block mapping SM (BMSM) scheme for increasing the transmit rate.
	Başar *et al.* [52]	Proposed a new TC-SM scheme with for achieving higher diversity and coding gains.
2012	Zhang *et al.* [68]	Introduced a novel SM scheme based on Ungerboeck's set partitioning for a correlated Rician fading scenario.
	Wang *et al.* [49]	Designed a novel high-rate Multiple Active-SM (MA-SM) schemes and a near-optimal decoder with linear complexity.
	Chang *et al.* [69], [70]	Proposed a new SSK modulation with Hamming code-aided constellation design for striking a flexible tradeoff among transmission rate, performance and power.
	Kuo [71]	Proposed a Symbol Coordinate Representations in Antenna Domains modulation , which leads superior performance to both SM and GSSK at the same data rate.
2013	Di Renzo *et al.* [15]	Illustrated the archived experimental results substantiating the benefits of SM and presented its beneficial application areas.
	Serafimovski *et al.* [26]	First practical testbed implementation of SM in indoors (laboratory environment).
	Younis *et al.* [25]	First performance evaluation of SM in indoors using real-world measured channels.

domains, as well as the frequency domain. In [56], the STFSK concept was extended to the Slow-Frequency-Hopping Multiple Access (SFHMA) philosophy for the sake of supporting multiple users and its Area Spectral Efficiency (ASE) gain over the classic Gaussian Minimum Shift Keying (GMSK)-aided SFHMA and GMSK assisted time-division/frequency-division multiple access (TD/FDMA) systems was quantified.

Inspired by the concept of SM/SSK, the subcarrier orthogonality can also be exploited and the indices of active subcarriers of Orthogonal Frequency-Division Multiplexing (OFDM) [57] symbols can be employed for conveying additional information, which is referred to as Subcarrier-Index Modulation (SIM) [58]. Based on the same principle, but following a different approach from that of [58], a novel transmission scheme termed as OFDM combined with Index Modulation (OFDM-IM) was proposed in [59] for frequency selective fading channels, with the objective of increasing the data rate as well as simultaneously improving the attainable BER performance. In Fig. 3, we classify the above-mentioned schemes, which exploit different degrees of freedom offered by the temporal domain, frequency domain and spatial domain fading. For completeness, we also briefly allude to the classic time hopping impulse modulation (THIM) [60], which exploits the indices of time-slots for implicitly conveying additional data. As a further

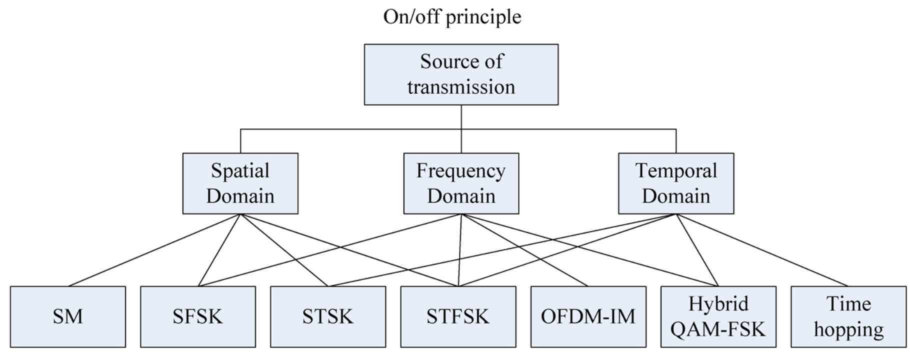

Fig. 3. Transmission techniques based on the on/off keying principle applied to the temporal domain, frequency domain and spatial domain. Here, we have "SM": spatial modulation, "SFSK": Space–Frequency Shift Keying, "STSK": Space–Time Shift Keying, "STFSK": Space–Time–Frequency Shift Keying, and "OFDM-IM": OFDM with Index Modulation.

improvement, hybrid **QAM-FSK** modulation [61] combine the time–frequency domain for the sake of exploiting their independent fading.

C. Detector Design

As seen in Fig. 2, the TA index is combined with the APM symbol index by the SM mapper. Hence, only the TA antenna index and the transmitted APM symbol index have to be estimated at the receiver. Note that most variants of SM, such as STSK and SSK, have an equivalent system model similar to (1), which is free from the effects of ICI, and each equivalent transmit vector includes only a single non-zero component [43], [44]. As a result, they may be able to use the same detection algorithm. As indicated in [72]–[88], the detection techniques of SM-MIMO systems may be broadly divided into four fundamental categories: Maximum Likelihood (ML) detection [72]–[74], Matched Filter (MF) based detection [11], [75], Sphere Decoding (SD) algorithm based detection [76]–[79] and hybrid detection, which combines the modified MF concept and the reduced-complexity exhaustive ML search of [12], [80]–[88]. An overview of the various detection techniques conceived for SM-related schemes is seen in Fig. 4. Next, they will be characterized in more detail.

An optimal ML-based SM detector, which carries out an exhaustive search for the global optimum in the entire signal space, was developed in [72]. This detector jointly detects the active TA index as well as the transmitted APM symbol and then retrieves the original data bit sequence. In [73], the authors have derived a soft-output ML detector for recovering the desired signals with the aid of soft decisions, and have shown that the soft-output ML detector outperforms its hard-decision counterpart. Moreover, in [74], the authors have exploited the inherent ML data detection in the context of STSK systems and proposed a semi-blind iterative channel estimation and data detection scheme for STSK, which is capable of reducing the training overhead required. Furthermore, a low-complexity multi-stage ML detector was proposed for the ICGH of [12], which adopts the principles of SM. The proposed detector estimates the APM symbol prior to detecting the TA index. Unlike the ML detector of other spatial multiplexing MIMO techniques, the complexity of the single-stream ML receiver only increases linearly with the number of TAs. However, as

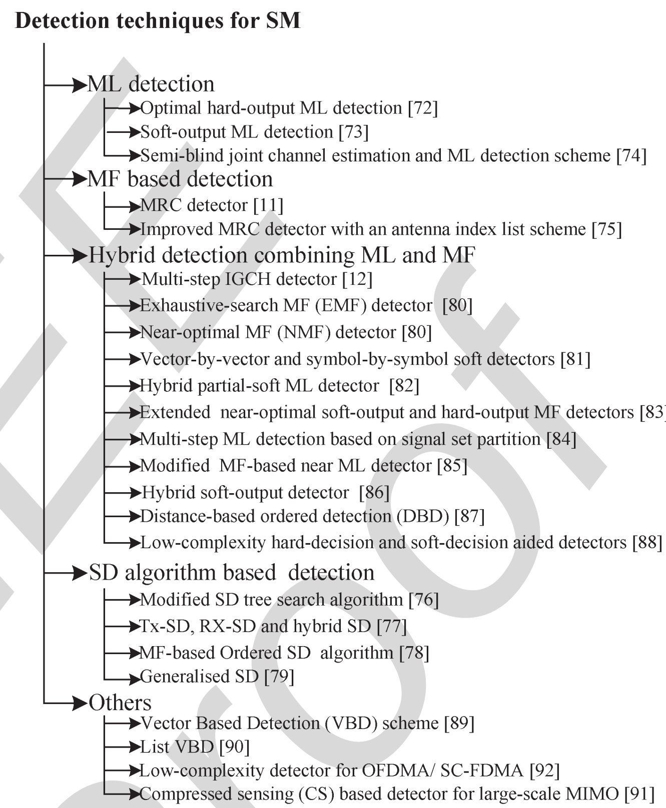

Fig. 4. Overview of SM detectors and related techniques.

the transmission rate increases, even the complexity of the ML single-stream detector might become excessive.

Among the promising alternatives, the MF-based detector exhibits a considerably reduced complexity, since the activated TA index and the modulated APM constellation point are separately estimated. However, as mentioned in [11], the conventional MF detector, namely the MRC, only performs well under the idealized assumption of perfect channel knowledge. This detector was improved in [75] and a TA index list based scheme was introduced for all the conventional MIMO channels.

For the sake of approaching the single-stream ML detector's performance without any substantial performance degradation, beneficial hybrid detectors were designed for the SM family in [80]–[88], which combine the modified MF concept of [11] and the reduced-complexity exhaustive ML search philosophy of [72]. For example, in [80], two modified MF-based detectors, namely the Exhaustive-search based MF (EMF) detector and the Near-optimal MF (NMF) detector were proposed for achieving a better performance than the conventional MF detector. However, the EMF has to invoke an exhaustive signal space search at the MF's output for maintaining the ML's performance, which prevents the detector from achieving a significant reduction in complexity, when high data rates are required. By contrast, the NMF detector further reduced the EMF's complexity, but naturally it performs worse than the ML detector [72]. To overcome this limitation, the authors of [83] proposed an extended NMF detector, which relies on finding multiple high-probability indices for the sake of attaining further performance improvements. Then, this improved NMF detector was further simplified in [87] and [88]. Considering that SM-MIMO systems typically rely on powerful channel codes, an attractive detector has to provide soft-decision-based information. In [44] and [73], an optimal Maximum a *Posteriori* (MAP) detector was invoked for turbo-coded SM schemes. However, it suffers from the problem of having a high complexity. In [81], the authors have proposed a low-complexity vector-by-vector based soft-detector operating on a symbol-by-symbol basis, where the associated complexity was considerably reduced compared to that of the *max-log* MAP detector's, albeit this was achieved at the cost of a modest performance degradation.

On the other hand, the SD [93], [94], which is widely used in spatial multiplexing systems, avoids the exhaustive search of the potentially excessive-complexity signal constellation by examining only those candidate solutions that lie inside an SNR-dependent decoding sphere. However, the conventional SD and the more advanced SD methods [94] are oblivious of the specific principle of SM, namely that only a single TA is active at any given time instant. As a result, the SD methods designed for spatial multiplexing MIMOs cannot be directly applied to SM-MIMO detection. In [76], a modified SD algorithm referred to as SM-SD was proposed, which is based on the tree-search structure. The SM-SD algorithm exploits the specific transmission mode of SM and hence attains a considerable complexity reduction. However, the performance of the SM-SD algorithm depends on the particular choice of the SNR-dependent initial search-radius as well as on the transmitter parameters. Hence, in [78], an Ordered SD (OSD) algorithm was proposed for the family of SM arrangements for the sake of reducing the receiver's complexity, while maintaining the optimum single-stream ML performance, which searches through the signal space sequentially according to the sorted TA set. Recently, a generalized version of the SM-SD was proposed in [77] and [79].

Relying on a novel approach, in [89] the authors have proposed a new Vector Based Detection (VBD) scheme for SM, which is suitable for high-order APM constellations. In [90], an improved VBD scheme, namely the list-VBD was proposed, where the TA index detection is performed first and a list of the best candidates survives. As indicated in Section I, the family of SM constitutes an attractive framework for the emerging family of large-scale MIMO systems in reducing the hardware costs and detection complexity, which becomes realistic at **microwave** frequencies. Since ML detection of high-order APM schemes in large-scale high-rate MIMO systems has a potentially excessive complexity, in [91] a low-complexity Compressed Sensing (CS) based detector was proposed for overcoming this problem by exploiting the sparsity in SM signaling. Again, the family of SM has also been effectively extended to the Orthogonal Frequency Division Multiple Access (OFDMA)/Single-Carrier Frequency Division Multiple Access (SC-FDMA)-aided architecture and some related low-complexity detectors were proposed in [92].

Additionally, most of the above-mentioned detectors assume that perfect CSI is available at the receiver. However, it is challenging to acquire accurate CSI in high-speed vehicles and multiple antenna systems. In order to dispense with CSI-estimation, the class of Differentially-encoded STC (DSTC) was proposed in [95] and [96]. Specifically, the Unitary Space–Time Modulation (USTM) scheme does not require CSI estimation and hence facilitates non-coherent detection at the receiver. Motivated by the concept of DSTC, the design of non-coherent SM-MIMO schemes was investigated in [43], [97], and [98]. To be specific, in [43], the differential STSK (DSTSK) concept was proposed with the aid of the Cayley unitary transformation, which has a low-complexity single-stream non-coherent detector. In [97], the DSTSK scheme was further developed for the sake of avoiding the nonlinear Cayley transform and a reduced-complexity multiple-symbol differential sphere detector was proposed for rapidly fading channels. Moreover, a PSK-aided differential modulation concept was conceived in [98], which relies on differential decoding while retaining the fundamental benefits of coherent SM-MIMO schemes.

D. Channel Capacity and Error Performance Metric

1) Channel Capacity: The capacity of SM constitutes a vitally important research topic. In [12], the authors have derived the capacity of SM in the context of Rayleigh fading channels, assuming continuous-amplitude discrete-time Gaussian distributed transmitted signals. This capacity is also referred to as the Continuous-input Continuous-output Memoryless Channel (CCMC) capacity [7]. However, this assumption cannot be readily satisfied in a practical communication system, unless carefully designed superposition modulation is used [99]. By contrast, in [43] the Discrete-input Continuous-output Memoryless Channel (DCMC) capacity [100] of the family of SM scheme was formulated, where the transmitted signals were drawn from finite-alphabet discrete constellations, such as the classic APM schemes [13]. Moreover, a closed-form expression of the mutual information of SM based Multiple-Input Single-Output (MISO) channels was derived and the impact of finite-alphabet inputs on the attainable performance of SM was investigated in [101]. Owing to its particular operating principle, its capacity and the corresponding optimization algorithms still require further research.

Fig. 5 shows the CCMC and DCMC capacity curves of the (4×2)-element SM-MIMO scheme. Furthermore, the G4-STBC arrangement of [3] was also considered as benchmarkers in Fig. 5. As shown in Fig. 5, the CCMC capacity of the SM scheme is higher than that of G4-STBC. Additionally, observe in Fig. 5 that the DCMC capacity tends to be increased upon

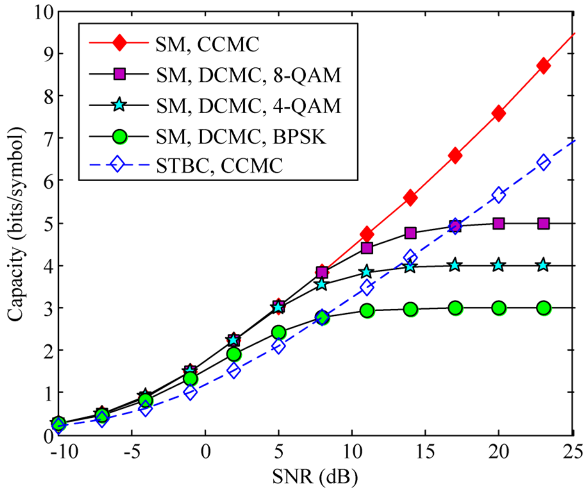

Fig. 5. Bandwidth efficiency of (4 × 2)-element SM system, comparing the CCMC and the DCMC capacity.

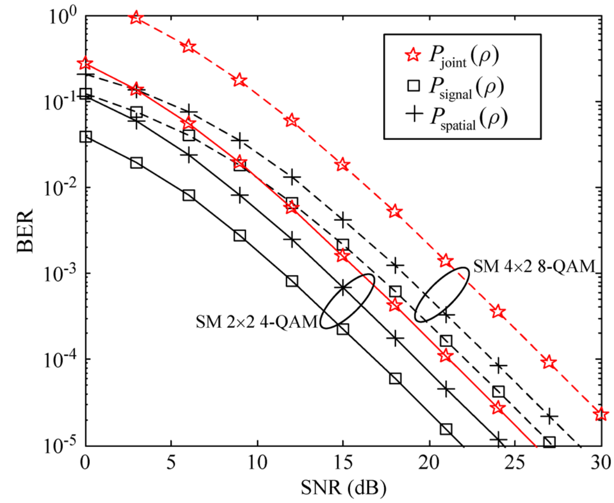

Fig. 6. The ABEPs of SM-MIMO: $P_{\text{signal}}(\rho)$, $P_{\text{joint}}(\rho)$ and $P_{\text{spatial}}(\rho)$.

increasing the modulation order, as noted in [12]. Moreover, as indicated in [8] and [26], the capacity of SM may be lower than that of the V-BLAST arrangement, however its detection complexity does not depend on the number of transmit antennas. This attractive advantage facilitates the practical application of SM-MIMO.

2) Error Performance Metric: The BER performance of SM has also been studied extensively in the context of various channel models and MIMO setups [28]–[34]. Generally, the analytical study of SM-MIMO systems tends to rely on its union bound based approximation [102]. However, apart from the STSK studies of [43] and the investigations of Di Renzo *et al.* [15], the studies in [27], [28], and [32]–[34] considered the simplified version of SM, namely SSK. For the conventional SM combining SSK with classic APM techniques for the sake of transmitting additional bits, the analytical studies disseminated in [11], [14], [29], and [103] exploited some of the fundamental properties of SM related to the channel's correlation, to its transmit diversity, channel estimation errors and coding gain. For example, in [103] the authors have provided a closed-form Average Bit Error Probability (ABEP) upper bound expression based on the conventional union-bound methods, which also quantified the transmit diversity order of SM. This framework is usually used as a reference for highlighting the advantages of SM over other MIMO arrangements, such as the classic STBC and VBLAST schemes. In [29], an improved union-bound is formulated, which partitions the ABEP expression of SM-MIMO systems into three terms: the term $P_{\text{spatial}}(\rho)$ only related to the spatial signals (i.e., TA index), the term $P_{\text{signal}}(\rho)$ is only related to the APM signals, while the joint term $P_{\text{joint}}(\rho)$ depends on both the spatial signals and on the APM signals, where ρ is the average SNR. This bound is formulated as

$$\mathrm{P}_{\mathrm{SM}}(\rho) \leq P_{\text{spatial}}(\rho) + P_{\text{signal}}(\rho) + P_{\text{joint}}(\rho). \tag{2}$$

Assuming i.i.d. Rayleigh fading channels, $P_{\text{signal}}(\rho)$ predominantly depends on the minimum ED $d_{\min}$ of the constellation points of APM, while $P_{\text{joint}}(\rho)$ and $P_{\text{spatial}}(\rho)$ mainly depend on the modulus values β_l $(l = 1, \cdots, L)$ of the APM constellation points, as detailed in [29]. As a result, $\mathrm{P}_{\mathrm{SM}}(\rho)$ of (2) depends both on the minimum ED of the specific APM constellations employed, as well as on the absolute values of the APM-symbols. This improved ABEP upper bound of SM provides deeper insights into the interactions of the APM signal constellation and the spatial signal constellation. For example, the interaction term $P_{\text{joint}}(\rho)$ of (2) dominates the performance of SM in diverse popular MIMO configurations, as indicated in Fig. 6. On the other hand, it can also be used for optimizing the system's performance by exploiting any statistical knowledge about the Channel State Information (CSI) at the transmitter and we will discuss in Section III.

Moreover, since the exact ABEP does not have a simple closed form solution, the nearest neighbor approximation was proposed in [104]. Assuming that all the channel inputs are equally likely, the nearest neighbor approximation of the Pairwise Error Probability (PEP) for a given channel matrix $\mathbf{H}$ can be expressed as [105]

$$P_{e|\mathbf{H}} \approx \lambda \cdot Q\left(\sqrt{\frac{1}{2N_0} d_{\min}^2(\mathbf{H})}\right) \tag{3}$$

where we have $Q(x) = (1/\sqrt{2\pi}) \int_x^\infty e^{-y^2/2} dy$, and λ is the number of neighboring constellation points [10] associated with the free distance (FD) $d_{\min}(\mathbf{H})$ defined as

$$d_{\min}(\mathbf{H}) = \min_{\substack{\mathbf{x}_i, \mathbf{x}_j \in \mathbb{X}, \\ \mathbf{x}_i \neq \mathbf{x}_j}} \|\mathbf{HP}(\mathbf{x}_i - \mathbf{x}_j)\| \tag{4}$$

where $\mathbb{X}$ is the set of legitimate transmit symbols, while $\mathbf{x}_i$ and $\mathbf{x}_j$ are two distinct transmitted symbols in $\mathbb{X}$. In (4), $\mathbf{P}$ is the transmit preprocessing (TPP) matrix, which is the $(N_t \times N_t)$-element identity matrix $\mathbf{I}$ for conventional open-loop SM schemes dispensing with TPP.

Note that the nearest neighbor approximation of the PEP will always be slightly lower than that provided by the union bound, since this approximation does not include the errors associated with those legitimate symbols that are farther apart than the FD. However, in case of low SNRs, there is a non-negligible probability of corrupting a symbol into more distant symbols.

Nonetheless, the result is quite close to the exact probability of symbol error at high SNRs, as detailed in [105]. Indeed, since the error events mainly arise from the nearest neighbors, the maximization of the FD in (3) directly reduces the probability of error, especially at high SNRs [106]. As a result, the bound of (3) can be adapted for system optimization by exploiting the knowledge of the near-instantaneous CSI, as discussed these in more detail in Section IV.

Furthermore, the effects of CSI errors on the achievable performance of SM-MIMOs were further researched in [34] and [107]–[109]. It was found that SM is quite robust to imperfect CSI compared to V-BLAST. For example, in [107] an asymptotically tight upper bound on the ABEP was derived for SM under imperfect CSI and the simulation results confirmed that SM is more robust to channel estimation errors than V-BLAST for reasonable practical channel estimation error values.

