Spatial Modulation for Multiple-Antenna Wireless Systems : A Survey

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Abstract

Multiple–antenna techniques constitute a key technology for modern wireless communications, which trade–off superior error performance and higher data rates for increased system complexity and cost. Among the many transmission principles that exploit multiple–antenna at either the transmitter, the receiver, or both, Spatial Modulation (SM) is a novel and recently proposed multiple–antenna transmission technique which can offer, with a very low system complexity, improved data rates compared to Single–Input–Single–Output (SISO) systems, and robust error performance even in correlated channel environments. SM is an entirely new modulation concept that exploits the uniqueness and randomness properties of the wireless channel for communication. This is achieved by adopting a simple but effective coding mechanism that establishes a one–to–one mapping between blocks of information bits to be transmitted and the spatial positions of the transmit–antenna in the antenna–array. In this article, we summarize the latest research achievements and outline some relevant open research issues of this recently proposed transmission technique.

Index Terms

Multiple–Input–Multiple–Output (MIMO) systems, Spatial Modulation (SM).

INTRODUCTION

The use of multiple–antenna for wireless communication systems has received an upsurge of research interest during the last decade, both in academia and industry [1]. The multiple–antenna in Multiple–Input–Multiple–Output (MIMO) systems can be exploited in different ways to get multiplexing, diversity, or antenna gains. However, regardless of the

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use as spatial multiplexing, diversity, or smart antenna system, the main drawback of any MIMO scheme is an increase in complexity and cost. This is primarily due to three main reasons [2], [3]: i) Inter–Channel Interference (ICI), which is introduced by superimposing independent information sequences to be transmitted by multiple transmit–antenna; ii) Inter–Antenna Synchronization (IAS), which represents the baseline assumption for space–time and delay–diversity encoded methods; and iii) multiple Radio Frequency (RF) chains, which are needed to transmit all the signals simultaneously and are, in general, expensive and do not follow Moore's law. Furthermore, several transceiver designs require a number of receive–antenna greater than the number of transmit–antenna, which may limit, due to economical reasons on mobile handsets, their application to downlink settings. These issues make the practical implementation of MIMO schemes difficult, especially in mobile stations, as the necessary hardware and digital signal processing require significant energy. However, due to the important advantages of MIMO techniques it must be a clear research goal to develop new approaches for multiple–antenna transmission in order to mitigate the practical limitations while retaining the key advantages.

Following this ambitious research objective, Spatial Modulation (SM) [4]–[6] has been recently proposed as a new modulation concept for MIMO systems, which aims at reducing the complexity and cost of multiple–antenna schemes without deteriorating the end–to–end system performance and still guaranteeing good data rates. More specifically, the low–complexity transceiver design and high spectral efficiency are simultaneously achieved by adopting the simple modulation and coding mechanisms in what follows:

1) *Just one transmit–antenna is activated for data transmission at any signaling time instance*. This allows SM to entirely avoid the ICI, to require no synchronization among the transmit–antenna, and to need only one RF chain for data transmission. This is in net contrast with respect to conventional MIMO schemes where the multiple–antenna are used to simultaneously transmit multiple data streams [1]. Furthermore, this allows SM to exploit a low–complexity single–stream receiver design for optimal Maximum–Likelihood (ML) decoding.
2) *The spatial position of each transmit–antenna in the antenna–array is used as a source of information*. This is obtained by establishing a one–to–one mapping between each antenna index and a block of information bits to be transmitted, which results in a coding mechanism that can be called *transmit–antenna index coded modulation*. This allows SM to achieve a spatial multiplexing gain with respect to conventional single–

antenna systems since part of the information is implicitly conveyed by the position of the transmit–antenna [2], [6]. Accordingly, even though just one antenna is active, SM can also achieve high data throughput.

The two distinguishable features above make SM a fundamentally new physical layer transmission technique which combines, in a unique fashion, digital modulation, coding, and multiple–antenna to achieve high data rates and low–complexity implementations. In particular, the coding mechanism in 2) makes SM very different from, apparently similar, Transmit–Antenna Selection (TAS) or Spatial Division Multiplexing (SDM) schemes [1]–[3]. Motivated by the appealing characteristics of SM for various practical applications, in this article we offer a careful overview of the most recent results related to this novel transmission technology and outline some important research issues and challenges that appear relevant to better aid the understanding and evaluation of its advantages and disadvantages with respect to other popular MIMO schemes.

Notation: In this article, N_t and N_r denote the number of transmit– and receive–antenna, respectively, M is the size of the complex signal–constellation diagram, and Rx denotes the received signal corrupted by additive noise. Furthermore, E_m and N_0 denote the energy radiated by each transmit–antenna and the noise power at the receiver input, respectively. For illustrative purposes, a Nakagami–*m* fading channel is considered [7, Ref. [7]], with Ω_i and m_i denoting the average power gain and the fading parameter of the i–th transmit–to–receive wireless link, and $\rho_{i,j}$ being the correlation coefficient between the i–th and j–th transmit–to–receive wireless links, respectively.

How It Works

The basic idea of SM is to map a block of information bits into two information carrying units: 1) a symbol that is chosen from a complex signal–constellation diagram, and 2) a unique transmit–antenna index that is chosen from the set of transmit–antenna in the antenna–array (*i.e.*, the so–called spatial–constellation diagram). The net result of embedding part of the information to be transmitted into the position of the transmit–antenna is a hybrid modulation and MIMO technique in which the modulated signals belong to a tridimensional constellation diagram, which jointly combines signal and spatial information. A simple example is shown in Fig. 1 **[Callout to Fig. 1]** for a linear antenna–array with $N_t = 4$ and a QPSK (Quadrature Phase Shift Keying) modulation. When the information carrying unit is only the transmit–antenna index, SM reduces to the so–called Space Shift Keying (SSK) modulation, which avoids any form of conventional modulation and trades–off receiver complexity for achievable data rates [3]. A simple example of the encoding and decoding processes are shown in Fig. 2 **[Callout to Fig. 2]** when $N_t = 4$, $N_r = 1$, and $M = 2$. If multiple–antenna are available at the receiver, they are exploited, under the assumption of ML–optimum detection, to get receive diversity gains via Maximal Ratio Combining (MRC).

The Transmitter

At the transmitter, the bitstream emitted by a binary source is divided into blocks containing $\log_2(N_t) + \log_2(M)$ bits each, with $\log_2(N_t)$ and $\log_2(M)$ being the number of bits needed to identify a transmit–antenna in the antenna–array and a symbol in the signal–constellation diagram, respectively. Each block is then processed by a SM mapper, which splits each of them into two sub–blocks of $\log_2(N_t)$ and $\log_2(M)$ bits each. The bits in the first sub–block are used to select the antenna that is switched on for data transmission, while all other transmit–antenna are kept silent in the current signaling time interval. The bits in the second sub–block are used to choose a symbol in the signal–constellation diagram. In the example shown in Fig. 2 **[Callout to Fig. 2]**, Tx2 will be activated for data transmission by the first two bits ("10") and a -1 binary signal will be sent from it out corresponding to the third bit ("1"). If SSK modulation instead of SM is considered, each transmit–antenna, when switched on, will send exactly the same signal out: the information is, thus, encoded only in the position within the antenna–array.

The Wireless Channel as a Modulation Unit

The signal emitted by the active antenna then goes through a generic wireless channel. Owing to the different spatial positions occupied by the transmit–antenna in the antenna–array, the signal transmitted by each antenna will experience different propagation conditions due to the different interacting environmental objects along any transmit–to–receive wireless link. This represents the fundamental working principle of SM as is shown in Fig. 2 **[Callout to Fig. 2]**, which depicts the signals impinging upon the single receive–antenna and corresponding to each of the four transmit–antenna. Let us emphasize that only one transmit–antenna is active at any time instance, so only one signal will be actually received. The other antennas will radiate no power. It is apparent from this working mechanism that, especially for SSK modulation, the wireless channel plays the role of a "modulation unit", by introducing a distinct fingerprint that makes the signal emitted by distinct transmit–antenna distinguishable at the receiver. If the transmit–to–receive wireless links are not sufficiently different, data communication might be impossible since the signals emitted by the transmit–antenna will look approximately the same.