III. APM Constellation Optimization

As indicated in (2), the performance of SM-MIMO systems is highly dependent on the specific APM signal constellation adopted. In a conventional Single-Input Single-Output (SISO) system, the Gray-coded Maximum–minimum distance (MMD) QAM constellation minimizes the Bit Error Ratio (BER) [13]. However, the advantage of MMD-QAM may be eroded in SM-MIMO systems [29]. This is due to the fact that the BER performance of SM-MIMO systems is jointly determined by the spatial signal (i.e., TA indices), by the classic APM constellation and by their interaction [29]. Hence, a suitable APM scheme has to be designed for this hybrid modulation scheme.

Furthermore, SM also allows us to achieve a high transmission rate by combining its benefits with those of the classic APM schemes, as detailed in [46]–[49]. However, when the source employs higher-order square QAM in order to increase the attainable transmission rate, a high Peak-to-Average-Power Ratio (PAPR) [110] is encountered, hence requiring a low-efficiency linear power amplifier [111]. To overcome this impediment, peak-power reduction constellation shaping [110] may be employed at the transmitter, albeit this technique imposes additional complexity. Thus, for the sake of achieving a high power-efficiency, the choice of the modulation scheme in SM-MIMO systems has to be revisited.

The effects of APM schemes on the performance of SM have been investigated in [112]–[114]. More specifically, in [112], the dispersion matrices and the signal constellations were jointly optimized for a near-capacity precoded STSK system, which includes SM as a special case and strikes a flexible rate-versus-diversity tradeoff. It was also shown in [80] that the star-QAM aided STSK scheme outperforms its MMD based square-QAM aided counterpart. This is because the STSK's achievable performance depends both on the minimum ED of the APM constellation employed, as well as on the absolute values of the modulated symbols, which may also be valid for SM systems, as shown in (2) [29]. More recently, in [31] low-complexity, yet single-stream ML transmit diversity schemes have been studied by analyzing the impact of the spatial constellation and shaping filters. In [70], a Hamming code construction technique was proposed as a modulation design strategy for SSK-based systems for the sake of improving their error probability. In [113], a new SM constellation design strategy was proposed based on the ED of the constellation, which retains the key advantages of SM, while activating multiple TAs. In [114], two approaches were investigated with the goal of designing the SSK's transmit constellation space by relying either on the idealized simplifying assumption of having perfect CSI or on the more practical scenario of imperfect CSI at the transmitter, in order to increase the distance between each pair of the received combined TA-APM vector. The above-mentioned techniques were however mainly conceived for STSK and SSK schemes, but may not be readily applicable to the conventional SM scheme.

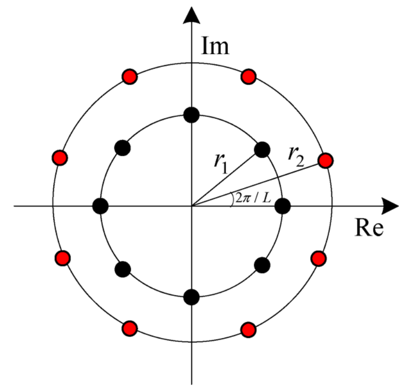

Fig. 7. The complex signal constellation of 16-ary star-QAM. The symbols are evenly distributed on two rings, and the phase differences between the neighboring symbols on the same ring are equal.

In [29], the performance of SM systems relying both on conventional QAM and PSK modulation were studied, demonstrating that in some MIMO setups, the PSK-modulated SM scheme may outperform the identical-throughput MMD-QAM SM scheme. More specifically, as shown in [29] and [115], for certain SM-MIMO configurations, $P_{\rm signal}(\rho)$ of (2) is significantly higher than the sum of $P_{\rm joint}(\rho)$ and $P_{\rm spatial}(\rho)$, which implies that the minimum ED of APM constellations dominates the performance of SM. In this scenario, MMD-QAM may constitute an attractive APM candidate for minimizing the ABEP. By contrast, as shown in Fig. 6, if $P_{\rm signal}(\rho)$ is lower than the sum of $P_{\rm joint}(\rho)$ and $P_{\rm spatial}(\rho)$, which implies that the moduli of the APM constellation points dominates the $\mathrm{P}_{\rm SM}(\rho)$ term, then a constant-modulus modulation scheme, such as PSK, may be optimal, as indicated in [29]. Recall that $P_{\rm signal}(\rho)$ of (2) is dominated by the minimum ED $d_{\rm min}$, while $P_{\rm joint}(\rho)$ and $P_{\rm spatial}(\rho)$ mainly depend on the modulus values β_l $(l = 1, \cdots, L)$ of the APM constellation adopted. Note that the modulus values β_l $(l = 1, \cdots, L)$ are represented by the Frobenius norms of the APM constellation points. These results suggested that for the sake of jointly minimizing $P_{\rm signal}(\rho)$, $P_{\rm joint}(\rho)$ and $P_{\rm spatial}(\rho)$ of (4), we can readily focus our attention on design of $d_{\rm min}$ and on the β_l parameters of APM.

On the other hand, star-QAM [13] constitutes a special case of circular APM, which is capable of outperforming the classic square-shaped QAM constellation in peak-power-limited systems. Hence its diverse relatives have been adopted in most of the recent satellite communication standards, such as the

TABLE II
THE MINIMUM ED OF DIFFERENT APM SCHEMES

Modulation order (L)	2	4	8	16	32
PSK	$d_{\min}$=2	$d_{\min}=\sqrt{2}$	$d_{\min}$= 0.76	$d_{\min}$=0.39	$d_{\min}$=0.19
QAM	- -	$d_{\min}=\sqrt{2}$	$d_{\min}$=0.81	$d_{\min}$=0.63	$d_{\min}$=0.41
Star-QAM	$d_{\min}$=2	$d_{\min}=\sqrt{2}$	$d_{\min}$=0.91	$d_{\min}$=0.57	$d_{\min}$=0.40

Digital Video Broadcast System (DVB) S2, DVB-SH, as well as in the Internet Protocol over Satellite (IPOS) and Advanced Broadcasting System via Satellite (ABS-S) [116]. To elaborate a little further, the star-QAM constellation is composed of multiple concentric circles and it was shown to be beneficial in the context of STSK systems [80]. However, the constellations' optimization has not been carried out for star-QAM aided SM.

In order to make the choice of the APM parameters $d_{\min}$ and β_l as flexible as possible, we consider a class of star-QAM constellations, which subsumes the classic PSK as a special case, but may also be configured for maximizing the minimum ED of the constellation by appropriately adjusting the ring ratios of the amplitude levels. For the sake of simplicity, we consider the example of a twin-ring 16-star-QAM constellation having a ring-ratio of $\alpha = r_2/r_1$ as shown in Fig. 7. The symbols are evenly distributed on the two rings and the phase differences between the neighboring symbols on the same ring are equal. Unlike the conventional twin-ring star-QAM constellation [116], the constellation points on the outer circle of star-QAM constellation are rotated by $2\pi/L$ degrees compared to the corresponding constellation points on the inner circle. Hence again, the conventional PSK constitutes an integral part of our star-QAM scheme, which is associated with a ring-ratio of $\alpha = 1$. Note that although this twin-ring star-QAM constellation has indeed been invoked for noncoherent detection [117], it has not been considered whether this constellation can be directly applied to SM for achieving performance improvements.

Table II summarizes the minimum EDs $d_{\min}$ between the constellation points for different APM schemes, where the modulation order is the number of the constellation points. Moreover, the L-PSK/L-QAM schemes in [13] are used. It is shown that the star-QAM is capable of achieving almost the same minimum ED as the MMD-based QAM [8].

Given an $(N_r \times N_t)$-element MIMO setup having a transmission rate of m_{all}, and L modulation levels, the goal of star-QAM aided signaling constellation optimization is to find the ring-ratio α, which minimizes the ABEP of SM-MIMO of (2). Following this approach, the related optimization problem may be formulated as

$$\begin{cases} \alpha^* = \min\limits_{\alpha} \mathrm{P}_{\mathrm{SM}}(\rho) \\ \quad s.t.\ \alpha \geq 1. \end{cases} \tag{5}$$

Based on an exhaustive numerical search, for example, for the 16-star-QAM aided (4 × 4)-element SM-MIMO, the optimal ring ratio was found to be $\alpha^* = 1.7$ [118]. According to (2), this optimized star-QAM aided SM scheme provides an SNR gain of about 3 dB over the conventional 16-PSK modulated SM scheme and an SNR gain of about 1.1 dB over the identical-throughput Gray-coded MMD 16-QAM modulated SM scheme at BER $= 10^{-5}$. Note that the optimized star-QAM constellation can be designed off-line based on the CSI statistics (i.e., the fading type) for different SM-MIMO systems and hence the resultant system does not need any feedback. Next, we will introduce a suite of beneficial adaptation techniques based on the assumption that the knowledge of the near-instantaneous channel matrix is available at the receiver in the frequency flat-fading channel.

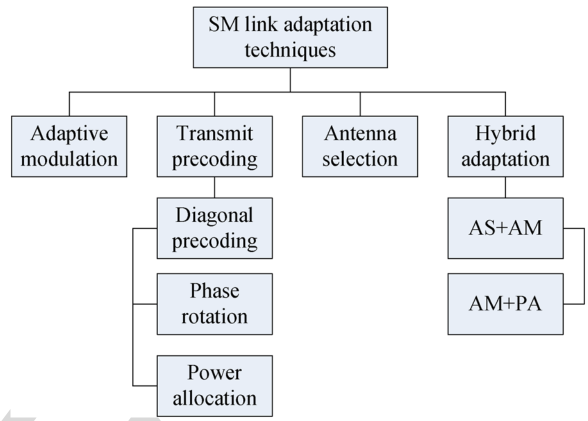

Fig. 8. Classification of the LA techniques designed for SM-MIMO. Here, AS+AM: antenna selection combined with adaptive modulation, AM+PA: adaptive modulation combined with power allocation.

IV. LINK ADAPTATION TECHNIQUES

Link Adaptation (LA) has an important role in wireless communication systems [39]–[41]. Traditionally, LA refers to the concept of dynamically adjusting the transmit parameters, such as the modulation order and coding rate according to the near-instantaneous channel conditions. LA has been extensively studied in the conventional MIMO context for the sake of improving the achievable multiplexing and diversity performance. However, it has not been considered, whether these existing LA techniques can be directly applied to SM-based transmission systems. Note that the introduction of LA techniques in SM-MIMO should not jeopardize the advantages of SM, such as the avoidance of the IAI, IAS and multiple RF chains [11]. This makes the design of LA algorithms more challenging. In order to increase the robustness of the SM-MIMO system, several limited-feedback aided LA techniques have been proposed in [30], [104], [115], and [119]–[130], as summarized in Fig. 8. Depending on the MIMO scheme's degree freedom, these techniques can be roughly divided into four types, namely into Adaptive Modulation (AM) [104], [115], [119], [120], transmit precoding (TPC) [30], [103], [121]–[125], Antenna Selection (AS) [126]–[128] and Hybrid Adaptation (HA) techniques relying on diverse combinations of the above three [115], [129], [130], as shown in Fig. 8. To elaborate a little further, the

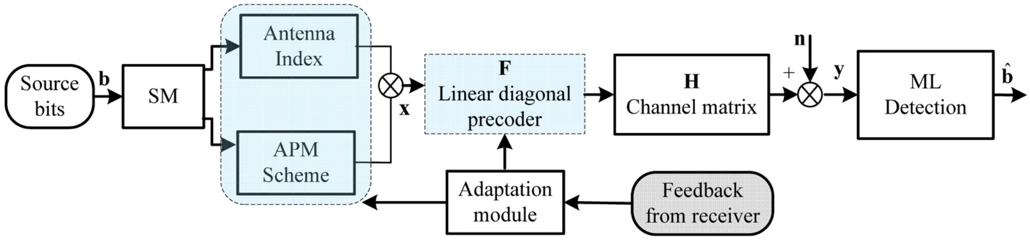

Fig. 9. Block diagram of LA-aided MIMO communication systems.

general philosophy of a LA-aided SM-MIMO system obeying the architecture of Fig. 9 can be summarized as follows.

Algorithm 2: The adaptation process of LA-aided SM-MIMO systems

---

1) Consider an $(N_r \times N_t)$-element SM-MIMO system associated with the transmission rate m_{all};
2) The receiver estimates the CSI and decides upon the optimum transmit mode, which is then sent back to the transmitter through a low-rate feedback channel;
3) The transmitter processes the feedback information and employs the optimum transmission mode (i.e., the modulation orders and the precoding matrix) for its transmission.

Having formulated the SM-MIMO's LA algorithm, let us now describe the class of LA techniques with the aid of Fig. 8 developed for the family of SM-MIMO schemes in more detail below. Note that in this treatise only the TPC matrix $\mathbf{P}$ and the transmit symbol $\mathbf{x}$ are adapted in response to the near-instantaneous channel conditions in order to improve the system's performance, as indicated in (4).

A. Adaptive Modulation

Again, AM techniques are capable of alleviating the adverse effects of channel fading, so as to achieve an increased data rate or a reduced BER [131], which have hence been adopted in most of the recent communication standards, such as 3GPP, 3GPP2, IEEE 802.11a, IEEE 802.15.3 and IEEE 802.16 [132].

SM may also be beneficially combined with AM for adjusting the transmission parameters for the sake of accommodating time-varying channels. Therefore, the beneficial combination of AM and SM-MIMO techniques is a promising design alternative for high-rate wireless systems.

To this end, adaptive SM-MIMO architectures relying on different combinations of modulation/coding schemes were proposed in [120], which aimed for maximizing the channel capacity at a predefined target BER, rather than for optimizing the BER. By contrast, in [104] a near-instantaneously Adaptive SM (ASM) scheme was proposed for improving the attainable system performance, while maintaining a fixed average transmit rate with the aid of AM techniques. In ASM, the receiver requests the most suitable modulation order to be used by the transmitter for each TA and/or time-slot. Assuming that no-transmission, BPSK and M-QAM are available for each TA, which are represented by the set $\mathbb{M}_{\text{all}}$, the detailed design procedure of ASM schemes can be summarized as follows:

Algorithm 3: Adaptive SM

---

1) Given the transmit parameters as: N_t, N_r and the transmission rate m_{all}, generate all the legitimate modulation order combinations for a given m_{all} and represent these combinations as a set $\mathbf{R} = \{\mathbf{r}_1, \mathbf{r}_2, \cdots, \mathbf{r}_j, \cdots, \mathbf{r}_J\}$, where we have $\mathbf{r}_j = [r_j^1, \cdots, r_j^n \cdots, r_j^{N_t}]$ and r_j^n denotes the modulation order for the nth $(n = 1, 2, \cdots N_t)$ TA of the jth ASM combination.
2) Based on the optimization rule, such as the nearest neighbor approximation of (3), we can achieve a performance gain by maximizing $d_{\min}(\mathbf{H})$ with the aid of switching among these candidates.
3) Then, the corresponding index of the optimal ASM mode is fed back to the transmitter, which transmits the symbols accordingly.

In (3), the conditioned PEP is a monotonically decreasing function of $d_{\min}(\mathbf{H})$. Hence, the attainable system performance can be improved by maximizing the FD $d_{\min}(\mathbf{H})$ by adapting the transmit parameters. As an example, let us consider a (2×2)-element SM-MIMO transmission scheme associated with $m_{\text{all}} = 3$ bits/symbol under a channel realization matrix $\mathbf{H}$, which is given by

$$\mathbf{H} = \begin{bmatrix} 0.26 - 0.75\text{i} & 1.33 + 0.49\text{i} \\ 0.03 + 1.30\text{i} & -0.61 + 0.25\text{i} \end{bmatrix}.$$

Let us assume that no-transmission, BPSK, QPSK, 8-QAM, 16-QAM, 32-QAM and 64-QAM are available for each TA and these schemes are represented as $\mathbb{M}_{\text{all}} = \{0, 2, 4, 8, 16, 32, 64\}$, where the no-transmission mode has the identifier of $M = 0$, while the BPSK and QPSK constellations are denoted as $M = 2$ and $M = 4$ respectively. For $m_{\text{all}} = 3$ bits/symbol, we have five ASM mode candidates denoted as $\mathbf{R} = \{\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3, \mathbf{r}_4, \mathbf{r}_5\} = \{[16, 0], [2, 8], [4, 4], [8, 2], [0, 16]\}$, where $\mathbf{r}_1 = [16, 0]$ represents that 16-QAM and no-transmission are assigned to the first and the second TA, respectively, while the candidate [4,4] corresponds to the conventional non-adaptive SM scheme using QPSK for both TAs.

Based on Algorithm 3, Fig. 10 shows the detailed actions of the ASM scheme for this 3-bits/channel-use system. As shown in Fig. 10, the five ASM modes (the legitimate modulation

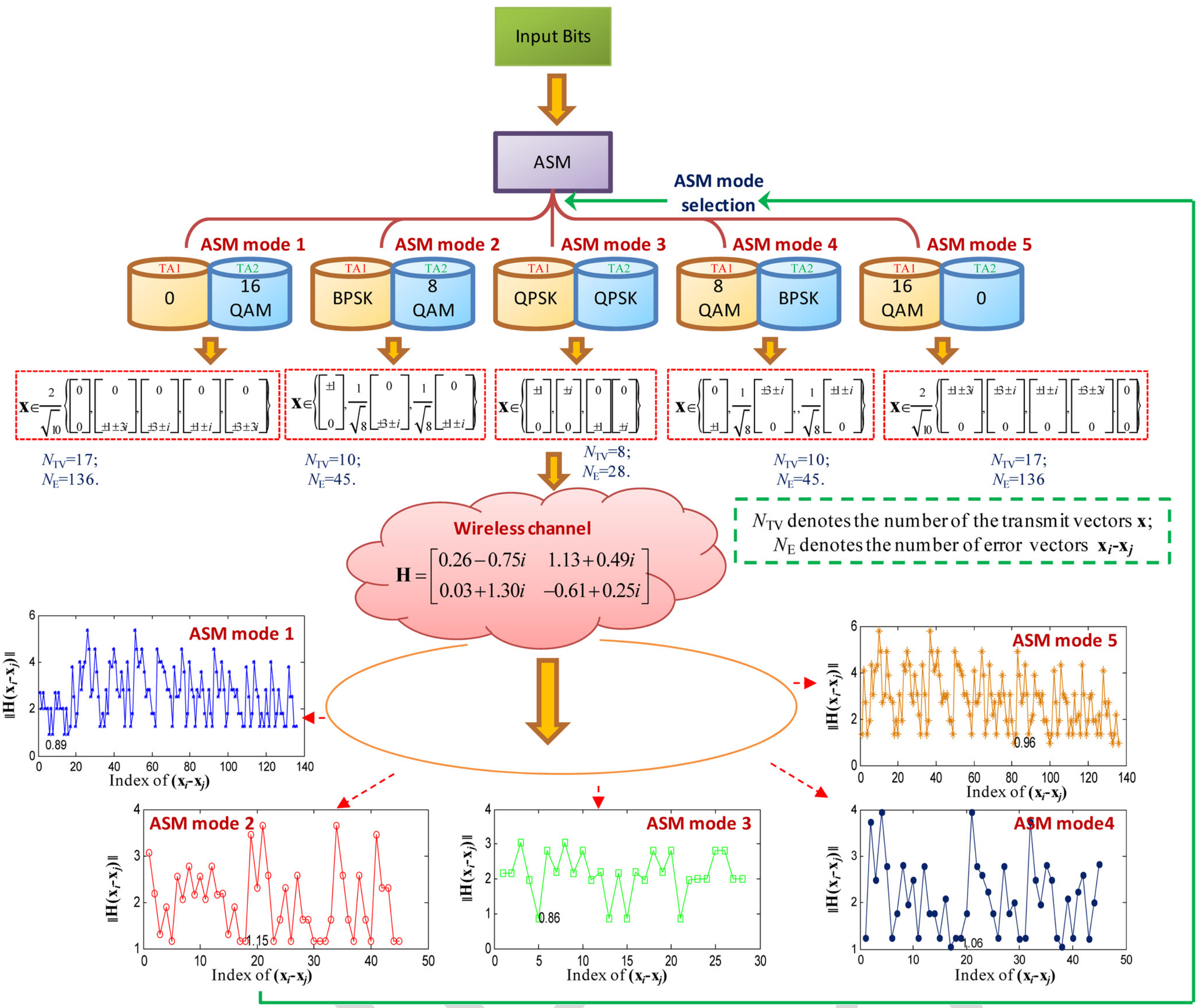

Fig. 10. The example of ASM associated with (2×2)-element MIMO channels at a throughput of $m_{\rm all} = 3$ bits/symbol.

order combinations) are generated first. For each ASM mode, we can calculate its legitimate transmit symbols $\mathbf{x}$ and its corresponding error vectors. For example, as shown in Fig. 10, the number of $\mathbf{x}$ combinations is $N_{\rm TV} = 8$ for the ASM mode 3 (the candidate [4,4]), while the corresponding number of the error vectors $\mathbf{e}_{ij} = \mathbf{x}_i - \mathbf{x}_j$, $i \neq j$ of (4) is $N_E = \binom{2}{N_{\rm TV}} = 28$. Here, each error vector $\mathbf{e}_{ij}$ is given a specific index, which is associated with its corresponding distance $\|\mathbf{H}\mathbf{e}_{ij}\|$. Then, the minimum value of $\|\mathbf{H}\mathbf{e}_{ij}\|$ among all the legitimate error vectors is found, which determines the FD of this ASM mode. In Fig. 10, the FD of the ASM mode 3 is 0.86. For other ASM modes, we can use the same method of determining the corresponding FDs. Observe in Fig. 10 that ASM mode 2 has the highest FD for the ASM candidate of [2,8]. The corresponding ASM mode index 2 is then fed back to the transmitter.