The Receiver

The receiver exploits the random modulation introduced by the wireless channel for signal detection. In particular, Fig. 2 **[Callout to Fig. 2]** shows a ML detector with perfect Channel State Information (CSI) at the receiver [8]. In order to detect the transmitted signal from the noisy received signal Rx, the receiver must know *a priori* (in practice this is obtained via channel estimation) the channel impulse response of all the transmit–to–receive wireless links. In Fig. 2 **[Callout to Fig. 2]**, the receiver must estimate four channel impulse responses (including the effects of the transmit– and receive–filters) since $N_t = 4$ and $N_r = 1$. In general, $N_t N_r$ channel impulse responses need to be estimated. According to the ML principle, the receiver computes the Euclidean distance between the received signal and the set of possible signals modulated by the wireless channel (including signal modulation if SM is used) and chooses the closest one. In general, $M N_t N_r$ Euclidean distances need to be computed. This way, all the bits in the transmitted block can be decoded and the original bitstream recovered [8].

In summary, the working principle of SM is based on the following facts: i) the wireless environment *naturally* modulates the transmitted signal, ii) each transmit–to–receive wireless link has a *different* channel, and iii) the receiver employs the *a priori* channel knowledge to detect the transmitted signal. In other words, SM exploits the location–specific property of the wireless channel, *i.e.*, the uniqueness of each transmit–to–receive wireless link, for communication. Accordingly, SM differs from Space Division Multiple Access (SDMA) [1] as well, as in SDMA the differences in the channel impulse responses are exploited for multiple–access and are not used for data modulation.

ADVANTAGES AND DISADVANTAGES

In this section, we summarize the main advantages and disadvantages of SM with respect to other MIMO schemes.

Advantages

1) With respect to conventional MIMO solutions, such as V–BLAST (Vertical–Bell Laboratories Layered–Space–Time) and Alamouti space–time schemes [1], SM entirely avoids ICI and IAS, and only requires a single RF chain at the transmitter. This is due to the working mechanism of SM: a single transmit–antenna is switched on for data transmission while all the other antennas are kept silent.
2) With respect to conventional single–antenna systems, the tridimensional constellation diagram inherent in SM introduces a multiplexing gain in the spatial domain that increases logarithmically with the number of transmit–antenna. This yields a net increase, by a factor of $\log_2(N_t)$ and without any bandwidth expansion, of the spectral efficiency [2]. When regarded as a coding technique, SM provides a high spectrally–efficient code with an equivalent code rate greater than one [6].
3) The receiver design is inherently simpler than the V–BLAST scheme since complicated interference cancelation algorithms are not required to cope with the ICI: unlike conventional spatial–multiplexing methods for MIMO systems, SM can attain ML decoding via a simple single–stream receiver.
4) SM can efficiently work if $N_r < N_t$ since the receive–antenna are used to get only a diversity gain. In principle, a single receive–antenna is needed to exploit the SM paradigm: this makes SM suitable for downlink settings with low–complexity mobile units.
5) SM is inherently able to work in multiple–access scenarios: since different pairs of transmitters and receivers usually occupy different spatial positions, the channel impulse response of each pair of users will likely be statistically different from the others. If each intended receiver uses, for data detection, the set of channel impulse responses of all the transmitters (*i.e.*, multi–user detection), several users might share the same wireless resources for communication. In other words, the wireless channel acts not just as a modulation unit, but also as a natural source of purely random signatures (*i.e.*, the channel impulse responses) for multiple–access. An example of the suitability of the SM concept to a multi–user scenario is shown in Fig. 3 **[Callout to Fig. 3]** for a setup with 2 transmitters and 1 receiver. It can be noticed that, by using a multi–user detector with perfect CSI at the receiver, both users can attain almost the same performance as in a single–user scenario (*i.e.*, the so–called single–user lower–bound). Let us emphasize

here that the performance assessment of SM in an interference channel is an open research problem.

6) Thanks to the multiplexing gain achieved by exploiting the spatial domain to convey part of the information bits, SM provides a larger capacity than conventional low–complexity coding methods for MIMO systems, such as Space–Time–Block–Codes (STBCs) [9].
7) SSK modulation can reduce further the receiver complexity since conventional modulation schemes are avoided. The price to be paid is a loss in the achievable data rate [2].

Disadvantages

1) At least two transmit–antenna are required to exploit the SM concept.
2) If the transmit–to–receive wireless links are not sufficiently different, the SM paradigm might not be used or might not yield adequate performance. This limitation is somehow similar to conventional spatial multiplexing techniques, which require a rich–scattering environment to guaranteeing a significant boost in the achievable data rate [1].
3) The receiver requires perfect channel knowledge for data detection: this may pose complexity constraints on the channel estimation unit, as well as some overhead for channel estimation ($N_t N_r$ channel impulse responses need to be estimated). In the space–time coding literature, advanced techniques to avoid the knowledge of the wireless channel at the transmitter and at the receiver have been proposed, which represent an advanced extension of well–known differential encoding/decoding modulation schemes for single–antenna systems [1, Sec. III–H]. Since the wireless channel is the actual modulation unit in SM, the development of such receiver structures poses some design challenges.
4) When compared to, *e.g.*, V–BLAST, SM can offer only a logarithmic (instead of linear) increase of the data rate with the number of transmit–antenna. This might limit SM to achieve very high spectral efficiencies for practical numbers of antennas at the transmitter.

The above list of advantages and disadvantages clearly indicates that SM appears to be a promising candidate for low–complexity MIMO implementations in asynchronous multiple–access scenarios and for wireless applications that require moderately high data rates.

State–of–the–Art

In this section, we provide an up–to–date overview of the most important results available in the literature for SM.

Historical Perspective

Along the history, the "space modulation" concept has been introduced for different application scenarios and termed in different ways. The first published contribution is [4], where the approach was called SSK modulation and the idea of exploiting the differences in the signals received from different antennas to discriminate the transmitted information messages was described for the first time. However, in [4] more than one antenna could be switched on at any time instance, thus requiring IAS and multiple RF chains. It is worth mentioning that in [4] the term SSK modulation was adopted even though, similar to Fig. 2 **[Callout to Fig. 2]**, two information carrying units were used. One year later, in [5] the principle of using the positions of the transmit–antenna as a source of information was exploited, for the first time, to accomplish a form of multiplexing in the spatial domain rather than, as usually done in Orthogonal Frequency–Division Multiplexing (OFDM) systems, in the frequency domain. For this reason, the spatial multiplexing method was called Orthogonal Spatial–Division Multiplexing (OSDM). Independently, in [6] other authors proposed a modulation technique based on the same principle as in [4]. The method was called Channel–Hopping modulation (later re–named by the same authors as Information–Guided Channel–Hopping (IGCH) modulation [9]), and, unlike [4], it was applicable to any number of transmit–antenna and foresaw the activation of a single antenna for each transmission time–slot. The term SM has been coined only recently in [10].

Overview of Recent Results

In the recent period, the main research interest has been focused on the application of the SM concept to MIMO wireless systems, in order to quantify the performance difference with other popular MIMO schemes. The main aim of this section is to summarize the most significant results available to date. The overview follows a chronological order according to the publication date.

In [9], the authors have developed an information–theoretic framework to compute the outage and ergodic capacity of SM (therein called IGCH) over Rayleigh fading channels, and have shown that SM offers a capacity gain with respect to STBCs when the number of transmit–antenna in greater than two. Furthermore, a low–complexity decoding algorithm has been proposed.

In [2], the authors have proposed a simple MRC–based receiver design for SM, which independently detects the bits conveyed by the two information carrying units. The performance of this receiver has been analyzed over independent and identically distributed (i.i.d.) Rayleigh fading channels and compared to V–BLAST and Alamouti space–time schemes. Furthermore, simulation results have been obtained over more realistic propagation environments that take into account Rician fading, channel correlation, and antenna coupling. All the results have been obtained for an OFDM–based implementation of the SM concept. The results in [2] have clearly showcased that SM can offer better error performance than V–BLAST and Alamouti space–time schemes with a lower receiver complexity (in terms of complex operations), while still guaranteeing the same spectral efficiency (simulation results for 6 bits/s/Hz and 8 bits/s/Hz are shown in [2]). In particular, [2] has pointed out that the superiority of SM with respect to V–BLAST is due to the avoidance of the ICI at the receiver and the simplified design of the detector, while the main advantage of SM with respect to the Alamouti code stems from the possibility of reducing the modulation order by increasing the number of antennas at the transmitter, which allows SM to exploit the multiplexing gain inherent in the transmit–antenna index coded modulation concept. More specifically, for high bits/s/Hz reducing the modulation order allows SM to overcoming the higher transmit–diversity gain achieved by the Alamouti code. Depending on the requested bits/s/Hz, a crossing point might be expected between the error probability curves of SM and Alamouti code for high values of the received SNR (Signal–to–Noise–Ratio).