As indicated above, the Modulation Order Selection (MOS) of ASM turns out to be a demanding process, because the global optimum is found by carrying out an exhaustive search across the entire ASM's mode-candidate set. For example, for an ASM scheme associated with $N_{\rm t} = 8$ and 4 bits/symbol transmission, we need a global search of 154, 645 candidates, which results in an excessive complexity and feedback load, when high data rates are required. To circumvent this problem, the probabilities of occurrence for the ASM candidates were evaluated theoretically in [119]. More specifically, all legitimate ASM-mode candidates were classified according to their variances and FD. It was shown that for most of the practical channel realizations the probability that the maximum FD occurs when all the TAs have the same modulation order is high. As a result, only the specific ASM mode candidates associated with lower variances were earmarked for the optimization in **Algorithm 3**. Based on this result, a One Bit Re-Allocation (OBRA) algorithm was proposed in [119] for the ASM mode selection. OBRA-ASM imposes both a lower complexity and a lower feedback requirement than that of the ASM relying on a potentially excessive-complexity exhaustive search, while imposing a marginal performance degradation.[1]

[1]Note that ASM may transmit an unequal number of bits in different time slot. Hence, this mismatch in the transmission frame-length will result in a potential error propagation effect at the detector, which may be mitigated using channel coding techniques, as detailed in [69].

B. Transmit Precoding Techniques

Similar to the AM technique, Transmit Precoding (TPC) is another attractive LA regime, which exploits the knowledge of the CSI at the transmitter, in order to match the transmission parameters to the instantaneous channel conditions. A beneficial solution to this problem is to use the TPC matrix $\mathbf{P}$ of (4) for enhancing the attainable performance. There is a paucity of literature on how to design both linear and non-linear precoders for conventional MIMO schemes [39]. To be specific, non-linear precoding may be more powerful than its linear counterparts, but linear TPC usually achieves a reasonable performance at a significantly lower complexity. Moreover, most of the precoders were designed using a capacity-maximization approach [39], although in practice minimizing the BER may be more important, than maximizing the mutual information or the capacity [40].

1) Diagonal Precoding: The SM technique employed in conjunction with a precoding scheme, where the transmitted symbols are appropriately weighted according to the near-instantaneous channel condition constitutes an attractive solution in terms of improving the system's BER performance. One of the key design challenges of the precoded SM-MIMO architectures is to construct a beneficial precoding matrix $\mathbf{P}$ that relies on a modest amount of feedback information, while retaining all the single-RF benefits of SM-MIMOs.

To this end, in [103] a beamforming codebook was designed for optimizing the coding gain of SM-MIMO in the presence of spatial correlation amongst the fading envelopes of the TAs. Recently, a closed-loop TPC method was invoked for providing both diversity and coding gains in the context of GSSK [124], which activated more than one TAs for transmission. However, the above-mentioned schemes considered only a special case of SM, namely SSK. As a result, the schemes proposed for SSK may not be directly applicable to the conventional SM scheme. By contrast, in [133] a TPC technique was used for improving the signal design for a new class of SM, namely for Receiver-SM (R-SM). Moreover, in [100] the authors investigated the effects of finite-alphabet inputs on the achievable capacity of SM for transmission over MISO channels and then developed a TPC scheme for improving this performance metric.

In this section, we continue by considering a novel TPC scheme based on maximizing the FD for the family of SM-MIMO systems. Note that since the attainable performance of the optimum single-stream ML receiver depends on the FD of the received signal constellation [29], the maximization of the FD directly reduces the probability of error. In order to retain all the single-RF related benefits of SM, we designed the TPC matrix $\mathbf{P}$ to be a diagonal matrix formulated as $\mathbf{P} = \mathrm{diag}\{p_1, \cdots, p_n, \cdots, p_{N_t}\}$. Note that although there are various diagonal matrix aided TPCs proposed for the family of conventional MIMO schemes, they tends to aim for diagonalizing the channel matrix [39], which may jeopardize the advantages of SM-MIMOs. As a result, the conventional TPC techniques proposed for classic MIMO schemes, such as the STBC and VBLAST, may not be directly suitable for the family of SM-MIMOs.

In order to identify the specific TPC parameters p_n $(n = 1, \cdots, N_t)$, which are capable of maximizing the FD, we have to determine all the N_t parameters p_n $(n = 1, \cdots, N_t)$. Since it may become excessively complex to jointly optimize these N_t parameters in the complex-valued field, we decomposed $\mathbf{P}$ as $\mathbf{P} = \bar{\mathbf{P}}\boldsymbol{\Theta} = \mathrm{diag}\{\bar{p}_1 e^{j\theta_1}, \cdots, \bar{p}_n e^{j\theta_n}, \cdots, \bar{p}_{N_t} e^{j\theta_{N_t}}\}$. Because the FD of this particular TA-pair predominantly determines the achievable performance, only the specific TA pair (g, k) associated with the FD is considered and the TPC parameters are selected for appropriately weighting the SM symbols. As a result, there are only two parameters, namely p_g and p_k, to be searched for. Finding the optimal values of p_g and p_k as a function of both $\mathbf{H}$ and of the optimal transmit parameters involves an exhaustive search over the vast design-space of $\bar{p}_g$, $\bar{p}_k$, θ_g and θ_k, which is overly complex. By considering the power constraint, we have $\bar{p}_k = \sqrt{2 - \bar{p}_g^2}$. Moreover, since the phase rotation of the symbol is only carried by two TAs, we can simplify the computation by fixing $\theta_k = 0$ and then finding the optimal θ_g. The proposed low-complexity TPC design algorithm is summarized as follows.

Algorithm 4: A low-complexity TPC design algorithm for SM-MIMO

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1) Given the transmit parameters N_t, N_r and the transmission rate m_{all} as well as the channel matrix $\mathbf{H}$, the indices of the TA pair (g, k) associated with the FD of (4) are first obtained. In order to offer an increased FD, the TPC parameters of this TA pair can be dynamically adapted.[2]
2) Generate all the legitimate diagonal TPC matrix candidates represented as $\mathbf{P}_{\mathrm{cand}} = \mathrm{diag}\{1, \cdots, \bar{p}_g e^{j\theta_g}, \cdots, \sqrt{2 - \bar{p}_g^2}, \cdots, 1\}$, where we have $\bar{p}_g = \sqrt{2}/L_1 * l_1, l_1 = 0, \cdots, L_1$ and $\theta_g = 2\pi/L_2 * l_2$, $l_2 = 0, \cdots, L_2$. Here, L_1 and L_2 are the quantized parameters, which can be flexibly selected according to the prevalent BER requirements.
3) Based on the above-mentioned optimization rule, we can achieve a performance gain by maximizing the FD $d_{\min}(\mathbf{H})$ by switching among these TPC candidates. Note that the FD of the TPC matrixes $\mathbf{P}_{\mathrm{cand}}$ generated will be compared to that of the conventional scheme and then we select the one having the largest FD as our final result.
4) Then, the index of the optimized TPC matrix has to be fed back to the transmitter.

Unlike in the traditional TPC method of [39], our proposed scheme is suitable for scenarios relying bandwidth-limited feedback channels, because the TPC design is reduced to the design of a diagonal matrix. Moreover, as demonstrated in **Algorithm 4** as few as two elements of the diagonal TPC matrix have to be fed back to the transmitter, regardless of the value of N_t.

[2]Note that if the value of g is the same as k, we have to adapt the TPC parameters of the pair (g, u), where the TA u has the maximum channel gain $\|\mathbf{h}_u\|_F$. Here, $\mathbf{h}_u$ is the uth column of $\mathbf{H}$ and $|\cdot|$ stands for the Frobenius norm.

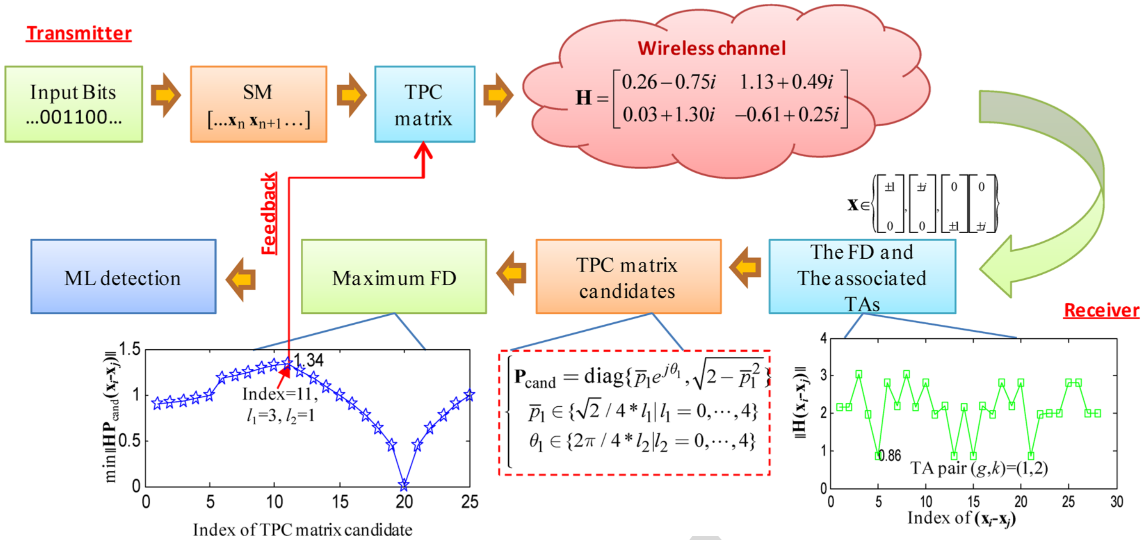

Fig. 11. The example of TPC aided SM.

More specifically, revisiting the previous example in **Algorithm 3**, as shown in Fig. 11, for the same channel realization $\mathbf{H}$, if the TPC matrix $\mathbf{P}$ of Algorithm 4 is used for optimizing the system's performance, where the specific TA-pair (1,2) associated with the FD of 0.86 is first found by using (4), which corresponds to the conventional SM scheme (the ASM mode 3 in Fig. 10). This result implies that the FD is computed for different TAs and the FD of this particular TA-pair predominantly determines the achievable performance. To improve the system's performance, the TPC parameters of this pair should be optimized. Here, the optimized TPC matrix is selected from the quantized TPC matrix set, as shown in Fig. 11, where the quantized parameters L_1 and L_2 are selected as $L_1 = L_2 = 4$. Hence, the number of TPC candidates is $(L_1 + 1) \times (L_2 + 1) = 25$. We can assign a specific index for each candidate and then calculate its corresponding FD according to (4). As shown in Fig. 11, the specific candidate associated with $l_1 = 3$ and $l_2 = 1$ has the highest FD of 1.34 among all the legitimate TPC matrix candidates. Note that if the highest FD of all the legitimate TPC matrix candidates is lower than that of the conventional SM. Based on step 3) of Algorithm 4, The optimal TPC matrix is $\mathbf{P} = \mathbf{I}_{N_t}$. The corresponding index of this candidate is then fed back to the transmitter, which appropriately weights the SM modulated symbol.

2) Phase Rotation Precoding and Power Allocation: Since the proposed precoder $\mathbf{P}$ consists of two different diagonal matrices $\bar{\mathbf{P}}$ and $\mathbf{\Theta}$, we may reduce the complexity of the precoding process in **Algorithm 4** by employing only a subset of matrices at a modest performance loss. Firstly, when only the diagonal matrix $\mathbf{\Theta}$ is considered, this solution may be referred to as the Phase Rotation Precoding (PRP) technique [134], which is usually used for improving the BER, when spatial correlation exists between the TAs of the ML-detection aided V-BLAST architecture.

An alternative complexity reduction is achieved by considering only the diagonal matrix $\bar{\mathbf{P}}$, which can be viewed as a simple form of Power Allocation (PA) [30], [121]–[123]. This arrangement has been intensively researched in the context of spatial multiplexing systems [30]. However, these PA approaches designed for spatial multiplexing based MIMO systems may not be directly suitable for the family of SM-MIMO systems, because only a single TA is active in each time slot and hence the PA between the TAs should be carefully considered. In [30], an opportunistic power allocation scheme was conceived for achieving a beneficial transmit diversity gain in SSK-aided MIMO systems relying on two TAs. Then, this feedback-aided PA scheme was further developed in [121]. However, no APM scheme was considered in the above-mentioned PA-aided SSK-MIMO systems and hence their throughput may remain limited. In order to realize the full potential of PA techniques in a SM-MIMO context, **Algorithm 4** can also be invoked by simply changing the legitimate diagonal TPC matrix to the PA matrix.

Still considering the example given in Fig. 11, if the PA technique is considered, we gradually assign the appropriate portion of power to each TA of the TA pair (1,2), where the number of PA matrix candidates is $L_1 + 1 = 5$, as shown in Fig. 12(a). Similar to Fig. 11, we can also assign a specific index for each candidate and then calculate its corresponding FD according to (4). As shown in Fig. 12(a), the PA matrix candidate associated with $l_1 = 3$ has the highest FD of 1.26 among all the legitimate PA matrix candidates. On the other hand, as shown in Fig. 12(b), if the PRP technique is invoked, only the phases of the TA pair (1,2) are adjusted, where the number of PRP matrix candidates is $L_2 + 1 = 5$. We observe from the results of Fig. 12(b) that the PRP matrix candidate associated with $l_2 = 3$ has the highest FD of 1.3 among all the legitimate PRP matrix candidates. The index of the optimized matrix is fed back to the transmitter for allowing the transmitter to compensate for the effects of channel fading.

3) Performance Results: In Fig. 13, we compared the various LA-aided SM schemes to the conventional non-adaptive SM scheme in the context of (2×2)-element MIMO channels at a throughput of $m_{\text{all}} = 3$ bits/symbol for transmission over independent Rayleigh block-flat channels. In all cases we

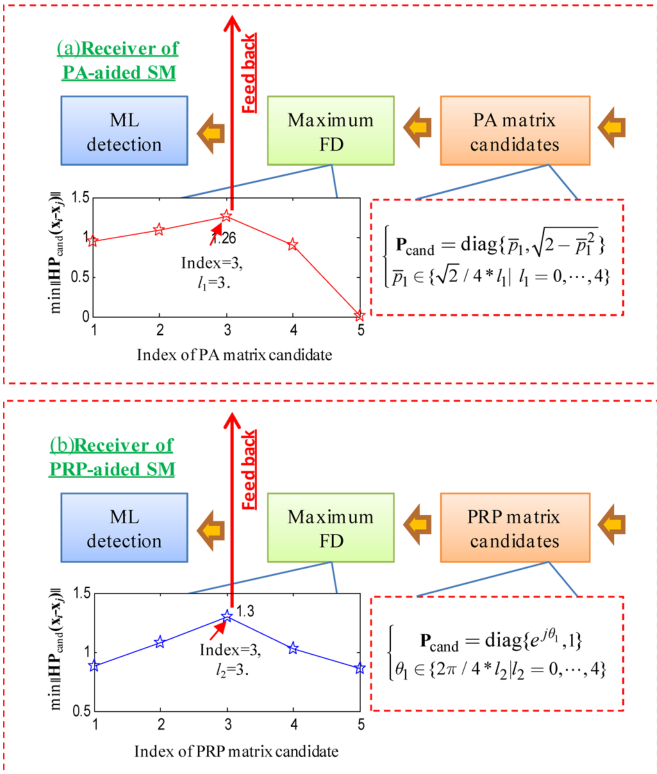

Fig. 12. The example of PA and PRP aided SM system.

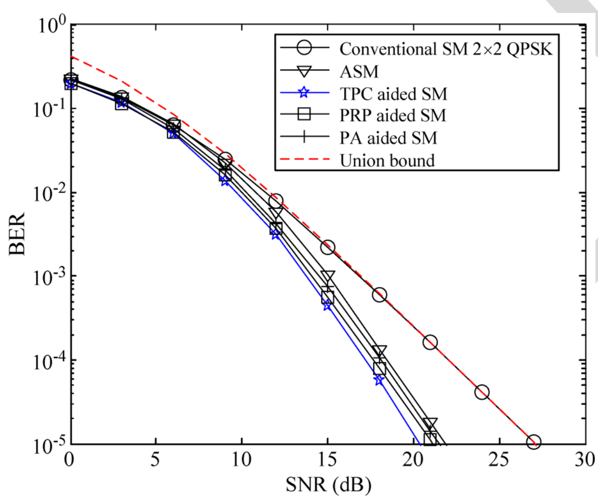

Fig. 13. BER performance of the conventional SM and the LA-aided SM schemes in (2 × 2)-element MIMO channels at a throughput of $m_{\text{all}} = 3$ bits/symbol.

assumed that the feedback channel is free of errors and delay.[3] For completeness, we also added the theoretical upper bound curve derived with the aid of the union bound [29], [103] of the conventional SM scheme. Moreover, in the TPC design of **Algorithm 4**, we selected $L_1 = L_2 = 4$.

[3]The error-free feedback channel assumption in SM-based schemes may be justifiable, since the feedback channel is usually protected using powerful error correction coding and hence has a low error probability [4]. The effect of imperfect feedback channels in closed-loop MIMO systems has been documented, for example in [135].

As expected, the proposed LA-aided schemes beneficially exploit the flexibility of the transmit parameters and as seen in Fig. 13, they provide an SNR gain of about 5.1–7.3 dB over the conventional SM scheme at the BER of 10^{-5}. Moreover, the TPC-aided SM achieves the best BER performance amongst all benchmark schemes, as seen in Fig. 13. This is mainly due to the fact that the PA-assisted SM and PRP-aided SM schemes are simplified versions of the TPC-aided SM scheme, which have a suboptimal BER performance. Moreover, the selection of TPC parameters is more flexible than that of ASM, because the modulation orders of ASM are selected from a discrete set, while the TPC parameters are chosen from the vast complex-valued field. The performance gain of the TPC-aided SM over ASM is explicitly seen in Fig. 13.

C. Antenna Selection

Antenna Selection (AS) constitutes another promising low-cost technique, since it enjoys the full-diversity benefits offered by MIMO architectures at the cost of requiring a low feedback rate. Due to its advantages, AS has been adopted in contemporary wireless systems such as IEEE 802.11n [136]. A detailed overview of AS techniques was presented in [136] and both the so-called norm-based selection and the successive selection scheme were detailed. Recently, a systematic overview of all physical and higher layer features of the LTE standard relying on Transmit AS (TAS) were presented in [137]. To be specific, TAS has been adopted by LTE for both its Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD) modes of operation.

SM can also be beneficially combined with the AS technique for the sake of enhancing its performance. In recent years, several AS methods have been introduced and extended to the class of SM-MIMO systems with the goal of enhancing its capacity or its BER. For example, in [127], a TAS method based on exhaustive search was proposed for exploiting the available CSI. As natural extensions of the existing literature on TAS for spatial multiplexing systems, in [128], a low-complexity maximum-ED based TAS method and a maximum-capacity TAS method were investigated. Moreover, three closed-loop AS-aided SSK schemes were proposed in [126], which relied on the classic norm-based AS criterion, on the minimal PEP criterion and on their hybrid.

D. Hybrid Adaptation and Other LA Schemes

As mentioned in Section IV-A, ASM is capable of transmitting different number of bits over different TAs. Hence this scheme may achieve increased benefits due to the associated channel gain difference by exploiting it with the aid of dissimilar channel matrix column vectors [104]. For example, as shown in **Algorithm 3**, the number of bits carried by the conventional 4-QAM symbol is 2 in each SM symbol, while the number of bits conveyed by the TA indices is only one. The AM scheme is capable of varying this bit-mapping strategy according to the near-instantaneous channel conditions, while the TPC aided schemes [30], [103], [121]–[125] have to utilize a fixed modulation order and hence they may fail to achieve this level of flexibility. However, TPC exhibits an extra grade of flexibility, since it can have arbitrary coefficients.

As discussed in the context of (4) and Fig. 9, apart from adapting the APM modes, LA-aided SM can also benefit from adapting the TPC parameters for the sake of improving the system's performance. For example, when a high power amplifier efficiency and a high transmission rate are required, the classic PSK scheme may be preferred to QAM in diverse SM-MIMO configurations both in terms of its BER and PAPR, because PSK may be conveniently combined with the above-mentioned PRP technique for creating a PRP-aided constant-modulus SM scheme. In this scheme, the APM constellation optimization technique of Section III may be efficiently combined with the TPC technique of Section IV-B for improving both the achievable energy efficiency and the BER performance.