In [8], the authors have moved from [2] and have developed the ML–optimum receiver for SM. The comparison with the heuristic detector in [2] has revealed a performance gain of approximately 4 dB with a slight increase in the receiver complexity. Performance comparisons with V–BLAST and MRC schemes have revealed that SM can offer performance gains between 1.5 dB and 3 dB over i.i.d. Rayleigh fading channels.

In [3], the authors have comprehensively analyzed the performance of SSK modulation for uncoded and bit interleaved coded systems. It has been shown that the performance of SSK modulation degrades when increasing the number of transmit–antenna, while it gets better when increasing the number of receive–antenna. In particular, it has been analytically proved that, over i.i.d. Rayleigh fading channels, the diversity order of the system is equal to the number of receive–antenna. Performance comparisons with conventional multi–level modulation schemes have shown that, under uncorrelated channel conditions, SSK modulation can yield a better error probability than conventional modulation schemes with a high modulation order.

In [11], the authors have proposed an improved version of the SSK modulation concept, by allowing, similar to [4], a sub–set of transmit–antenna (not just one) to be switched on for data transmission at any time instance. The main contribution of this paper is the optimization criterion to design the spatial–constellation diagram, *i.e.*, the set of antennas to be switched on and kept silent, by minimizing the error probability. The proposed method offers performance similar to SM but with lower complexity. However, the price to be paid to implement this scheme is the need of IAS and multiple RF chains.

In [12], the authors have extended to correlated Nakagami–m fading channels the analytical framework to compute the Average Bit Error Probability (ABEP) of the heuristic detector in [2]. Furthermore, in [13] the ML–optimum receiver based on hard–decision decoding [8] has been generalized by using a ML–optimum soft–decision decoding algorithm. It has been shown that soft–decision decoding can improve the performance of approximately 3 dB if compared to hard–decision decoding.

Finally, in [14] the authors have proposed a new modulation concept that aims at reducing the effect of channel correlation on the performance of SM. As a matter of fact, if, *e.g.*, due to closely–spaced radiating elements, the transmit–to–receive wireless links experience channel correlation, the detector might be unable to distinguish the different transmit–antenna since they will appear almost the same at the receiver. The proposed scheme is called Trellis Coded Spatial Modulation (TCSM). It exploits convolutional encoding and Maximum–Likelihood Sequence Estimation (MLSE) decoding to increase the free distance between sequences of spatial–constellation points. Simulation results in [14] have indicated that TCSM can provide better performance than SM and V–BLAST schemes over correlated Rician fading channels, while still guaranteeing the same spectral efficiency.

THE CHALLENGES AHEAD

Owing to its peculiar working principle, SM turns out to be a very new transmission technique for data communication over wireless channels. Research in this field is still at its infancy, and fundamental issues need to be still addressed to assess the possibilities of exploitation of this technology over realistic propagation environments and for practical operating conditions. This section aims at summarizing some research problems that seem of paramount importance in this area.

Key Role Played by the Wireless Channel

The statistical properties of the wireless channel play a fundamental role to enable the application of SM to MIMO wireless systems: SM might offer different error probabilities and spectral efficiencies depending on the capability of the wireless channel to make the signals emitted by a transmit–antenna distinguishable from the others. The results available in the literature so far have mainly analyzed the system performance in simplified fading conditions, which can capture only in part the unique characteristics of SM. The basic understanding of the performance and achievable rates offered by SM over more realistic fading scenarios appears instrumental to assess its potential, possibility of exploitation, and adaptive optimization.