V. Further SM-Related Studies

A. Cooperative SM-Related Systems

Cooperative techniques are capable of gleaning some of the advantages of classic multiple-antenna aided transmission techniques with the aid of cooperating single-antenna assisted nodes within a network [139]. Based on a philosophy similar to that of the STC-based schemes, relay-aided SM schemes have been proposed in [140]–[147]. For example, in [140], a decode-and-forward (DF) relaying aided coherent STSK system was proposed, where the dispersion-vector was activated based on cyclic redundancy checking (CRC)-assisted error detection. The proposed design is capable of adapting both the number of the RNs as well as the transmission rate and the achievable diversity order, depending on the associated system requirements and channel conditions. Moreover, a differentially-encoded and non-coherently detected version of STSK was developed in [140], which dispenses with CSI estimation at all of the nodes, while retaining the benefits of the cooperative coherent STSK. In order to further improve the cooperative STSK's performance as well as to combat the effects of frequency-selective channels, in [141], Successive-Relaying (SR)aided cooperative multicarrier (MC) STSK was proposed. This technique invokes the selective DF and SR principles for the sake of recovering the half-duplex multiplexing loss while relying on the MC Code-Division Multiple Access (MC-CDMA) [148] principle for supporting multiple users, and simultaneously circumventing the dispersive effects of wireless channels. Moreover, in [142] a so-called Information Guided Transmission (IGT) scheme was employed for carrying out the random selection of the active nodes from the set of candidate Relay Nodes (RNs) for the sake of achieving a high relay throughput. Note that the above-mentioned SM-related cooperative systems may rely on single-antenna based transmissions at the Source-Node (SN), but some form of loose inter-relay synchronization (IRS) should be considered, unless the so-called Large-Area-Synchronized (LAS) spreading codes of [149], [150] are employed.

Moreover, in [121], an Amplify-and-Forward (AF)-relaying-aided SSK scheme was conceived for reducing the number of TAs and for mitigating the effects of deep fading. More recently, Mesleh *et al.* [143], [144] invoked dual-hop AF and DF relaying aided SSK schemes, which were characterized by the corresponding BER performance upper-bounds. However, as mentioned in Section II, the throughput of the SSK-aided cooperative schemes may remain somewhat limited. To eliminate this impediment, a dual-hop cooperative SM scheme [145] was conceived for combining SSK with classic APM techniques for the sake of transmitting additional bits. More specifically, the spatial domain of dual-hop SM has been exploited for transmitting additional information bits, hence this system may have the potential of providing substantial spectral efficiency and coding gains in the context of wireless relay networks. In [146], the SSK-MIMO principle is studied for the uplink of cellular networks. The source broadcasts its data packet to the available relays. The data packets are decoded by each relay individually and each decoded symbol is compared against unique identifiers of the relays. The specific relays that demodulate the data associated with their own identifier become active and transmit the associated SSK symbol to the destination. Hence, the set of relays act as a distributed spatial-constellation diagram for the source, similar to the SSK-MIMO communications concept with co-located TAs. The distributed encoding principle of [146] was then extended in [147] with the objective of improving the achievable bandwidth efficiency of half-duplex relaying. The associated transmission protocol is similar to that of [146], with one main exception, namely that active relays transmit the first data packet stored in their buffers during the second phase. This enables the relay to simultaneously transmit both the data received from the source and its own data. This is due to the fact that when a relay is active, the source data is conveyed by conventional APM modulation through this relay, while an additional data symbol can be implicitly mapped onto the relay's index. The results show that the adoption of a distributed SM-MIMO scheme is indeed capable of improving the attainable performance.

B. SM-Related Systems for Frequency Selective Channels

Despite its rich literature, the family of SM-related schemes has been predominantly investigated in the context of single-user flat fading channels. However, in high-rate SM-MIMO communication systems, the Inter-Symbol Interference (ISI) caused by multipath components of the frequency selective channel has to be considered.

Hence various SM-related systems have been investigated not only in the context of single carrier (SC) contexts [148] and but also in multi-carrier systems [151]. More specifically, in [55] the authors proposed the STFSK regime for overcoming the effects of dispersive channels, while striking a flexible trade-off between the attainable diversity and multiplexing gain. STFSK is capable of flexibly exploiting the available time-, space- and frequency-diversity, hence attaining an attractive performance in frequency-selective fading environments. In [152], an OFDM-aided STSK system was proposed, which achieves almost the same BER performance as that of its single-carrier counterpart operating in a narrowband channel. Moreover, in order to support high-rate multiuser transmissions, a novel multiuser STSK scheme was conceived for frequency-selective channels in [153], which was combined with the classic OFDMA/SC-FDMA techniques for the sake of converting the frequency-selective wideband channel to numerous parallel non-dispersive narrowband channels. In [154], an antenna-hopping space-division multiple-access aided SM scheme was advocated for exploiting the advantages of SM. For efficiently detecting this scheme, a range of linear and nonlinear detection schemes have been investigated.

Recently, SM-related schemes were investigated in a frequency selective channel by combining the classic Cyclic-Prefixed (CP) single carrier technique [155], [156], which is capable of avoiding the PAPR problem encountered in multicarrier based systems. A comparison between CP-aided SC-SM and the CP-aided SM-OFDM systems was also presented for the sake of identifying the advantages of the single-carrier-SM scheme. Then, Rajashekar *et al.* further generalized the solutions of [156], where a Zero-Padded (ZP) single-carrier SM system was proposed for achieving the maximum attainable multi-path diversity order with the aid of low-complexity single-stream ML detection. It was shown that the proposed ZP-aided SC-SM system provides beneficial system performance improvements compared to both the CP-aided SC-SM and the CP-aided SM-OFDM systems.

C. The Energy-Efficient SM-Related Systems

Recently, the energy consumption issue in wireless communication has attracted increasing attention, especially in MIMO-aided LTE and LTE-A networks [111], [157]. As a new kind of MIMO transmission technique and a promising candidate for future wireless applications and standards, SM can be realized by using a single RF front-end, hence it has a high power-efficiency [15]. However, how to further improve the energy-efficiency of SM-MIMO schemes is important in practical deployments.

Some of the above-mentioned issues have been already investigated in [16], [17], [69], and [158]. More specifically, in [16] the authors evaluated the energy efficiency of a multi-antenna assisted base station employing SM based on a realistic power consumption model. It was found that the SM-aided base station has a considerable power consumption gain compared to multi-RF chain aided MIMO arrangements. This advantage of SM was further confirmed in [17] by considering different base station types. Then, in [158], the energy consumption of a class of adaptive SM was evaluated. Moreover, in [69], an energy-efficient SM-MIMO scheme was designed, which relied on the Hamming coding and Huffman coding techniques. This scheme was capable of striking a flexible spectral-efficiency versus energy-efficiency tradeoff. Note that although the above-mentioned research demonstrated that SM constitutes an energy-efficient design [111], [157], the current research results are still preliminary and hence further investigations are required.

VI. Conclusion

A. Summary of the Paper

In this tutorial, we reviewed a range of recent research achievements on SM and its potential applications. We considered some of its transceiver design aspects, the spatial constellation optimization, the associated link adaptation techniques, the distributed/cooperative system design issues and their beneficial combinations.

In Section II, we provided a rudimentary system overview of the conventional SM technique and its variants, emphasizing the associated transceiver design techniques for striking an attractive trade-off amongst the range of potentially conflicting system requirements. More specifically, the bit-to-symbol mapping principle of the SM transmitter was presented Section II-A. Then, various generalized versions of SM were introduced in Section II-B. Section II-C summarized the class of hard- and soft-detection techniques designed for SM-related schemes, which was roughly divided into four fundamental categories. In Section II-D, both the channel capacity and error performance metrics of SM-related schemes were summarized, which were used as a reference for the sake of highlighting the advantages of SM compared to other MIMO arrangements. These metrics were also used for system optimization by exploiting the knowledge of CSI.

In Section III, the effects of APM schemes on the performance of SM were characterized and we proposed a class of star-QAM constellations for minimizing the system's BER. In Section IV, we introduced the family of limited-feedback aided LA techniques designed for SM-related schemes. Depending on the specific degree of freedom exploited, these techniques were divided into four types constituted by AM, TPC, AS and their hybrid techniques. Specifically, the near-instantaneously ASM scheme of Section IV-A has been proposed in [104], [115], and [119] for improving the attainable system performance, while maintaining a fixed average transmit rate with the aid of AM techniques. Moreover, the diagonal TPC scheme of Section IV-B has been proposed in [118] and [122] based on maximizing the FD for the family of SM-MIMO systems, where the transmitted symbols are appropriately pre-weighted according to the channel condition. Finally, we discussed a variety of other SM-related classes including those designed for frequency selective channels, for cooperative SM scenarios and for energy-efficient applications.

B. Future Research Ideas

In this paper, we considered only the minimum-distance based approach of extracting the LA parameters, in order to achieve beneficial performance improvements in the high-SNR regime. As further work, one can formulate and solve the LA problems by considering a range of other optimization criteria depending on the amount of channel state information available as well as on other system requirements, such as capacity- and SNR-optimized design rules [39]. Moreover, the integration of trellis coding as well as space–time block coding and other coding techniques [4] into the proposed LA schemes may also be further researched. Perhaps the most challenging of all is the design of non-coherent detection aided or blind-detection assisted schemes, which are capable of dispensing with channel information. These are particularly important in the context of relay-aided systems, where the source-relay channel cannot be readily estimated.

VII. Glossary

ABEP	Average Bit Error Probability.
AM	Adaptive Modulation.
APM	Amplitude and Phase Modulation.
AS	Antenna Selection.
ASM	Adaptive SM.
BER	Bit Error Ratio.
BP-IGCH	Bit-Padding IGCH.
CS	Compressed Sensing.
CSI	Channel State Information.
C-SM	Concatenated SM.
CSTSK	Coherent STSK.
DSTC	Differentially-encoded STC.
ED	Euclidean distance.
EMF	Exhaustive-search MF.
FD	Free Distance.
FSK	Frequency-Shift Keying.
FBE	Fractional Bit Encoded.
GSM	Generalized SM.
G-STSK	Generalized STSK.
IAI	Inter Antenna Interference.
IAS	Inter-Antenna-Synchronization.
IGCH	Information-Guided Channel Hopping.
ISI	Inter-Symbol Interference.
LA	Link adaptation.
LTE	Long-Term Evolution.
MA-SM	Multiple Active-SM.
MAP	Maximum *a posteriori*.
MF	Matched Filter.
MIMO	Multiple-Input Multiple-Output.
MISO	Multiple-Input Single-Output.
ML	Maximum Likelihood.
MMD	Maximum–Minimum Distance.
MOS	Modulation Order Selection.
MRC	Maximum Ratio Combining.
NMF	Near-optimal MF.
OFDM	Orthogonal Frequency-Division Multiplexing.
OFDMA	Orthogonal Frequency Division Multiple Access.
OFDM-IM	OFDM with Index Modulation.
OH-SM	Optimal Hybrid-SM.
OSD	Ordered SD.
OSDM	Orthogonal Spatial-Division Multiplexing.
PA	Power Allocation.
PAPR	Peak-to-Average-Power Ratio.
PEP	Pairwise Error Probability.
PRP	Phase Rotation Precoding.
PSK	Phase Shift Keying.
QAM	Quadrature Amplitude Modulation.
RF	Radio Frequency.
R-SM	Receiver-SM.
SC-FDMA	Single-Carrier Frequency Division Multiple Access.
SD	Sphere Decoding.
SDM	Spatial Division Multiplexing.
SFSK	Space–Frequency Shift Keying.
SIM	Subcarrier-Index Modulation.
SISO	Single-Input Single-Output.
SM	Spatial Modulation.
STBC	Space Time Block Codes.
STC	Space–Time Coding.
STFSK	Space–Time–Frequency Shift Keying.
SSK	Space Shift Keying.
STSK	Space–Time Shift Keying.
VBD	Vector Based Detection.
TA	Transmit Antenna.
TAS	Transmit Antenna Selection.
TC	Trellis Coding.
TCM	Trellis Coded Modulation.
TOSD-SM	Time-Orthogonal Signal Design assisted SM.
TPC	Transmit Precoding.
TMS	Transmit Mode Switching.
USTM	Unitary Space–Time Modulation.
V-BLAST	Vertical-Bell Laboratories Layered Space–Time.

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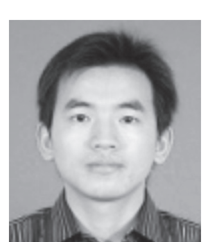

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Design Guidelines for Spatial Modulation

Ping Yang, Marco Di Renzo, *Senior Member, IEEE*, Yue Xiao, Shaoqian Li, *Senior Member, IEEE*, and Lajos Hanzo, *Fellow, IEEE*

***Abstract*—A new class of low-complexity, yet energy-efficient Multiple-Input Multiple-Output (MIMO) transmission techniques, namely, the family of Spatial Modulation (SM) aided MIMOs (SM-MIMO), has emerged. These systems are capable of exploiting the spatial dimensions (i.e., the antenna indices) as an additional dimension invoked for transmitting information, apart from the traditional Amplitude and Phase Modulation (APM). SM is capable of efficiently operating in diverse MIMO configurations in the context of future communication systems. It constitutes a promising transmission candidate for large-scale MIMO design and for the indoor optical wireless communication while relying on a single-Radio Frequency (RF) chain. Moreover, SM may be also viewed as an entirely new hybrid modulation scheme, which is still in its infancy. This paper aims for providing a general survey of the SM design framework as well as of its intrinsic limits. In particular, we focus our attention on the associated transceiver design, on spatial constellation optimization, on link adaptation techniques, on distributed/cooperative protocol design issues, and on their meritorious variants.**

***Index Terms*—Cooperative communications, large-scale MIMO, link adaptation, space–time coding, spatial modulation.**

I. Introduction

MULTIPLE-INPUT multiple-output (MIMO) systems are capable of achieving a capacity gain and/or diversity gain, which is based on striking a beneficial trade-off, depending on the near-instantaneous channel conditions [1]–[4]. Hence they have been adopted in most of the recent communication standards, such as IEEE 802.11n, IEEE 802.16e, and 3GPP Long-Term Evolution (LTE) [5], [6]. In a wireless MIMO transmission system, the transmission technique employed plays an important role in determining the achievable system performance. Recently, the conventional spatial-domain MIMO transmission techniques have been extended to the time-domain, the frequency-domain as well as to their combinations [7], [8]. In order to efficiently exploit the associated grade of freedom offered by MIMO channels, a meritorious transmission technique should be designed to satisfy a diverse range of practical requirements and to strike an attractive tradeoff amongst the conflicting factors of the computational complexity imposed, the attainable bit error ratio (BER) and the achievable transmission rate [9], [10].

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In the diverse family of MIMO techniques, the recently proposed spatial modulation (SM) [11] (which was referred to as Information-Guided Channel Hopping (IGCH) modulation in [12]) is particularly promising, since it is capable of exploiting the indices of the transmit antennas (TAs) as an additional dimension invoked for transmitting information, apart from the traditional Amplitude and Phase Modulation (APM) [13]. At a given Signal to Noise Ratio (SNR), the throughput of the SM-MIMO may potentially become higher than that of Space–Time Coding (STC) [14], but this is not necessarily its most prominent benefit, because in SM only a single TA is activated at any time instant. Hence SM is capable of dispensing with the requirement of multiple Radio Frequency (RF) chains, therefore relaxing the Inter-Antenna-Synchronization (IAS) specifications, whilst mitigating the Inter Antenna Interference (IAI) of conventional MIMO techniques [15]. Additionally, the single-RF design is capable of reducing the total power consumption. In fact, only a single power amplifier is needed for implementing SM-MIMO systems, which is typically responsible for the vast majority of power dissipation at the transmitter [16], [17]. Another advantage of SM is that it may be flexibly configured for diverse transmit and receive antenna constellations, especially for the challenging scenario of asymmetric/unbalanced MIMO systems, whose channel matrix is rank-deficient [15].

Due to the above-mentioned advantages, SM constitutes an attractive option for the emerging family of large-scale MIMO systems [18], [19]. As a further advance, the principle of SMs was also extended to indoor optical wireless communication in [20]–[23], which relies on optical transmissions for conveying information. Altogether, SM constitutes a promising low-complexity energy-efficient MIMO transmission technique, which relies on a low-cost transceiver and is capable of efficiently operating in diverse MIMO configurations in the context of future communication systems. Recently, the potential benefits of SM have been validated not only via simulations [11], [14] but also by experiments [24]–[26]. The benefits of SM-MIMOs aided wireless communications are summarized in Fig. 1. In the sequel, they are characterized in more detail.

The wide-ranging simulation based and analytical studies disseminated in [27]–[34] have characterized some of the

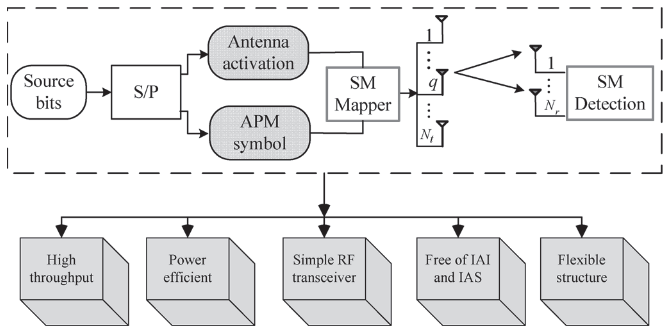

Fig. 1. Benefits of SM-MIMOs for wireless communications.

fundamental properties of SM related to the channel's correlation [27], [28]. Furthermore, the issues of achieving transmit diversity [29], the effects of power imbalance [30], the specific choice of the APM scheme used [31], the impact of the specific channel encountered [29], [32] as well as the effects of channel estimation errors [33], [34] were also characterized. It was found that the performance of SM-MIMOs is highly dependent on the specific type of the APM scheme used. For example, as a hybrid modulation scheme, which combines the classic APM constellation and the spatial-domain (SD) constellation, the SM's achievable performance depends both on the minimum Euclidean distance (ED) of the APM constellation employed, as well as the on absolute values of the modulated symbols [29]. Hence, a suitable APM scheme has to be carefully designed for exploiting the benefits of this hybrid modulation scheme.

On the other hand, it was also noted that the conventional open-loop SM schemes [11], [12] only offer receive-diversity gains. Hence there is also a paucity of SM-MIMO solutions on how to increase the system's robustness to time-varying channel conditions with the aid of either open or closed-loop transmit-symbol design techniques [14]. Additionally, unlike in conventional MIMO techniques, the transmit vectors of SM-MIMO schemes are sparsely populated, since they have mostly zero values [11]. This constraint makes SM rather different from classic Space Time Block Codes (STBC) [35] designed for achieving a diversity gain or from Spatial Division Multiplexing (SDM) [36] conceived for attaining a multiplexing gain as well as from the hybrid SDM-STBC schemes [37] aiming for striking a compromise. In order to increase the robustness of SM-MIMO systems, the classic time-variant parameter adaptation techniques [38], such as power allocation and precoding [39]–[41], which were proposed for conventional MIMO techniques may not be directly applied to SM schemes owing to their specific transmission mode.

In this treatise, we provide a general survey of the SM design framework as well as of its intrinsic limitations. We summarize the most recent research achievements and outline their potential applications, as well as their impediments, which have to be overcome before these MIMO technique may be used as mainstream solutions in practical systems. In particular, we focus our attention on the associated transceiver design, on spatial constellation optimization, on link adaptation techniques, on distributed/cooperative protocol design and on their meritorious variants.

The paper is organized as follows. Section II reviews the conventional SM technique and its relevant variants, emphasizing the flexible transceiver design techniques conceived for striking an attractive trade-off amongst the often conflicting system requirements. The spatial constellation optimization and the associated link adaptation techniques are presented in Sections III and IV, respectively. Section V surveys the family of relay aided SM schemes, which exploits the particular information transmission characteristics of SM and introduces the class of SM-related systems designed for dispersive channels. Finally, Section VI concludes the paper.

Although the list of the references is not exhaustive, the papers cited as well as the references therein can serve as a good starting point for further reading. In particular, there are several tutorial-style articles, [8], [14] and [15], which tend to have quite a different focus. To be specific, in [8], the authors have reviewed diverse MIMO arrangements and then focus on a new class of MIMOs based on the concept of space–time shift keying. In [14], the authors have evaluated the advantages and disadvantages of SM with respect to other popular MIMO schemes and summarized some early research achievements. Moreover, in [15], some of the co-authors of this treatise have provided a comprehensive survey of spatial modulation research, with an emphasis on a generalized transceiver scheme combining spatial modulation with spatial multiplexing and space–time block coding in order to increase either the spectral efficiency or the diversity gain. The price to pay for this flexibility is the need for multiple radio frequency chains. Moreover, in [15] the authors emphasized the energy efficiency of MIMO-based transmission schemes and the first SM-MIMO-based testbed results recorded both in realistic outdoor and indoor propagation environments were reported. Suffice to say that [15] was conceived for stimulating cross-disciplinary research across different communities, whilst this contribution is targeted at readers with a background in wireless communications, who might like to delve into SM-research.

Against this background, this contribution firstly provides a succinct description of the basic spatial modulation principle. To be specific, the SM techniques are classified and then the corresponding detection techniques are categorized with the aid of tables for explicit clarity. Moreover, this paper is more focused on illustrating those results that lead to new design guidelines, as exemplified by the constellation optimization issues of SM. Furthermore, there is a special emphasis on powerful adaptive modulation aided SM and on precoding aided SM. A range of performance metrics are introduced for optimizing spatial modulation, which rely either on the available long-term statistical or on the near-instantaneous knowledge about the channel.