In order to substantiate the importance of the wireless channel, which is the actual modulation unit in SM, we have investigated in Fig. 4 **[Callout to Fig. 4]** and Fig. 5 **[Callout to Fig. 5]** the ABEP of a simple SSK modulation scheme with $N_t = 2$ and $N_r = 1$. A Nakagami–m fading channel [7, Ref. [7]] with ML–optimum detection has been considered. The following important trends can be observed: i) the performance of SM is significantly affected by different fading conditions; ii) SM offers better performance in the presence of power imbalance (*i.e.*, the channel power gains Ω_1, Ω_2 are different) between the wireless links: in this scenario the links are inherently more distinguishable from one another, and, since the effective SNR at the receiver is given by the difference of the instantaneous channel gains [8], the ABEP gets better; iii) by comparing the curves in Fig. 4 **[Callout to Fig. 4]** (independent fading) and Fig. 5 **[Callout to Fig. 5]** (correlated fading) we note that channel correlation can improve the ABEP when the wireless links are unbalanced: in this scenario, the average power gap between the wireless links (*i.e.*, $\Omega_1 - \Omega_2$) can unlikely be offset by channel fading because the wireless links are subject to correlated fluctuations. On the contrary, if the wireless links are balanced, the ABEP degrades for increasing values of the correlation coefficient, as expected; iv) different values of the fading parameter m, which gives the amount of fading ($AF = 1/m$) of each wireless link [7, Ref. [7]], can yield a substantially different ABEP in the presence of power imbalance; and v) by looking into all the results in Fig. 4 **[Callout to Fig. 4]** and Fig. 5 **[Callout to Fig. 5]** we can argue that the best propagation scenario for SM is given by correlated and non–identically distributed wireless links, while the worst one arises when the wireless links are correlated but identically distributed. All these results point out a fundamentally different behavior with respect to conventional MIMO schemes [1]: i) channel correlation can improve the ABEP by keeping the average power gap almost constant regardless of the fading fluctuations, and ii) power imbalance can assist in making the wireless links more distinguishable from one another. These intriguing results clearly highlight that more emphasis should be given to understanding the performance of SM over realistic fading conditions. Further results, supported by analytical derivation, about the performance of SM in fading channels are in available in [7, Ref. [7]].

Opportunistic Power Allocation Methods

The results in Fig. 4 **[Callout to Fig. 4]** and Fig. 5 **[Callout to Fig. 5]** clearly establish that the ABEP of SM can substantially change for different fading conditions. All these results are obtained by assuming that each transmit–antenna, when switched on, radiates the same power. However, it can be easily shown that power imbalance between the wireless links can be artificially created by allowing the transmit–antenna to emit a different power while still transmitting the same signal according to the SM principle. This way, a wireless environment with identically distributed fading could be made equivalent, at the receiver, to a non–identically distributed fading scenario, thus yielding better performance. This consideration allows for opportunistic power allocation mechanisms that could be used to allocate the available power at the transmitter by either emphasizing or de–emphasizing, according to the actual fading conditions, the propagation modes corresponding to the transmit–to–receive wireless links. This approach requires a feedback channel to make available the required CSI at the transmitter. However, this method may yield a substantial reduction in terms of minimum SNR required at the receiver to satisfy some quality of service requirements. This could potentially offer important possibilities for green radio applications. Initial results confirming the potential benefits of opportunistic power allocation methods for improving the performance of SM can be found in [7].

Receiver Complexity vs. Achievable Performance

The possibility to exploit the paradigm of SM is conditioned upon making available at the receiver the channel impulse response of all the transmit–to–receive wireless links (see Fig. 2 **[Callout to Fig. 2]**). All the performance studies and receiver designs available for SM have implicitly retained this assumption so far. However, the perfect estimation of such CSI might be impractical due to the complexity of the channel estimator and the required overhead for channel estimation. It is widely accepted that in some mobile scenarios the channel fading might be sufficiently rapid to preclude the availability of the perfect knowledge of the channel phase. In Fig. 6 **[Callout to Fig. 6]**, we have compared the performance of SSK modulation by considering two ML–optimum receivers with Full CSI (F–CSI) and Partial CSI (P–CSI) [7, Ref. [7]]. In particular, in the latter case the receiver is blind to the channel phase. The results in Fig. 6 **[Callout to Fig. 6]** show, for various system setups, an unexpected high performance loss when the receiver has only P–CSI. This result showcases the important trade–off between receiver performance and complexity of the channel estimator. Accordingly, the development of optimal and sub–optimal receiver schemes with good performance, moderate complexity, and low *a priori* channel knowledge is expected to play an important role for the successful exploitation of the SM concept in a wireless context, especially in high dynamic environments.

Channel–Aware Coding Methods

With respect to conventional modulation schemes in which the set of signals to be transmitted belong to a fixed and known signal space, in SM the effective constellation space is purely random and highly dependent on the channel characteristics. Over time, several techniques have been proposed to design optimal coding mechanisms for conventional modulation schemes with the aim of improving the end–to–end performance for channels impaired by additive white Gaussian noise and fading. Owing to the implicit role as a modulation unit played by the wireless channel, in SM the development of channel–aware coding methods that aim either at the maximization of the channel capacity or at the minimization of the error probability appears an open and challenging research issue. Solutions with either full or partial channel knowledge are of interest to trade–off complexity for performance.

Development of Novel Communication– and Information–Theoretic Tools for Performance Analysis and Optimization

By carefully looking at all the performance results available in the literature so far, it follows that frameworks for the analysis and design of SM exist mainly for the simple and not very realistic propagation scenario with i.i.d. Rayleigh fading. However, the results in Fig. 4 **[Callout to Fig. 4]** and Fig. 5 **[Callout to Fig. 5]** clearly show that slightly different channel conditions can yield substantially different performance. Owing to the particular characteristics of both the transmitter and the receiver along with the role as a modulation unit played by the wireless channel, novel specific communication– and information–theoretic frameworks seem to be required to understand and analyze the performance of this new technology over fading channels. These new tools appear important for a systematic system optimization based on either capacity or error probability requirements. An interesting information–theoretic framework for computing the capacity of SM over Rayleigh fading channels has been recently proposed in [9].

Design of SM–based Schemes with Transmit–Diversity Gains

Looking into the various forms of SM proposed so far, it can be readily argued that all of them provide only receive diversity gains, while the transmit–antenna are used only for enabling data transmission. However, it is well–known that various MIMO schemes that can guarantee transmit diversity gains exist in the literature [1]. It is believed that the development of novel MIMO schemes based on the SM principle and offering diversity gains by exploiting the antennas at the transmitter may find remarkable applications in downlink settings with low–complexity and compact mobile units.

Design of SM–based Schemes for an Arbitrary Number of Transmit–Antenna

Unlike conventional MIMO schemes, SM requires that the number of transmit–antenna is a power of two. Thus, only 2, 4, 8, 16, etc. antennas at the transmitter can be used. Since in SM the spatial multiplexing gain increases logarithmically with the transmit–antenna, this fact might pose practical limits on the bit rates achievable by small–size portable devices. In fact, especially for these systems, there is a limit, in cost and physical space, on the maximum number of antennas (and so on the achievable multiplexing gain) that can be installed on them. For example, it might not be possible to install 8 antennas in such devices, while 5 or 6 antennas might still be a cost–effective option. However, SM will allow us to use, in practice, only 4 antennas. The development of flexible SM schemes accommodating an arbitrary number of antennas at the transmitter seem of practical relevance to offer the desired degrees of freedom for trading–off achievable performance and rates for system complexity and cost. Initial results about this research challenge have been reported in [15].

Ultra Wide Band (UWB–) Assisted Design of SM

In [3], it has been recently argued that UWB technology could be an important enabler for SM. We believe that the integration of SM and UWB technologies in a common framework might be a very interesting research area, and pulse–based transmission methods could significantly improve the performance and offer further degrees of freedom for system optimization.

Application of SM to Multi–Hop and Cooperative Networks: Can SM go Distributed?

It is well–known that the benefits of multiple–antenna systems can be applied to distributed settings, where multiple transmitting or receiving nodes cooperate in terms of a joint transmission/reception strategy. These systems are known as virtual MIMO or cooperative networks. To date, the paradigm of SM has been applied to MIMO schemes where the antennas are electrically connected, while the application of this principle to distributed settings has not yet received sufficient attention. We believe that the implicit role as a "compressing unit" (*i.e.*, a block of bits is compressed into a single antenna index) realized by the SM mapper in Fig. 2 **[Callout to Fig. 2]** may be exploited in distributed MIMO settings to overcome the well–known spectral efficiency loss of some conventional cooperative protocols. The application of SM to virtual MIMO systems and the understanding of its potential in distributed networks seem a very intriguing area of research. A first step towards the application of SM to relay networks has been achieved in [16], where the author has introduced a new Information–Guided Relay–Selection (IGRS) scheme and has shown, via a capacity analysis, its improved performance with respect to state–of–the–art solutions.