II. Transceiver Design of SM-MIMO

A. The Transmitter Design of SM

In this section, we consider the $(N_t \times N_r)$-element SM-MIMO system, which relies on N_t transmit and N_r receive antennas, while communicating over frequency-flat Rayleigh fading channels. The conventional bit-to-symbol mapping rule

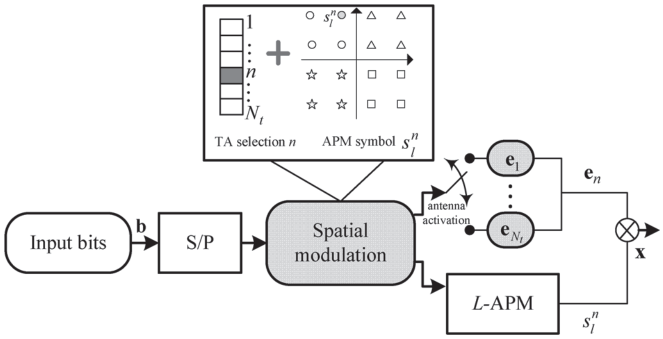

Fig. 2. SM bit-to-symbol mapping rule.

[11] of SM is portrayed in Fig. 2, which can be divided into three steps as follows:

Algorithm 1: Bit-to-symbol mapping principle of the SM transmitter of Fig. 2

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1) First, the information bit stream is divided into vectors containing $m_{\text{all}} = \log_2(L \cdot N_t)$ bits each.
2) Next, each vector is further split into two sub-vectors of $\log_2(N_t)$ and $\log_2(L)$ bits each. The bits in the first sub-vector are used for activating a unique TA for transmission, while the bits in the second sub-vector are mapped to an APM symbol s_l^n. Note that the TA activation process can be described by the N_t-dimensional standard basis vector $\mathbf{e}_n$ $(1 \le n \le N_t)$ (i.e., $\mathbf{e}_1 = [1, 0, \cdots, 0]^T$).
3) Finally, the transmitted symbol $\mathbf{x}$ is comprised of the APM symbol s_l^n emitted from the activated TA n. The resultant modulated symbol can be formulated as $\mathbf{x} = s_l^q \mathbf{e}_q \in \mathbb{C}^{N_t \times 1}$.

The corresponding vector-based signal received at the SM-MIMO receiver is given by

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} = \mathbf{h}_n s_l^n + \mathbf{n} \tag{1}$$

where $\mathbf{H}$ is an $(N_r \times N_t)$-element channel matrix, $\mathbf{h}_n$ is the nth column of $\mathbf{H}$ and the elements of the N_r-dimensional noise vector $\mathbf{n}$ are **complex** Gaussian random variables obeying $\mathcal{CN}(0, N_0)$.

B. *Variants of the SM Principle*

The first conference paper on SM was published in 2001 [45], but its extensive research was mainly fueled by the pioneering works of Haas *et al.* [42], Mesleh *et al.* [11], followed by Sugiura *et al.* [43], Yang *et al.* [12] and Jeganathan *et al.* [44]. Throughout its decade-long history, the SM concept has been termed in different ways and it was extended to different scenarios. A range of major contributions on the subject of SM and its related variants are listed in Table I. Specifically, the concept of SM was first touched upon in [45], where the distinct multipath components were exploited for detection. In [42], a novel Orthogonal Spatial-Division Multiplexing (OSDM) scheme was proposed, which utilizes the index of the TAs as a means of conveying additional source information. In [11], a beneficial framework was established for the bit-to-symbol mapping rule of SM. It was also demonstrated in [11] that SM may be capable of attaining a better performance than other conventional MIMO schemes, such as the Vertical Bell Laboratories Layered Space–Time (V-BLAST) and STBC [4], even without reducing the achievable data rate,. The above-mentioned IGCH technique was proposed in [12] for achieving a high throughput. Later, Space Shift Keying (SSK) [44] modulation was conceived for relying exclusively on the TA indices to convey information, whilst entirely dispensing with any classic Phase Shift Keying (PSK)/Quadrature Amplitude Modulation (QAM) signaling [13]. In a nutshell, all of the above-mentioned schemes activate only a single TA at any instant in order to maintain a low complexity, whilst mitigating to IAI and IAS specifications, as well as reducing to total power consumed.

Motivated by the above concepts, various generalized versions of SM were proposed. First, as a natural extension of SSK, the Generalized SSK (GSSK) scheme was proposed in [46], which activates multiple TAs for the sake of achieving an increased-rate data transmission. This extension has also been incorporated into the SM scheme and two classes of Generalized SM (GSM) schemes were obtained [47]–[49]. To be specific, in [47] a class of GSM arrangements was proposed for the sake of attaining increased transmit diversity gains, which uses all the active TAs for transmitting the same APM-modulated symbols. By contrast, in [48] and [49], another class of GSM arrangements was proposed for attaining an increased multiplexing gain, which uses the active transmit antennas to carry different information symbols during each time slot. Note that the above-mentioned generalized SM schemes of [46]–[49] allow us to activate several—rather than only a single antenna—at the transmitter for bit-to-symbol mapping, hence they are capable of overcoming a specific constraint of SM, namely that the number of TAs has to be a power of two. Moreover, SM was combined with the classic STBC scheme in [50] and with Trellis Coding (TC) in [51]–[53] in order to take advantage of the benefits of both.

Recently, Space–Time Shift Keying (STSK) [43] and its generalized form, namely GSTSK [54] was further extended by applying SSK/SM to both the space and to the time dimensions upon combining SSK/SM with space–time block codes, which resulted in an improved diversity versus multiplexing tradeoff. In contrast to the TA-index of conventional SM, in STSK [43], the specific indices of the pre-designed space–time dispersion matrices were exploited for conveying additional data. To be specific, one out of N_t dispersion matrices was activated rather than simply activating one out of N_t TAs in order to disperse a PSK/QAM symbol in STSK, where a beneficial diversity gain may be achieved as a merit of the simultaneous transmissions from the multiple TAs. As a further advance, the STSK concept was extended to the frequency domain in [55] and [56] with the assistance of a Frequency-Shift Keying (FSK) modulator. To be specific, in [55] the Space–Frequency Shift Keying (SFSK) as well as the Space–Time–Frequency Shift Keying (STFSK) schemes were proposed, which have the added benefit of spreading the transmit signal across both the space and time

TABLE I
CONTRIBUTION TO SM SCHEME AND ITS RELATED VARIANTS

Year	Authors	Contributions
2001	Chau and Yu [45]	Introduced the concept of SM and exploited the distinct multipath fading characteristics for antenna index detection.
2002	Haas *et al.* [42]	Proposed an OSDM scheme, which uses Walsh-Hadamard codes and an antenna array for data multiplexing.
2004	Song *et al.* [62]	Proposed channel hopping modulation, which is applicable to an arbitrary number of TAs.
2006	Mesleh *et al.* [63]	Proposed an efficient MIMO scheme, namely SM, which maps multiple information bits into a single information symbol and to the index of a single TA transmitting antenna.
2008	Jeganathan *et al.* [46]	Conceived an SSK concept and its improved version of the SSK modulation, namely GSSK, which activates multiple TAs for data transmission.
	Yang *et al.* [12]	Introduced the IGCH technique based on the fact that the independent fading of multiple channel can be used as an additional information channel.
	Mesleh *et al.* [11]	Proposed a simple MRC-based receiver design for SM, which detects the TA index and APM separately.
2009	Abu-alhiga *et al.* [58]	Designed a power-efficient SIM scheme, which maps a stream of bits into the indices of the available subcarriers in an on-off keying fashion.
	Jeganathan *et al.* [44]	Presented the framework of SSK, which is a low-complexity version of SM concept and exclusively employs the TA indices for data transmission.
2010	Di Renzo *et al.* [30]	Introduced an opportunistic power allocation scheme for SSK modulation, which exploits CSI for performance improvement
	Mesleh *et al.* [51]	Proposed a trellis coded SM (TC-SM) scheme, where the Trellis Coded Modulation is applied to SM to improve its performance in correlated channels.
	Serafimovski *et al.* [64]	Introduced a Fractional Bit Encoded (FBE)-SM scheme, which allows the transmitter to be equipped with an arbitrary number of TAs.
	Fu *et al.* [47]	Proposed high-rate generalized SM, which uses multiple active TAs to encode information bits.
	Younis *et al.* [48]	Proposed a GSM scheme, which sends the same symbol from more than one transmit antenna at a time.
	Sugiura *et al.* [43]	A novel STSK modulation scheme is proposed, which constitutes a generalized shift keying architecture utilizing both the space as well as time dimensions and hence includes the SM and SSK schemes as special cases.
	Renzo *et al.* [65]	Introduced the Time-Orthogonal Signal Design assisted SM (TOSD-SM) for offering transmit-diversity.
2011	Yang *et al.* [66]	Designed a Bit-Padding IGCH (BP-IGCH) scheme, which eliminates the limitation that the number of TAs has to be a power of two based on the IGCH concept.
	Başar *et al.* [50]	Combined SM and STBC to take advantage of the benefits of both, while avoiding their drawbacks.
	Sugiura *et al.* [54]	Proposed a novel Generalized STSK (G-STSK) architecture for striking a flexible tradeoff among diversity, throughput as well as complexity.
	Ngo *et al.* [55]	Proposed the SFSK modulation as well as the STFSK concept, which spreads the transmit signal across the space- and time- and frequency-domain.
	Qu *et al.* [67]	Conceived a block mapping SM (BMSM) scheme for increasing the transmit rate.
	Başar *et al.* [52]	Proposed a new TC-SM scheme with for achieving higher diversity and coding gains.
2012	Zhang *et al.* [68]	Introduced a novel SM scheme based on Ungerboeck's set partitioning for a correlated Rician fading scenario.
	Wang *et al.* [49]	Designed a novel high-rate Multiple Active-SM (MA-SM) schemes and a near-optimal decoder with linear complexity.
	Chang *et al.* [69], [70]	Proposed a new SSK modulation with Hamming code-aided constellation design for striking a flexible tradeoff among transmission rate, performance and power.
	Kuo [71]	Proposed a Symbol Coordinate Representations in Antenna Domains modulation , which leads superior performance to both SM and GSSK at the same data rate.
2013	Di Renzo *et al.* [15]	Illustrated the archived experimental results substantiating the benefits of SM and presented its beneficial application areas.
	Serafimovski *et al.* [26]	First practical testbed implementation of SM in indoors (laboratory environment).
	Younis *et al.* [25]	First performance evaluation of SM in indoors using real-world measured channels.

domains, as well as the frequency domain. In [56], the STFSK concept was extended to the Slow-Frequency-Hopping Multiple Access (SFHMA) philosophy for the sake of supporting multiple users and its Area Spectral Efficiency (ASE) gain over the classic Gaussian Minimum Shift Keying (GMSK)-aided SFHMA and GMSK assisted time-division/frequency-division multiple access (TD/FDMA) systems was quantified.

Inspired by the concept of SM/SSK, the subcarrier orthogonality can also be exploited and the indices of active subcarriers of Orthogonal Frequency-Division Multiplexing (OFDM) [57] symbols can be employed for conveying additional information, which is referred to as Subcarrier-Index Modulation (SIM) [58]. Based on the same principle, but following a different approach from that of [58], a novel transmission scheme termed as OFDM combined with Index Modulation (OFDM-IM) was proposed in [59] for frequency selective fading channels, with the objective of increasing the data rate as well as simultaneously improving the attainable BER performance. In Fig. 3, we classify the above-mentioned schemes, which exploit different degrees of freedom offered by the temporal domain, frequency domain and spatial domain fading. For completeness, we also briefly allude to the classic time hopping impulse modulation (THIM) [60], which exploits the indices of time-slots for implicitly conveying additional data. As a further

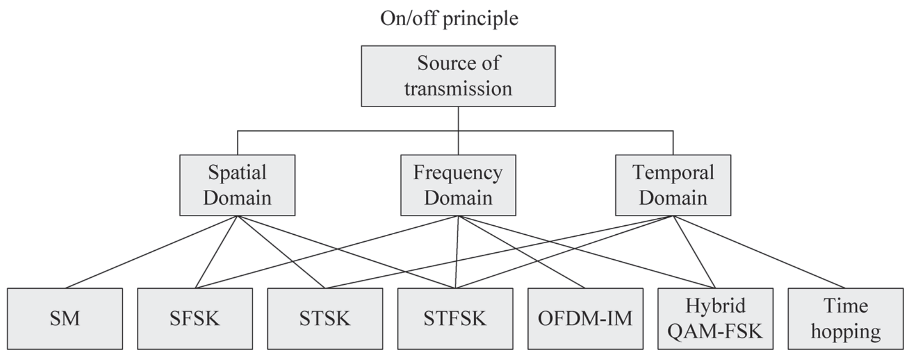

Fig. 3. Transmission techniques based on the on/off keying principle applied to the temporal domain, frequency domain and spatial domain. Here, we have "SM": spatial modulation, "SFSK": Space–Frequency Shift Keying, "STSK": Space–Time Shift Keying, "STFSK": Space–Time–Frequency Shift Keying, and "OFDM-IM": OFDM with Index Modulation.

improvement, hybrid **QAM-FSK** modulation [61] combine the time–frequency domain for the sake of exploiting their independent fading.

C. Detector Design

As seen in Fig. 2, the TA index is combined with the APM symbol index by the SM mapper. Hence, only the TA antenna index and the transmitted APM symbol index have to be estimated at the receiver. Note that most variants of SM, such as STSK and SSK, have an equivalent system model similar to (1), which is free from the effects of ICI, and each equivalent transmit vector includes only a single non-zero component [43], [44]. As a result, they may be able to use the same detection algorithm. As indicated in [72]–[88], the detection techniques of SM-MIMO systems may be broadly divided into four fundamental categories: Maximum Likelihood (ML) detection [72]–[74], Matched Filter (MF) based detection [11], [75], Sphere Decoding (SD) algorithm based detection [76]–[79] and hybrid detection, which combines the modified MF concept and the reduced-complexity exhaustive ML search of [12], [80]–[88]. An overview of the various detection techniques conceived for SM-related schemes is seen in Fig. 4. Next, they will be characterized in more detail.

An optimal ML-based SM detector, which carries out an exhaustive search for the global optimum in the entire signal space, was developed in [72]. This detector jointly detects the active TA index as well as the transmitted APM symbol and then retrieves the original data bit sequence. In [73], the authors have derived a soft-output ML detector for recovering the desired signals with the aid of soft decisions, and have shown that the soft-output ML detector outperforms its hard-decision counterpart. Moreover, in [74], the authors have exploited the inherent ML data detection in the context of STSK systems and proposed a semi-blind iterative channel estimation and data detection scheme for STSK, which is capable of reducing the training overhead required. Furthermore, a low-complexity multi-stage ML detector was proposed for the ICGH of [12], which adopts the principles of SM. The proposed detector estimates the APM symbol prior to detecting the TA index. Unlike the ML detector of other spatial multiplexing MIMO techniques, the complexity of the single-stream ML receiver only increases linearly with the number of TAs. However, as

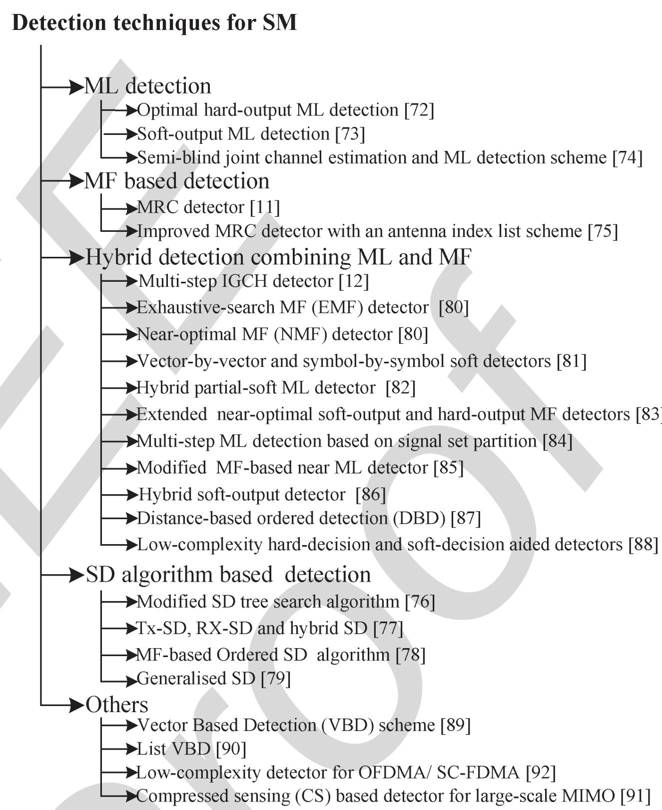

Fig. 4. Overview of SM detectors and related techniques.

the transmission rate increases, even the complexity of the ML single-stream detector might become excessive.

Among the promising alternatives, the MF-based detector exhibits a considerably reduced complexity, since the activated TA index and the modulated APM constellation point are separately estimated. However, as mentioned in [11], the conventional MF detector, namely the MRC, only performs well under the idealized assumption of perfect channel knowledge. This detector was improved in [75] and a TA index list based scheme was introduced for all the conventional MIMO channels.

For the sake of approaching the single-stream ML detector's performance without any substantial performance degradation, beneficial hybrid detectors were designed for the SM family in [80]–[88], which combine the modified MF concept of [11] and the reduced-complexity exhaustive ML search philosophy of [72]. For example, in [80], two modified MF-based detectors, namely the Exhaustive-search based MF (EMF) detector and the Near-optimal MF (NMF) detector were proposed for achieving a better performance than the conventional MF detector. However, the EMF has to invoke an exhaustive signal space search at the MF's output for maintaining the ML's performance, which prevents the detector from achieving a significant reduction in complexity, when high data rates are required. By contrast, the NMF detector further reduced the EMF's complexity, but naturally it performs worse than the ML detector [72]. To overcome this limitation, the authors of [83] proposed an extended NMF detector, which relies on finding multiple high-probability indices for the sake of attaining further performance improvements. Then, this improved NMF detector was further simplified in [87] and [88]. Considering that SM-MIMO systems typically rely on powerful channel codes, an attractive detector has to provide soft-decision-based information. In [44] and [73], an optimal Maximum a *Posteriori* (MAP) detector was invoked for turbo-coded SM schemes. However, it suffers from the problem of having a high complexity. In [81], the authors have proposed a low-complexity vector-by-vector based soft-detector operating on a symbol-by-symbol basis, where the associated complexity was considerably reduced compared to that of the *max-log* MAP detector's, albeit this was achieved at the cost of a modest performance degradation.

On the other hand, the SD [93], [94], which is widely used in spatial multiplexing systems, avoids the exhaustive search of the potentially excessive-complexity signal constellation by examining only those candidate solutions that lie inside an SNR-dependent decoding sphere. However, the conventional SD and the more advanced SD methods [94] are oblivious of the specific principle of SM, namely that only a single TA is active at any given time instant. As a result, the SD methods designed for spatial multiplexing MIMOs cannot be directly applied to SM-MIMO detection. In [76], a modified SD algorithm referred to as SM-SD was proposed, which is based on the tree-search structure. The SM-SD algorithm exploits the specific transmission mode of SM and hence attains a considerable complexity reduction. However, the performance of the SM-SD algorithm depends on the particular choice of the SNR-dependent initial search-radius as well as on the transmitter parameters. Hence, in [78], an Ordered SD (OSD) algorithm was proposed for the family of SM arrangements for the sake of reducing the receiver's complexity, while maintaining the optimum single-stream ML performance, which searches through the signal space sequentially according to the sorted TA set. Recently, a generalized version of the SM-SD was proposed in [77] and [79].

Relying on a novel approach, in [89] the authors have proposed a new Vector Based Detection (VBD) scheme for SM, which is suitable for high-order APM constellations. In [90], an improved VBD scheme, namely the list-VBD was proposed, where the TA index detection is performed first and a list of the best candidates survives. As indicated in Section I, the family of SM constitutes an attractive framework for the emerging family of large-scale MIMO systems in reducing the hardware costs and detection complexity, which becomes realistic at **microwave** frequencies. Since ML detection of high-order APM schemes in large-scale high-rate MIMO systems has a potentially excessive complexity, in [91] a low-complexity Compressed Sensing (CS) based detector was proposed for overcoming this problem by exploiting the sparsity in SM signaling. Again, the family of SM has also been effectively extended to the Orthogonal Frequency Division Multiple Access (OFDMA)/Single-Carrier Frequency Division Multiple Access (SC-FDMA)-aided architecture and some related low-complexity detectors were proposed in [92].

Additionally, most of the above-mentioned detectors assume that perfect CSI is available at the receiver. However, it is challenging to acquire accurate CSI in high-speed vehicles and multiple antenna systems. In order to dispense with CSI-estimation, the class of Differentially-encoded STC (DSTC) was proposed in [95] and [96]. Specifically, the Unitary Space–Time Modulation (USTM) scheme does not require CSI estimation and hence facilitates non-coherent detection at the receiver. Motivated by the concept of DSTC, the design of non-coherent SM-MIMO schemes was investigated in [43], [97], and [98]. To be specific, in [43], the differential STSK (DSTSK) concept was proposed with the aid of the Cayley unitary transformation, which has a low-complexity single-stream non-coherent detector. In [97], the DSTSK scheme was further developed for the sake of avoiding the nonlinear Cayley transform and a reduced-complexity multiple-symbol differential sphere detector was proposed for rapidly fading channels. Moreover, a PSK-aided differential modulation concept was conceived in [98], which relies on differential decoding while retaining the fundamental benefits of coherent SM-MIMO schemes.

D. Channel Capacity and Error Performance Metric

1) Channel Capacity: The capacity of SM constitutes a vitally important research topic. In [12], the authors have derived the capacity of SM in the context of Rayleigh fading channels, assuming continuous-amplitude discrete-time Gaussian distributed transmitted signals. This capacity is also referred to as the Continuous-input Continuous-output Memoryless Channel (CCMC) capacity [7]. However, this assumption cannot be readily satisfied in a practical communication system, unless carefully designed superposition modulation is used [99]. By contrast, in [43] the Discrete-input Continuous-output Memoryless Channel (DCMC) capacity [100] of the family of SM scheme was formulated, where the transmitted signals were drawn from finite-alphabet discrete constellations, such as the classic APM schemes [13]. Moreover, a closed-form expression of the mutual information of SM based Multiple-Input Single-Output (MISO) channels was derived and the impact of finite-alphabet inputs on the attainable performance of SM was investigated in [101]. Owing to its particular operating principle, its capacity and the corresponding optimization algorithms still require further research.

Fig. 5 shows the CCMC and DCMC capacity curves of the (4×2)-element SM-MIMO scheme. Furthermore, the G4-STBC arrangement of [3] was also considered as benchmarkers in Fig. 5. As shown in Fig. 5, the CCMC capacity of the SM scheme is higher than that of G4-STBC. Additionally, observe in Fig. 5 that the DCMC capacity tends to be increased upon

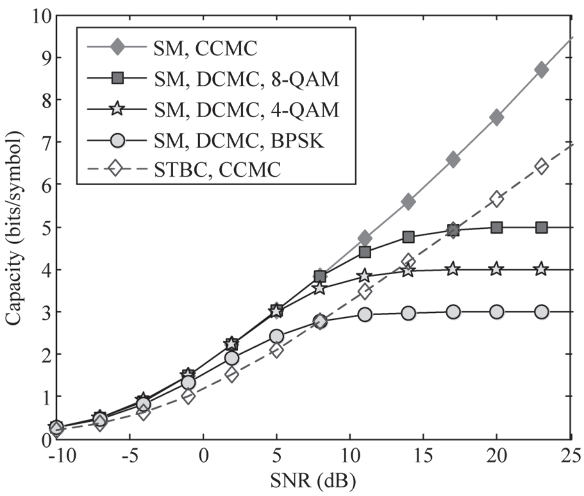

Fig. 5. Bandwidth efficiency of (4 × 2)-element SM system, comparing the CCMC and the DCMC capacity.

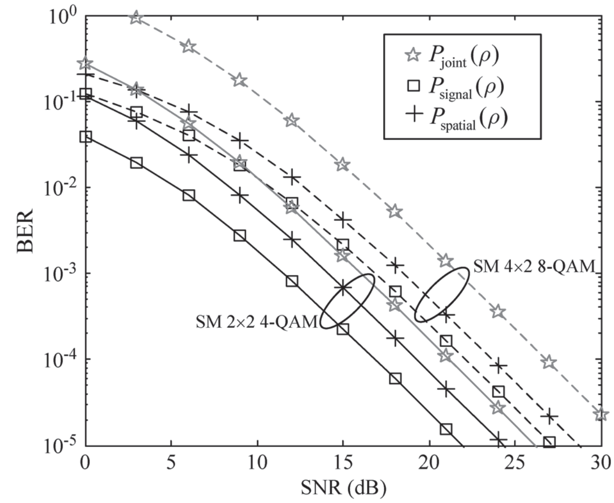

Fig. 6. The ABEPs of SM-MIMO: $P_{\text{signal}}(\rho)$, $P_{\text{joint}}(\rho)$ and $P_{\text{spatial}}(\rho)$.

increasing the modulation order, as noted in [12]. Moreover, as indicated in [8] and [26], the capacity of SM may be lower than that of the V-BLAST arrangement, however its detection complexity does not depend on the number of transmit antennas. This attractive advantage facilitates the practical application of SM-MIMO.

2) Error Performance Metric: The BER performance of SM has also been studied extensively in the context of various channel models and MIMO setups [28]–[34]. Generally, the analytical study of SM-MIMO systems tends to rely on its union bound based approximation [102]. However, apart from the STSK studies of [43] and the investigations of Di Renzo *et al.* [15], the studies in [27], [28], and [32]–[34] considered the simplified version of SM, namely SSK. For the conventional SM combining SSK with classic APM techniques for the sake of transmitting additional bits, the analytical studies disseminated in [11], [14], [29], and [103] exploited some of the fundamental properties of SM related to the channel's correlation, to its transmit diversity, channel estimation errors and coding gain. For example, in [103] the authors have provided a closed-form Average Bit Error Probability (ABEP) upper bound expression based on the conventional union-bound methods, which also quantified the transmit diversity order of SM. This framework is usually used as a reference for highlighting the advantages of SM over other MIMO arrangements, such as the classic STBC and VBLAST schemes. In [29], an improved union-bound is formulated, which partitions the ABEP expression of SM-MIMO systems into three terms: the term $P_{\text{spatial}}(\rho)$ only related to the spatial signals (i.e., TA index), the term $P_{\text{signal}}(\rho)$ is only related to the APM signals, while the joint term $P_{\text{joint}}(\rho)$ depends on both the spatial signals and on the APM signals, where ρ is the average SNR. This bound is formulated as

$$\mathrm{P}_{\mathrm{SM}}(\rho) \leq P_{\text{spatial}}(\rho) + P_{\text{signal}}(\rho) + P_{\text{joint}}(\rho). \quad (2)$$

Assuming i.i.d. Rayleigh fading channels, $P_{\text{signal}}(\rho)$ predominantly depends on the minimum ED $d_{\min}$ of the constellation points of APM, while $P_{\text{joint}}(\rho)$ and $P_{\text{spatial}}(\rho)$ mainly depend on the modulus values β_l $(l = 1, \cdots, L)$ of the APM constellation points, as detailed in [29]. As a result, $\mathrm{P}_{\mathrm{SM}}(\rho)$ of (2) depends both on the minimum ED of the specific APM constellations employed, as well as on the absolute values of the APM-symbols. This improved ABEP upper bound of SM provides deeper insights into the interactions of the APM signal constellation and the spatial signal constellation. For example, the interaction term $P_{\text{joint}}(\rho)$ of (2) dominates the performance of SM in diverse popular MIMO configurations, as indicated in Fig. 6. On the other hand, it can also be used for optimizing the system's performance by exploiting any statistical knowledge about the Channel State Information (CSI) at the transmitter and we will discuss in Section III.

Moreover, since the exact ABEP does not have a simple closed form solution, the nearest neighbor approximation was proposed in [104]. Assuming that all the channel inputs are equally likely, the nearest neighbor approximation of the Pairwise Error Probability (PEP) for a given channel matrix $\mathbf{H}$ can be expressed as [105]

$$P_{e|\mathbf{H}} \approx \lambda \cdot Q\left(\sqrt{\frac{1}{2N_0} d_{\min}^2(\mathbf{H})}\right) \quad (3)$$

where we have $Q(x) = (1/\sqrt{2\pi}) \int_x^\infty e^{-y^2/2} dy$, and λ is the number of neighboring constellation points [10] associated with the free distance (FD) $d_{\min}(\mathbf{H})$ defined as

$$d_{\min}(\mathbf{H}) = \min_{\substack{\mathbf{x}_i, \mathbf{x}_j \in \mathbb{X}, \\ \mathbf{x}_i \neq \mathbf{x}_j}} \|\mathbf{H}\mathbf{P}(\mathbf{x}_i - \mathbf{x}_j)\| \quad (4)$$

where $\mathbb{X}$ is the set of legitimate transmit symbols, while $\mathbf{x}_i$ and $\mathbf{x}_j$ are two distinct transmitted symbols in $\mathbb{X}$. In (4), $\mathbf{P}$ is the transmit preprocessing (TPP) matrix, which is the $(N_t \times N_t)$-element identity matrix $\mathbf{I}$ for conventional open-loop SM schemes dispensing with TPP.

Note that the nearest neighbor approximation of the PEP will always be slightly lower than that provided by the union bound, since this approximation does not include the errors associated with those legitimate symbols that are farther apart than the FD. However, in case of low SNRs, there is a non-negligible probability of corrupting a symbol into more distant symbols.

Nonetheless, the result is quite close to the exact probability of symbol error at high SNRs, as detailed in [105]. Indeed, since the error events mainly arise from the nearest neighbors, the maximization of the FD in (3) directly reduces the probability of error, especially at high SNRs [106]. As a result, the bound of (3) can be adapted for system optimization by exploiting the knowledge of the near-instantaneous CSI, as discussed these in more detail in Section IV.

Furthermore, the effects of CSI errors on the achievable performance of SM-MIMOs were further researched in [34] and [107]–[109]. It was found that SM is quite robust to imperfect CSI compared to V-BLAST. For example, in [107] an asymptotically tight upper bound on the ABEP was derived for SM under imperfect CSI and the simulation results confirmed that SM is more robust to channel estimation errors than V-BLAST for reasonable practical channel estimation error values.

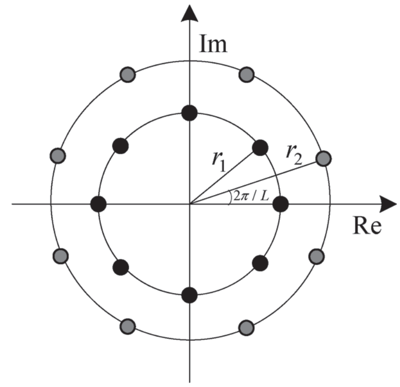

Fig. 7. The complex signal constellation of 16-ary star-QAM. The symbols are evenly distributed on two rings, and the phase differences between the neighboring symbols on the same ring are equal.

III. APM Constellation Optimization

As indicated in (2), the performance of SM-MIMO systems is highly dependent on the specific APM signal constellation adopted. In a conventional Single-Input Single-Output (SISO) system, the Gray-coded Maximum–minimum distance (MMD) QAM constellation minimizes the Bit Error Ratio (BER) [13]. However, the advantage of MMD-QAM may be eroded in SM-MIMO systems [29]. This is due to the fact that the BER performance of SM-MIMO systems is jointly determined by the spatial signal (i.e., TA indices), by the classic APM constellation and by their interaction [29]. Hence, a suitable APM scheme has to be designed for this hybrid modulation scheme.

Furthermore, SM also allows us to achieve a high transmission rate by combining its benefits with those of the classic APM schemes, as detailed in [46]–[49]. However, when the source employs higher-order square QAM in order to increase the attainable transmission rate, a high Peak-to-Average-Power Ratio (PAPR) [110] is encountered, hence requiring a low-efficiency linear power amplifier [111]. To overcome this impediment, peak-power reduction constellation shaping [110] may be employed at the transmitter, albeit this technique imposes additional complexity. Thus, for the sake of achieving a high power-efficiency, the choice of the modulation scheme in SM-MIMO systems has to be revisited.

The effects of APM schemes on the performance of SM have been investigated in [112]–[114]. More specifically, in [112], the dispersion matrices and the signal constellations were jointly optimized for a near-capacity precoded STSK system, which includes SM as a special case and strikes a flexible rate-versus-diversity tradeoff. It was also shown in [80] that the star-QAM aided STSK scheme outperforms its MMD based square-QAM aided counterpart. This is because the STSK's achievable performance depends both on the minimum ED of the APM constellation employed, as well as on the absolute values of the modulated symbols, which may also be valid for SM systems, as shown in (2) [29]. More recently, in [31] low-complexity, yet single-stream ML transmit diversity schemes have been studied by analyzing the impact of the spatial constellation and shaping filters. In [70], a Hamming code construction technique was proposed as a modulation design strategy for SSK-based systems for the sake of improving their error probability. In [113], a new SM constellation design strategy was proposed based on the ED of the constellation, which retains the key advantages of SM, while activating multiple TAs. In [114], two approaches were investigated with the goal of designing the SSK's transmit constellation space by relying either on the idealized simplifying assumption of having perfect CSI or on the more practical scenario of imperfect CSI at the transmitter, in order to increase the distance between each pair of the received combined TA-APM vector. The above-mentioned techniques were however mainly conceived for STSK and SSK schemes, but may not be readily applicable to the conventional SM scheme.

In [29], the performance of SM systems relying both on conventional QAM and PSK modulation were studied, demonstrating that in some MIMO setups, the PSK-modulated SM scheme may outperform the identical-throughput MMD-QAM SM scheme. More specifically, as shown in [29] and [115], for certain SM-MIMO configurations, $P_{\mathrm{signal}}(\rho)$ of (2) is significantly higher than the sum of $P_{\mathrm{joint}}(\rho)$ and $P_{\mathrm{spatial}}(\rho)$, which implies that the minimum ED of APM constellations dominates the performance of SM. In this scenario, MMD-QAM may constitute an attractive APM candidate for minimizing the ABEP. By contrast, as shown in Fig. 6, if $P_{\mathrm{signal}}(\rho)$ is lower than the sum of $P_{\mathrm{joint}}(\rho)$ and $P_{\mathrm{spatial}}(\rho)$, which implies that the moduli of the APM constellation points dominates the $\mathrm{P}_{\mathrm{SM}}(\rho)$ term, then a constant-modulus modulation scheme, such as PSK, may be optimal, as indicated in [29]. Recall that $P_{\mathrm{signal}}(\rho)$ of (2) is dominated by the minimum ED $d_{\min}$, while $P_{\mathrm{joint}}(\rho)$ and $P_{\mathrm{spatial}}(\rho)$ mainly depend on the modulus values β_l $(l = 1, \cdots, L)$ of the APM constellation adopted. Note that the modulus values β_l $(l = 1, \cdots, L)$ are represented by the Frobenius norms of the APM constellation points. These results suggested that for the sake of jointly minimizing $P_{\mathrm{signal}}(\rho)$, $P_{\mathrm{joint}}(\rho)$ and $P_{\mathrm{spatial}}(\rho)$ of (4), we can readily focus our attention on design of $d_{\min}$ and on the β_l parameters of APM.

On the other hand, star-QAM [13] constitutes a special case of circular APM, which is capable of outperforming the classic square-shaped QAM constellation in peak-power-limited systems. Hence its diverse relatives have been adopted in most of the recent satellite communication standards, such as the

TABLE II
THE MINIMUM ED OF DIFFERENT APM SCHEMES

Modulation order (L)	2	4	8	16	32
PSK	$d_{\min}$=2	$d_{\min}=\sqrt{2}$	$d_{\min}$= 0.76	$d_{\min}$=0.39	$d_{\min}$=0.19
QAM	- -	$d_{\min}=\sqrt{2}$	$d_{\min}$=0.81	$d_{\min}$=0.63	$d_{\min}$=0.41
Star-QAM	$d_{\min}$=2	$d_{\min}=\sqrt{2}$	$d_{\min}$=0.91	$d_{\min}$=0.57	$d_{\min}$=0.40

Digital Video Broadcast System (DVB) S2, DVB-SH, as well as in the Internet Protocol over Satellite (IPOS) and Advanced Broadcasting System via Satellite (ABS-S) [116]. To elaborate a little further, the star-QAM constellation is composed of multiple concentric circles and it was shown to be beneficial in the context of STSK systems [80]. However, the constellations' optimization has not been carried out for star-QAM aided SM.

In order to make the choice of the APM parameters $d_{\min}$ and β_l as flexible as possible, we consider a class of star-QAM constellations, which subsumes the classic PSK as a special case, but may also be configured for maximizing the minimum ED of the constellation by appropriately adjusting the ring ratios of the amplitude levels. For the sake of simplicity, we consider the example of a twin-ring 16-star-QAM constellation having a ring-ratio of $\alpha = r_2/r_1$ as shown in Fig. 7. The symbols are evenly distributed on the two rings and the phase differences between the neighboring symbols on the same ring are equal. Unlike the conventional twin-ring star-QAM constellation [116], the constellation points on the outer circle of star-QAM constellation are rotated by $2\pi/L$ degrees compared to the corresponding constellation points on the inner circle. Hence again, the conventional PSK constitutes an integral part of our star-QAM scheme, which is associated with a ring-ratio of $\alpha = 1$. Note that although this twin-ring star-QAM constellation has indeed been invoked for noncoherent detection [117], it has not been considered whether this constellation can be directly applied to SM for achieving performance improvements.

Table II summarizes the minimum EDs $d_{\min}$ between the constellation points for different APM schemes, where the modulation order is the number of the constellation points. Moreover, the L-PSK/L-QAM schemes in [13] are used. It is shown that the star-QAM is capable of achieving almost the same minimum ED as the MMD-based QAM [8].

Given an $(N_r \times N_t)$-element MIMO setup having a transmission rate of m_{all}, and L modulation levels, the goal of star-QAM aided signaling constellation optimization is to find the ring-ratio α, which minimizes the ABEP of SM-MIMO of (2). Following this approach, the related optimization problem may be formulated as

$$\begin{cases} \alpha^* = \min\limits_{\alpha} \mathrm{P}_{\mathrm{SM}}(\rho) \\ \quad s.t.\ \alpha \geq 1. \end{cases} \tag{5}$$

Based on an exhaustive numerical search, for example, for the 16-star-QAM aided (4 × 4)-element SM-MIMO, the optimal ring ratio was found to be $\alpha^* = 1.7$ [118]. According to (2), this optimized star-QAM aided SM scheme provides an SNR gain of about 3 dB over the conventional 16-PSK modulated SM scheme and an SNR gain of about 1.1 dB over the identical-throughput Gray-coded MMD 16-QAM modulated SM scheme at BER $= 10^{-5}$. Note that the optimized star-QAM constellation can be designed off-line based on the CSI statistics (i.e., the fading type) for different SM-MIMO systems and hence the resultant system does not need any feedback. Next, we will introduce a suite of beneficial adaptation techniques based on the assumption that the knowledge of the near-instantaneous channel matrix is available at the receiver in the frequency flat-fading channel.

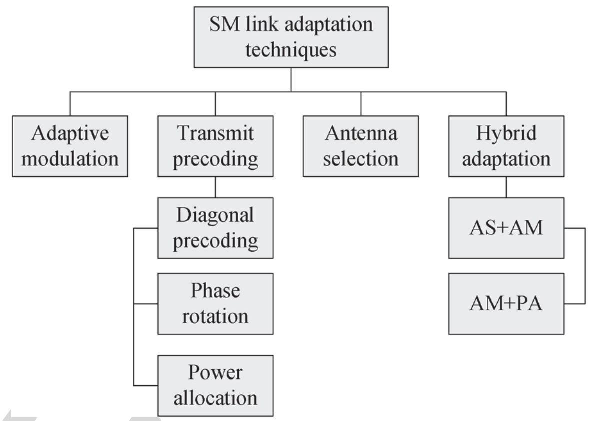

Fig. 8. Classification of the LA techniques designed for SM-MIMO. Here, AS+AM: antenna selection combined with adaptive modulation, AM+PA: adaptive modulation combined with power allocation.

IV. LINK ADAPTATION TECHNIQUES

Link Adaptation (LA) has an important role in wireless communication systems [39]–[41]. Traditionally, LA refers to the concept of dynamically adjusting the transmit parameters, such as the modulation order and coding rate according to the near-instantaneous channel conditions. LA has been extensively studied in the conventional MIMO context for the sake of improving the achievable multiplexing and diversity performance. However, it has not been considered, whether these existing LA techniques can be directly applied to SM-based transmission systems. Note that the introduction of LA techniques in SM-MIMO should not jeopardize the advantages of SM, such as the avoidance of the IAI, IAS and multiple RF chains [11]. This makes the design of LA algorithms more challenging. In order to increase the robustness of the SM-MIMO system, several limited-feedback aided LA techniques have been proposed in [30], [104], [115], and [119]–[130], as summarized in Fig. 8. Depending on the MIMO scheme's degree freedom, these techniques can be roughly divided into four types, namely into Adaptive Modulation (AM) [104], [115], [119], [120], transmit precoding (TPC) [30], [103], [121]–[125], Antenna Selection (AS) [126]–[128] and Hybrid Adaptation (HA) techniques relying on diverse combinations of the above three [115], [129], [130], as shown in Fig. 8. To elaborate a little further, the

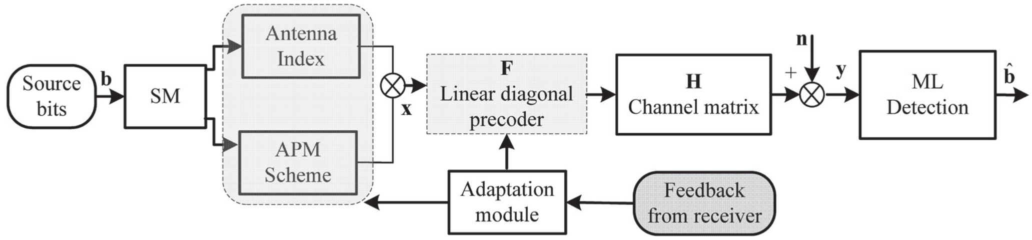

Fig. 9. Block diagram of LA-aided MIMO communication systems.

general philosophy of a LA-aided SM-MIMO system obeying the architecture of Fig. 9 can be summarized as follows.

Algorithm 2: The adaptation process of LA-aided SM-MIMO systems

---

1) Consider an $(N_r \times N_t)$-element SM-MIMO system associated with the transmission rate m_{all};
2) The receiver estimates the CSI and decides upon the optimum transmit mode, which is then sent back to the transmitter through a low-rate feedback channel;
3) The transmitter processes the feedback information and employs the optimum transmission mode (i.e., the modulation orders and the precoding matrix) for its transmission.

Having formulated the SM-MIMO's LA algorithm, let us now describe the class of LA techniques with the aid of Fig. 8 developed for the family of SM-MIMO schemes in more detail below. Note that in this treatise only the TPC matrix $\mathbf{P}$ and the transmit symbol $\mathbf{x}$ are adapted in response to the near-instantaneous channel conditions in order to improve the system's performance, as indicated in (4).

A. *Adaptive Modulation*

Again, AM techniques are capable of alleviating the adverse effects of channel fading, so as to achieve an increased data rate or a reduced BER [131], which have hence been adopted in most of the recent communication standards, such as 3GPP, 3GPP2, IEEE 802.11a, IEEE 802.15.3 and IEEE 802.16 [132].

SM may also be beneficially combined with AM for adjusting the transmission parameters for the sake of accommodating time-varying channels. Therefore, the beneficial combination of AM and SM-MIMO techniques is a promising design alternative for high-rate wireless systems.

To this end, adaptive SM-MIMO architectures relying on different combinations of modulation/coding schemes were proposed in [120], which aimed for maximizing the channel capacity at a predefined target BER, rather than for optimizing the BER. By contrast, in [104] a near-instantaneously Adaptive SM (ASM) scheme was proposed for improving the attainable system performance, while maintaining a fixed average transmit rate with the aid of AM techniques. In ASM, the receiver requests the most suitable modulation order to be used by the transmitter for each TA and/or time-slot. Assuming that no-transmission, BPSK and M-QAM are available for each TA, which are represented by the set $\mathbb{M}_{\text{all}}$, the detailed design procedure of ASM schemes can be summarized as follows:

Algorithm 3: Adaptive SM

---

1) Given the transmit parameters as: N_t, N_r and the transmission rate m_{all}, generate all the legitimate modulation order combinations for a given m_{all} and represent these combinations as a set $\mathbf{R} = \{\mathbf{r}_1, \mathbf{r}_2, \cdots, \mathbf{r}_j, \cdots, \mathbf{r}_J\}$, where we have $\mathbf{r}_j = [r_j^1, \cdots, r_j^n \cdots, r_j^{N_t}]$ and r_j^n denotes the modulation order for the nth $(n = 1, 2, \cdots N_t)$ TA of the jth ASM combination.
2) Based on the optimization rule, such as the nearest neighbor approximation of (3), we can achieve a performance gain by maximizing $d_{\min}(\mathbf{H})$ with the aid of switching among these candidates.
3) Then, the corresponding index of the optimal ASM mode is fed back to the transmitter, which transmits the symbols accordingly.

In (3), the conditioned PEP is a monotonically decreasing function of $d_{\min}(\mathbf{H})$. Hence, the attainable system performance can be improved by maximizing the FD $d_{\min}(\mathbf{H})$ by adapting the transmit parameters. As an example, let us consider a (2×2)-element SM-MIMO transmission scheme associated with $m_{\text{all}} = 3$ bits/symbol under a channel realization matrix $\mathbf{H}$, which is given by

$$\mathbf{H} = \begin{bmatrix} 0.26 - 0.75\text{i} & 1.33 + 0.49\text{i} \\ 0.03 + 1.30\text{i} & -0.61 + 0.25\text{i} \end{bmatrix}.$$

Let us assume that no-transmission, BPSK, QPSK, 8-QAM, 16-QAM, 32-QAM and 64-QAM are available for each TA and these schemes are represented as $\mathbb{M}_{\text{all}} = \{0, 2, 4, 8, 16, 32, 64\}$, where the no-transmission mode has the identifier of $M = 0$, while the BPSK and QPSK constellations are denoted as $M = 2$ and $M = 4$ respectively. For $m_{\text{all}} = 3$ bits/symbol, we have five ASM mode candidates denoted as $\mathbf{R} = \{\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3, \mathbf{r}_4, \mathbf{r}_5\} = \{[16, 0], [2, 8], [4, 4], [8, 2], [0, 16]\}$, where $\mathbf{r}_1 = [16, 0]$ represents that 16-QAM and no-transmission are assigned to the first and the second TA, respectively, while the candidate [4,4] corresponds to the conventional non-adaptive SM scheme using QPSK for both TAs.

Based on Algorithm 3, Fig. 10 shows the detailed actions of the ASM scheme for this 3-bits/channel-use system. As shown in Fig. 10, the five ASM modes (the legitimate modulation

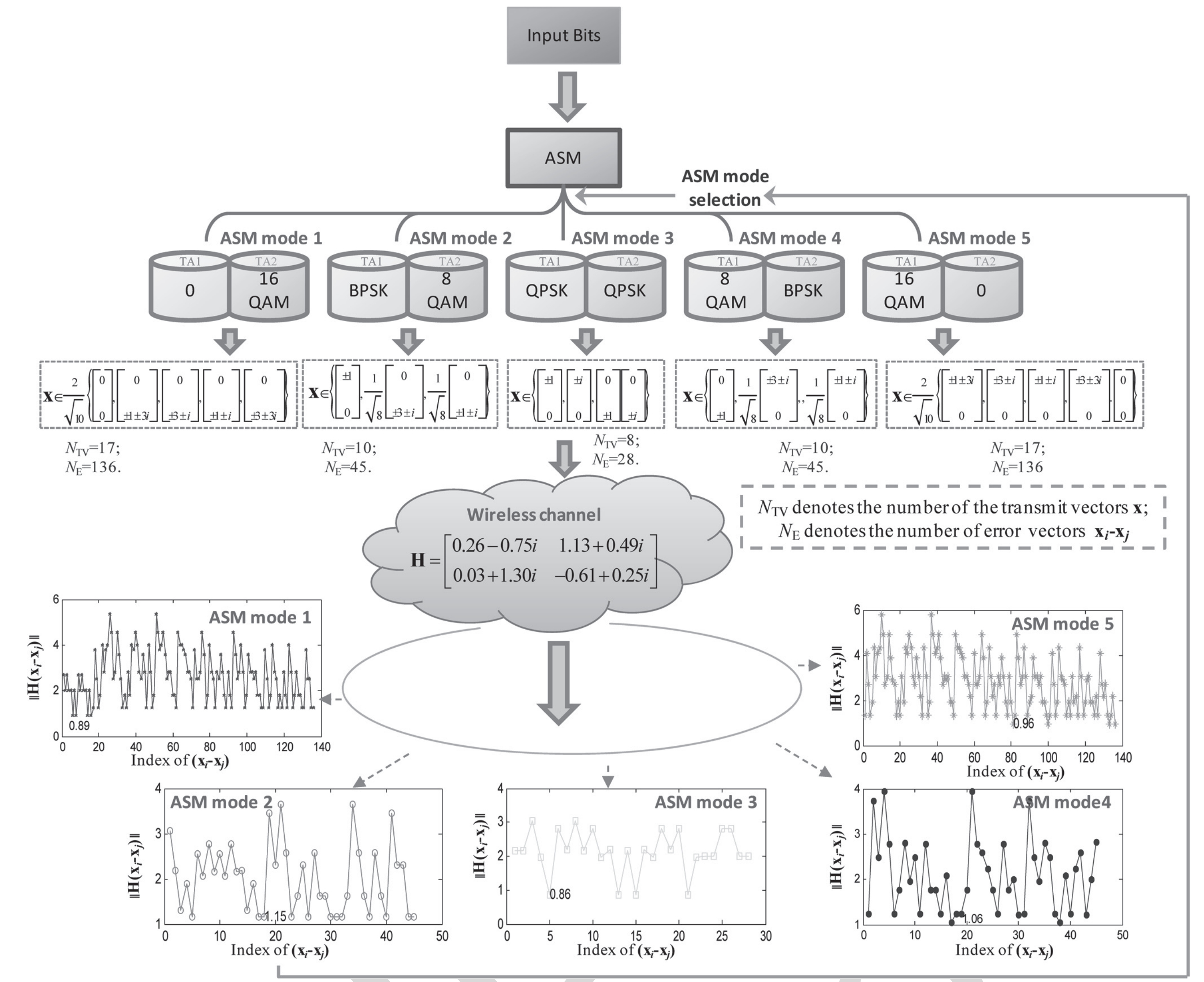

Fig. 10. The example of ASM associated with (2 × 2)-element MIMO channels at a throughput of $m_{\mathrm{all}} = 3$ bits/symbol.

order combinations) are generated first. For each ASM mode, we can calculate its legitimate transmit symbols $\mathbf{x}$ and its corresponding error vectors. For example, as shown in Fig. 10, the number of $\mathbf{x}$ combinations is $N_{\mathrm{TV}} = 8$ for the ASM mode 3 (the candidate [4,4]), while the corresponding number of the error vectors $\mathbf{e}_{ij} = \mathbf{x}_i - \mathbf{x}_j,\ i \neq j$ of (4) is $N_E = \binom{2}{N_{\mathrm{TV}}} = 28$. Here, each error vector $\mathbf{e}_{ij}$ is given a specific index, which is associated with its corresponding distance $\|\mathbf{He}_{ij}\|$. Then, the minimum value of $\|\mathbf{He}_{ij}\|$ among all the legitimate error vectors is found, which determines the FD of this ASM mode. In Fig. 10, the FD of the ASM mode 3 is 0.86. For other ASM modes, we can use the same method of determining the corresponding FDs. Observe in Fig. 10 that ASM mode 2 has the highest FD for the ASM candidate of [2,8]. The corresponding ASM mode index 2 is then fed back to the transmitter.

As indicated above, the Modulation Order Selection (MOS) of ASM turns out to be a demanding process, because the global optimum is found by carrying out an exhaustive search across the entire ASM's mode-candidate set. For example, for an ASM scheme associated with $N_{\mathrm{t}} = 8$ and 4 bits/symbol transmission, we need a global search of 154, 645 candidates, which results in an excessive complexity and feedback load, when high data rates are required. To circumvent this problem, the probabilities of occurrence for the ASM candidates were evaluated theoretically in [119]. More specifically, all legitimate ASM-mode candidates were classified according to their variances and FD. It was shown that for most of the practical channel realizations the probability that the maximum FD occurs when all the TAs have the same modulation order is high. As a result, only the specific ASM mode candidates associated with lower variances were earmarked for the optimization in **Algorithm 3**. Based on this result, a One Bit Re-Allocation (OBRA) algorithm was proposed in [119] for the ASM mode selection. OBRA-ASM imposes both a lower complexity and a lower feedback requirement than that of the ASM relying on a potentially excessive-complexity exhaustive search, while imposing a marginal performance degradation.[1]

[1]Note that ASM may transmit an unequal number of bits in different time slot. Hence, this mismatch in the transmission frame-length will result in a potential error propagation effect at the detector, which may be mitigated using channel coding techniques, as detailed in [69].

B. Transmit Precoding Techniques

Similar to the AM technique, Transmit Precoding (TPC) is another attractive LA regime, which exploits the knowledge of the CSI at the transmitter, in order to match the transmission parameters to the instantaneous channel conditions. A beneficial solution to this problem is to use the TPC matrix $\mathbf{P}$ of (4) for enhancing the attainable performance. There is a paucity of literature on how to design both linear and non-linear precoders for conventional MIMO schemes [39]. To be specific, non-linear precoding may be more powerful than its linear counterparts, but linear TPC usually achieves a reasonable performance at a significantly lower complexity. Moreover, most of the precoders were designed using a capacity-maximization approach [39], although in practice minimizing the BER may be more important, than maximizing the mutual information or the capacity [40].

1) Diagonal Precoding: The SM technique employed in conjunction with a precoding scheme, where the transmitted symbols are appropriately weighted according to the near-instantaneous channel condition constitutes an attractive solution in terms of improving the system's BER performance. One of the key design challenges of the precoded SM-MIMO architectures is to construct a beneficial precoding matrix $\mathbf{P}$ that relies on a modest amount of feedback information, while retaining all the single-RF benefits of SM-MIMOs.

To this end, in [103] a beamforming codebook was designed for optimizing the coding gain of SM-MIMO in the presence of spatial correlation amongst the fading envelopes of the TAs. Recently, a closed-loop TPC method was invoked for providing both diversity and coding gains in the context of GSSK [124], which activated more than one TAs for transmission. However, the above-mentioned schemes considered only a special case of SM, namely SSK. As a result, the schemes proposed for SSK may not be directly applicable to the conventional SM scheme. By contrast, in [133] a TPC technique was used for improving the signal design for a new class of SM, namely for Receiver-SM (R-SM). Moreover, in [100] the authors investigated the effects of finite-alphabet inputs on the achievable capacity of SM for transmission over MISO channels and then developed a TPC scheme for improving this performance metric.

In this section, we continue by considering a novel TPC scheme based on maximizing the FD for the family of SM-MIMO systems. Note that since the attainable performance of the optimum single-stream ML receiver depends on the FD of the received signal constellation [29], the maximization of the FD directly reduces the probability of error. In order to retain all the single-RF related benefits of SM, we designed the TPC matrix $\mathbf{P}$ to be a diagonal matrix formulated as $\mathbf{P} = \mathrm{diag}\{p_1, \cdots, p_n, \cdots, p_{N_t}\}$. Note that although there are various diagonal matrix aided TPCs proposed for the family of conventional MIMO schemes, they tends to aim for diagonalizing the channel matrix [39], which may jeopardize the advantages of SM-MIMOs. As a result, the conventional TPC techniques proposed for classic MIMO schemes, such as the STBC and VBLAST, may not be directly suitable for the family of SM-MIMOs.

In order to identify the specific TPC parameters p_n $(n = 1, \cdots, N_t)$, which are capable of maximizing the FD, we have to determine all the N_t parameters p_n $(n = 1, \cdots, N_t)$. Since it may become excessively complex to jointly optimize these N_t parameters in the complex-valued field, we decomposed $\mathbf{P}$ as $\mathbf{P} = \bar{\mathbf{P}}\boldsymbol{\Theta} = \mathrm{diag}\{\bar{p}_1 e^{j\theta_1}, \cdots, \bar{p}_n e^{j\theta_n}, \cdots, \bar{p}_{N_t} e^{j\theta_{N_t}}\}$. Because the FD of this particular TA-pair predominantly determines the achievable performance, only the specific TA pair (g, k) associated with the FD is considered and the TPC parameters are selected for appropriately weighting the SM symbols. As a result, there are only two parameters, namely p_g and p_k, to be searched for. Finding the optimal values of p_g and p_k as a function of both $\mathbf{H}$ and of the optimal transmit parameters involves an exhaustive search over the vast design-space of $\bar{p}_g$, $\bar{p}_k$, θ_g and θ_k, which is overly complex. By considering the power constraint, we have $\bar{p}_k = \sqrt{2 - \bar{p}_g^2}$. Moreover, since the phase rotation of the symbol is only carried by two TAs, we can simplify the computation by fixing $\theta_k = 0$ and then finding the optimal θ_g. The proposed low-complexity TPC design algorithm is summarized as follows.

Algorithm 4: A low-complexity TPC design algorithm for SM-MIMO

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1) Given the transmit parameters N_t, N_r and the transmission rate m_{all} as well as the channel matrix $\mathbf{H}$, the indices of the TA pair (g, k) associated with the FD of (4) are first obtained. In order to offer an increased FD, the TPC parameters of this TA pair can be dynamically adapted.[2]
2) Generate all the legitimate diagonal TPC matrix candidates represented as $\mathbf{P}_{\mathrm{cand}} = \mathrm{diag}\{1, \cdots, \bar{p}_g e^{j\theta_g}, \cdots, \sqrt{2 - \bar{p}_g^2}, \cdots, 1\}$, where we have $\bar{p}_g = \sqrt{2}/L_1 * l_1, l_1 = 0, \cdots, L_1$ and $\theta_g = 2\pi/L_2 * l_2$, $l_2 = 0, \cdots, L_2$. Here, L_1 and L_2 are the quantized parameters, which can be flexibly selected according to the prevalent BER requirements.
3) Based on the above-mentioned optimization rule, we can achieve a performance gain by maximizing the FD $d_{\min}(\mathbf{H})$ by switching among these TPC candidates. Note that the FD of the TPC matrixes $\mathbf{P}_{\mathrm{cand}}$ generated will be compared to that of the conventional scheme and then we select the one having the largest FD as our final result.
4) Then, the index of the optimized TPC matrix has to be fed back to the transmitter.

Unlike in the traditional TPC method of [39], our proposed scheme is suitable for scenarios relying bandwidth-limited feedback channels, because the TPC design is reduced to the design of a diagonal matrix. Moreover, as demonstrated in **Algorithm 4** as few as two elements of the diagonal TPC matrix have to be fed back to the transmitter, regardless of the value of N_t.

[2]Note that if the value of g is the same as k, we have to adapt the TPC parameters of the pair (g, u), where the TA u has the maximum channel gain $\|\mathbf{h}_u\|_F$. Here, $\mathbf{h}_u$ is the uth column of $\mathbf{H}$ and $|\cdot|$ stands for the Frobenius norm.

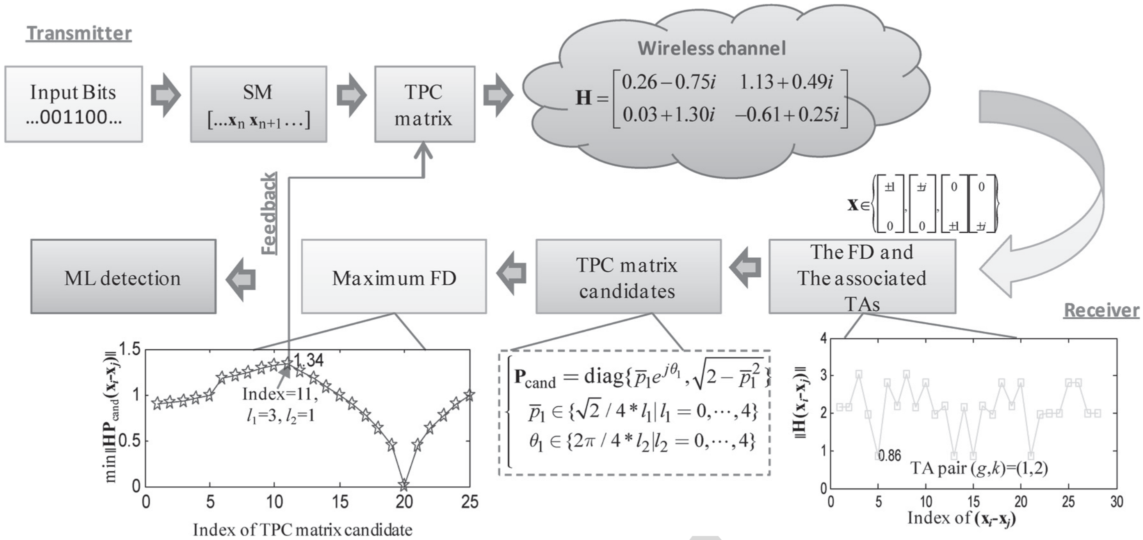

Fig. 11. The example of TPC aided SM.

More specifically, revisiting the previous example in **Algorithm 3**, as shown in Fig. 11, for the same channel realization $\mathbf{H}$, if the TPC matrix $\mathbf{P}$ of Algorithm 4 is used for optimizing the system's performance, where the specific TA-pair (1,2) associated with the FD of 0.86 is first found by using (4), which corresponds to the conventional SM scheme (the ASM mode 3 in Fig. 10). This result implies that the FD is computed for different TAs and the FD of this particular TA-pair predominantly determines the achievable performance. To improve the system's performance, the TPC parameters of this pair should be optimized. Here, the optimized TPC matrix is selected from the quantized TPC matrix set, as shown in Fig. 11, where the quantized parameters L_1 and L_2 are selected as $L_1 = L_2 = 4$. Hence, the number of TPC candidates is $(L_1 + 1) \times (L_2 + 1) = 25$. We can assign a specific index for each candidate and then calculate its corresponding FD according to (4). As shown in Fig. 11, the specific candidate associated with $l_1 = 3$ and $l_2 = 1$ has the highest FD of 1.34 among all the legitimate TPC matrix candidates. Note that if the highest FD of all the legitimate TPC matrix candidates is lower than that of the conventional SM. Based on step 3) of Algorithm 4, The optimal TPC matrix is $\mathbf{P} = \mathbf{I}_{N_t}$. The corresponding index of this candidate is then fed back to the transmitter, which appropriately weights the SM modulated symbol.

2) Phase Rotation Precoding and Power Allocation: Since the proposed precoder $\mathbf{P}$ consists of two different diagonal matrices $\bar{\mathbf{P}}$ and $\boldsymbol{\Theta}$, we may reduce the complexity of the precoding process in **Algorithm 4** by employing only a subset of matrices at a modest performance loss. Firstly, when only the diagonal matrix $\boldsymbol{\Theta}$ is considered, this solution may be referred to as the Phase Rotation Precoding (PRP) technique [134], which is usually used for improving the BER, when spatial correlation exists between the TAs of the ML-detection aided V-BLAST architecture.

An alternative complexity reduction is achieved by considering only the diagonal matrix $\bar{\mathbf{P}}$, which can be viewed as a simple form of Power Allocation (PA) [30], [121]–[123]. This arrangement has been intensively researched in the context of spatial multiplexing systems [30]. However, these PA approaches designed for spatial multiplexing based MIMO systems may not be directly suitable for the family of SM-MIMO systems, because only a single TA is active in each time slot and hence the PA between the TAs should be carefully considered. In [30], an opportunistic power allocation scheme was conceived for achieving a beneficial transmit diversity gain in SSK-aided MIMO systems relying on two TAs. Then, this feedback-aided PA scheme was further developed in [121]. However, no APM scheme was considered in the above-mentioned PA-aided SSK-MIMO systems and hence their throughput may remain limited. In order to realize the full potential of PA techniques in a SM-MIMO context, **Algorithm 4** can also be invoked by simply changing the legitimate diagonal TPC matrix to the PA matrix.

Still considering the example given in Fig. 11, if the PA technique is considered, we gradually assign the appropriate portion of power to each TA of the TA pair (1,2), where the number of PA matrix candidates is $L_1 + 1 = 5$, as shown in Fig. 12(a). Similar to Fig. 11, we can also assign a specific index for each candidate and then calculate its corresponding FD according to (4). As shown in Fig. 12(a), the PA matrix candidate associated with $l_1 = 3$ has the highest FD of 1.26 among all the legitimate PA matrix candidates. On the other hand, as shown in Fig. 12(b), if the PRP technique is invoked, only the phases of the TA pair (1,2) are adjusted, where the number of PRP matrix candidates is $L_2 + 1 = 5$. We observe from the results of Fig. 12(b) that the PRP matrix candidate associated with $l_2 = 3$ has the highest FD of 1.3 among all the legitimate PRP matrix candidates. The index of the optimized matrix is fed back to the transmitter for allowing the transmitter to compensate for the effects of channel fading.

3) Performance Results: In Fig. 13, we compared the various LA-aided SM schemes to the conventional non-adaptive SM scheme in the context of (2×2)-element MIMO channels at a throughput of $m_{\text{all}} = 3$ bits/symbol for transmission over independent Rayleigh block-flat channels. In all cases we

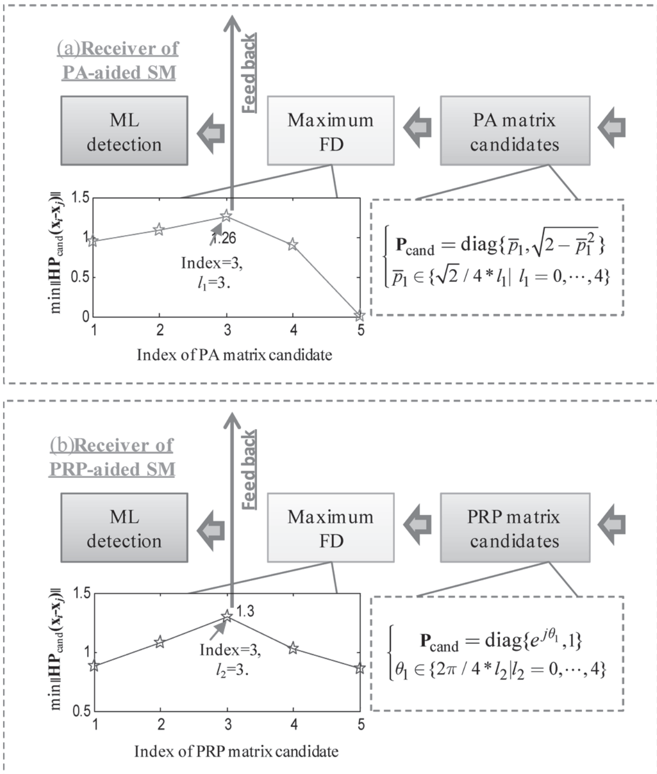

Fig. 12. The example of PA and PRP aided SM system.

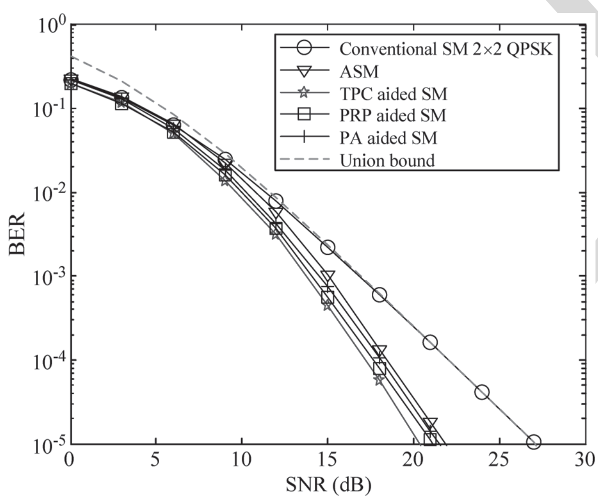

Fig. 13. BER performance of the conventional SM and the LA-aided SM schemes in (2 × 2)-element MIMO channels at a throughput of $m_{\text{all}} = 3$ bits/symbol.

assumed that the feedback channel is free of errors and delay.[3] For completeness, we also added the theoretical upper bound curve derived with the aid of the union bound [29], [103] of the conventional SM scheme. Moreover, in the TPC design of **Algorithm 4**, we selected $L_1 = L_2 = 4$.

[3]The error-free feedback channel assumption in SM-based schemes may be justifiable, since the feedback channel is usually protected using powerful error correction coding and hence has a low error probability [4]. The effect of imperfect feedback channels in closed-loop MIMO systems has been documented, for example in [135].

As expected, the proposed LA-aided schemes beneficially exploit the flexibility of the transmit parameters and as seen in Fig. 13, they provide an SNR gain of about 5.1–7.3 dB over the conventional SM scheme at the BER of 10^{-5}. Moreover, the TPC-aided SM achieves the best BER performance amongst all benchmark schemes, as seen in Fig. 13. This is mainly due to the fact that the PA-assisted SM and PRP-aided SM schemes are simplified versions of the TPC-aided SM scheme, which have a suboptimal BER performance. Moreover, the selection of TPC parameters is more flexible than that of ASM, because the modulation orders of ASM are selected from a discrete set, while the TPC parameters are chosen from the vast complex-valued field. The performance gain of the TPC-aided SM over ASM is explicitly seen in Fig. 13.

C. Antenna Selection

Antenna Selection (AS) constitutes another promising low-cost technique, since it enjoys the full-diversity benefits offered by MIMO architectures at the cost of requiring a low feedback rate. Due to its advantages, AS has been adopted in contemporary wireless systems such as IEEE 802.11n [136]. A detailed overview of AS techniques was presented in [136] and both the so-called norm-based selection and the successive selection scheme were detailed. Recently, a systematic overview of all physical and higher layer features of the LTE standard relying on Transmit AS (TAS) were presented in [137]. To be specific, TAS has been adopted by LTE for both its Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD) modes of operation.

SM can also be beneficially combined with the AS technique for the sake of enhancing its performance. In recent years, several AS methods have been introduced and extended to the class of SM-MIMO systems with the goal of enhancing its capacity or its BER. For example, in [127], a TAS method based on exhaustive search was proposed for exploiting the available CSI. As natural extensions of the existing literature on TAS for spatial multiplexing systems, in [128], a low-complexity maximum-ED based TAS method and a maximum-capacity TAS method were investigated. Moreover, three closed-loop AS-aided SSK schemes were proposed in [126], which relied on the classic norm-based AS criterion, on the minimal PEP criterion and on their hybrid.

D. Hybrid Adaptation and Other LA Schemes

As mentioned in Section IV-A, ASM is capable of transmitting different number of bits over different TAs. Hence this scheme may achieve increased benefits due to the associated channel gain difference by exploiting it with the aid of dissimilar channel matrix column vectors [104]. For example, as shown in **Algorithm 3**, the number of bits carried by the conventional 4-QAM symbol is 2 in each SM symbol, while the number of bits conveyed by the TA indices is only one. The AM scheme is capable of varying this bit-mapping strategy according to the near-instantaneous channel conditions, while the TPC aided schemes [30], [103], [121]–[125] have to utilize a fixed modulation order and hence they may fail to achieve this level of flexibility. However, TPC exhibits an extra grade of flexibility, since it can have arbitrary coefficients.

As discussed in the context of (4) and Fig. 9, apart from adapting the APM modes, LA-aided SM can also benefit from adapting the TPC parameters for the sake of improving the system's performance. For example, when a high power amplifier efficiency and a high transmission rate are required, the classic PSK scheme may be preferred to QAM in diverse SM-MIMO configurations both in terms of its BER and PAPR, because PSK may be conveniently combined with the above-mentioned PRP technique for creating a PRP-aided constant-modulus SM scheme. In this scheme, the APM constellation optimization technique of Section III may be efficiently combined with the TPC technique of Section IV-B for improving both the achievable energy efficiency and the BER performance.

V. Further SM-Related Studies

A. Cooperative SM-Related Systems

Cooperative techniques are capable of gleaning some of the advantages of classic multiple-antenna aided transmission techniques with the aid of cooperating single-antenna assisted nodes within a network [139]. Based on a philosophy similar to that of the STC-based schemes, relay-aided SM schemes have been proposed in [140]–[147]. For example, in [140], a decode-and-forward (DF) relaying aided coherent STSK system was proposed, where the dispersion-vector was activated based on cyclic redundancy checking (CRC)-assisted error detection. The proposed design is capable of adapting both the number of the RNs as well as the transmission rate and the achievable diversity order, depending on the associated system requirements and channel conditions. Moreover, a differentially-encoded and non-coherently detected version of STSK was developed in [140], which dispenses with CSI estimation at all of the nodes, while retaining the benefits of the cooperative coherent STSK. In order to further improve the cooperative STSK's performance as well as to combat the effects of frequency-selective channels, in [141], Successive-Relaying (SR)aided cooperative multicarrier (MC) STSK was proposed. This technique invokes the selective DF and SR principles for the sake of recovering the half-duplex multiplexing loss while relying on the MC Code-Division Multiple Access (MC-CDMA) [148] principle for supporting multiple users, and simultaneously circumventing the dispersive effects of wireless channels. Moreover, in [142] a so-called Information Guided Transmission (IGT) scheme was employed for carrying out the random selection of the active nodes from the set of candidate Relay Nodes (RNs) for the sake of achieving a high relay throughput. Note that the above-mentioned SM-related cooperative systems may rely on single-antenna based transmissions at the Source-Node (SN), but some form of loose inter-relay synchronization (IRS) should be considered, unless the so-called Large-Area-Synchronized (LAS) spreading codes of [149], [150] are employed.

Moreover, in [121], an Amplify-and-Forward (AF)-relaying-aided SSK scheme was conceived for reducing the number of TAs and for mitigating the effects of deep fading. More recently, Mesleh *et al.* [143], [144] invoked dual-hop AF and DF relaying aided SSK schemes, which were characterized by the corresponding BER performance upper-bounds. However, as mentioned in Section II, the throughput of the SSK-aided cooperative schemes may remain somewhat limited. To eliminate this impediment, a dual-hop cooperative SM scheme [145] was conceived for combining SSK with classic APM techniques for the sake of transmitting additional bits. More specifically, the spatial domain of dual-hop SM has been exploited for transmitting additional information bits, hence this system may have the potential of providing substantial spectral efficiency and coding gains in the context of wireless relay networks. In [146], the SSK-MIMO principle is studied for the uplink of cellular networks. The source broadcasts its data packet to the available relays. The data packets are decoded by each relay individually and each decoded symbol is compared against unique identifiers of the relays. The specific relays that demodulate the data associated with their own identifier become active and transmit the associated SSK symbol to the destination. Hence, the set of relays act as a distributed spatial-constellation diagram for the source, similar to the SSK-MIMO communications concept with co-located TAs. The distributed encoding principle of [146] was then extended in [147] with the objective of improving the achievable bandwidth efficiency of half-duplex relaying. The associated transmission protocol is similar to that of [146], with one main exception, namely that active relays transmit the first data packet stored in their buffers during the second phase. This enables the relay to simultaneously transmit both the data received from the source and its own data. This is due to the fact that when a relay is active, the source data is conveyed by conventional APM modulation through this relay, while an additional data symbol can be implicitly mapped onto the relay's index. The results show that the adoption of a distributed SM-MIMO scheme is indeed capable of improving the attainable performance.

B. SM-Related Systems for Frequency Selective Channels

Despite its rich literature, the family of SM-related schemes has been predominantly investigated in the context of single-user flat fading channels. However, in high-rate SM-MIMO communication systems, the Inter-Symbol Interference (ISI) caused by multipath components of the frequency selective channel has to be considered.

Hence various SM-related systems have been investigated not only in the context of single carrier (SC) contexts [148] and but also in multi-carrier systems [151]. More specifically, in [55] the authors proposed the STFSK regime for overcoming the effects of dispersive channels, while striking a flexible trade-off between the attainable diversity and multiplexing gain. STFSK is capable of flexibly exploiting the available time-, space- and frequency-diversity, hence attaining an attractive performance in frequency-selective fading environments. In [152], an OFDM-aided STSK system was proposed, which achieves almost the same BER performance as that of its single-carrier counterpart operating in a narrowband channel. Moreover, in order to support high-rate multiuser transmissions, a novel multiuser STSK scheme was conceived for frequency-selective channels in [153], which was combined with the classic OFDMA/SC-FDMA techniques for the sake of converting the frequency-selective wideband channel to numerous parallel non-dispersive narrowband channels. In [154], an antenna-hopping space-division multiple-access aided SM scheme was advocated for exploiting the advantages of SM. For efficiently detecting this scheme, a range of linear and non-linear detection schemes have been investigated.

Recently, SM-related schemes were investigated in a frequency selective channel by combining the classic Cyclic-Prefixed (CP) single carrier technique [155], [156], which is capable of avoiding the PAPR problem encountered in multicarrier based systems. A comparison between CP-aided SC-SM and the CP-aided SM-OFDM systems was also presented for the sake of identifying the advantages of the single-carrier-SM scheme. Then, Rajashekar *et al.* further generalized the solutions of [156], where a Zero-Padded (ZP) single-carrier SM system was proposed for achieving the maximum attainable multi-path diversity order with the aid of low-complexity single-stream ML detection. It was shown that the proposed ZP-aided SC-SM system provides beneficial system performance improvements compared to both the CP-aided SC-SM and the CP-aided SM-OFDM systems.

C. The Energy-Efficient SM-Related Systems

Recently, the energy consumption issue in wireless communication has attracted increasing attention, especially in MIMO-aided LTE and LTE-A networks [111], [157]. As a new kind of MIMO transmission technique and a promising candidate for future wireless applications and standards, SM can be realized by using a single RF front-end, hence it has a high power-efficiency [15]. However, how to further improve the energy-efficiency of SM-MIMO schemes is important in practical deployments.

Some of the above-mentioned issues have been already investigated in [16], [17], [69], and [158]. More specifically, in [16] the authors evaluated the energy efficiency of a multi-antenna assisted base station employing SM based on a realistic power consumption model. It was found that the SM-aided base station has a considerable power consumption gain compared to multi-RF chain aided MIMO arrangements. This advantage of SM was further confirmed in [17] by considering different base station types. Then, in [158], the energy consumption of a class of adaptive SM was evaluated. Moreover, in [69], an energy-efficient SM-MIMO scheme was designed, which relied on the Hamming coding and Huffman coding techniques. This scheme was capable of striking a flexible spectral-efficiency versus energy-efficiency tradeoff. Note that although the above-mentioned research demonstrated that SM constitutes an energy-efficient design [111], [157], the current research results are still preliminary and hence further investigations are required.

VI. Conclusion

A. Summary of the Paper

In this tutorial, we reviewed a range of recent research achievements on SM and its potential applications. We considered some of its transceiver design aspects, the spatial constellation optimization, the associated link adaptation techniques, the distributed/cooperative system design issues and their beneficial combinations.

In Section II, we provided a rudimentary system overview of the conventional SM technique and its variants, emphasizing the associated transceiver design techniques for striking an attractive trade-off amongst the range of potentially conflicting system requirements. More specifically, the bit-to-symbol mapping principle of the SM transmitter was presented Section II-A. Then, various generalized versions of SM were introduced in Section II-B. Section II-C summarized the class of hard- and soft-detection techniques designed for SM-related schemes, which was roughly divided into four fundamental categories. In Section II-D, both the channel capacity and error performance metrics of SM-related schemes were summarized, which were used as a reference for the sake of highlighting the advantages of SM compared to other MIMO arrangements. These metrics were also used for system optimization by exploiting the knowledge of CSI.

In Section III, the effects of APM schemes on the performance of SM were characterized and we proposed a class of star-QAM constellations for minimizing the system's BER. In Section IV, we introduced the family of limited-feedback aided LA techniques designed for SM-related schemes. Depending on the specific degree of freedom exploited, these techniques were divided into four types constituted by AM, TPC, AS and their hybrid techniques. Specifically, the near-instantaneously ASM scheme of Section IV-A has been proposed in [104], [115], and [119] for improving the attainable system performance, while maintaining a fixed average transmit rate with the aid of AM techniques. Moreover, the diagonal TPC scheme of Section IV-B has been proposed in [118] and [122] based on maximizing the FD for the family of SM-MIMO systems, where the transmitted symbols are appropriately pre-weighted according to the channel condition. Finally, we discussed a variety of other SM-related classes including those designed for frequency selective channels, for cooperative SM scenarios and for energy-efficient applications.

B. Future Research Ideas

In this paper, we considered only the minimum-distance based approach of extracting the LA parameters, in order to achieve beneficial performance improvements in the high-SNR regime. As further work, one can formulate and solve the LA problems by considering a range of other optimization criteria depending on the amount of channel state information available as well as on other system requirements, such as capacity- and SNR-optimized design rules [39]. Moreover, the integration of trellis coding as well as space–time block coding and other coding techniques [4] into the proposed LA schemes may also be further researched. Perhaps the most challenging of all is the design of non-coherent detection aided or blind-detection assisted schemes, which are capable of dispensing with channel information. These are particularly important in the context of relay-aided systems, where the source-relay channel cannot be readily estimated.

VII. Glossary

ABEP	Average Bit Error Probability.
AM	Adaptive Modulation.
APM	Amplitude and Phase Modulation.
AS	Antenna Selection.
ASM	Adaptive SM.
BER	Bit Error Ratio.
BP-IGCH	Bit-Padding IGCH.
CS	Compressed Sensing.
CSI	Channel State Information.
C-SM	Concatenated SM.
CSTSK	Coherent STSK.
DSTC	Differentially-encoded STC.
ED	Euclidean distance.
EMF	Exhaustive-search MF.
FD	Free Distance.
FSK	Frequency-Shift Keying.
FBE	Fractional Bit Encoded.
GSM	Generalized SM.
G-STSK	Generalized STSK.
IAI	Inter Antenna Interference.
IAS	Inter-Antenna-Synchronization.
IGCH	Information-Guided Channel Hopping.
ISI	Inter-Symbol Interference.
LA	Link adaptation.
LTE	Long-Term Evolution.
MA-SM	Multiple Active-SM.
MAP	Maximum *a posteriori*.
MF	Matched Filter.
MIMO	Multiple-Input Multiple-Output.
MISO	Multiple-Input Single-Output.
ML	Maximum Likelihood.
MMD	Maximum–Minimum Distance.
MOS	Modulation Order Selection.
MRC	Maximum Ratio Combining.
NMF	Near-optimal MF.
OFDM	Orthogonal Frequency-Division Multiplexing.
OFDMA	Orthogonal Frequency Division Multiple Access.
OFDM-IM	OFDM with Index Modulation.
OH-SM	Optimal Hybrid-SM.
OSD	Ordered SD.
OSDM	Orthogonal Spatial-Division Multiplexing.
PA	Power Allocation.
PAPR	Peak-to-Average-Power Ratio.
PEP	Pairwise Error Probability.
PRP	Phase Rotation Precoding.
PSK	Phase Shift Keying.
QAM	Quadrature Amplitude Modulation.
RF	Radio Frequency.
R-SM	Receiver-SM.
SC-FDMA	Single-Carrier Frequency Division Multiple Access.
SD	Sphere Decoding.
SDM	Spatial Division Multiplexing.
SFSK	Space–Frequency Shift Keying.
SIM	Subcarrier-Index Modulation.
SISO	Single-Input Single-Output.
SM	Spatial Modulation.
STBC	Space Time Block Codes.
STC	Space–Time Coding.
STFSK	Space–Time–Frequency Shift Keying.
SSK	Space Shift Keying.
STSK	Space–Time Shift Keying.
VBD	Vector Based Detection.
TA	Transmit Antenna.
TAS	Transmit Antenna Selection.
TC	Trellis Coding.
TCM	Trellis Coded Modulation.
TOSD-SM	Time-Orthogonal Signal Design assisted SM.
TPC	Transmit Precoding.
TMS	Transmit Mode Switching.
USTM	Unitary Space–Time Modulation.
V-BLAST	Vertical-Bell Laboratories Layered Space–Time.

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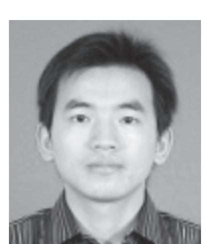

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