Experimental Assessment: From Theory to Practice

Although numerical simulations and theoretical analysis can give an important and often reliable taste of the performance offered by novel transmission technologies, it is believed that only practical experiences and testbed validations can yield definitive answers about the achievable performance in real–world devices. In order to fully capture the benefits of SM in real–world settings, we are firmly persuaded that research on SM should evolve from pure theoretical studies to more practical experimental assessments.

Conclusion

This article has summarized recent research achievements and open research issues of a novel transmission technology named SM. SM is an entirely new physical layer transmission technique, which combines digital modulation, coding, and multiple–antenna transmission in a unique fashion, and exploits the location–specific property of the wireless channel for communication. This enables the position of each transmit–antenna in the antenna–array to be used as an additional dimension for conveying information. Recent results have indicated that SM can be a promising candidate for low–complexity MIMO implementations. However, SM is still a young–born research field and several issues need to be addressed to fully understand its potential and limitations in practical and realistic propagation environments.

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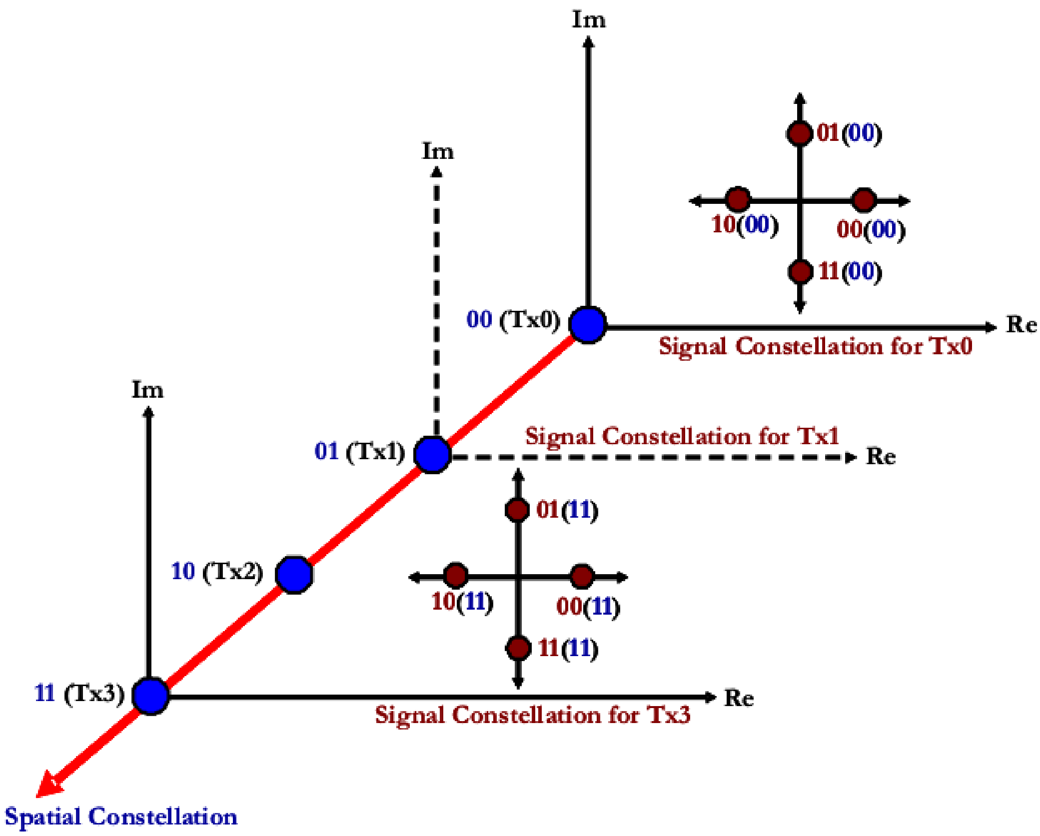

Fig. 1. Tridimensional constellation diagram of SM: each spatial–constellation point (*i.e.*, the antenna index) defines an independent complex plane of signal–constellation points. For illustration purposes, only two of such planes are shown in the figure for: i) $N_t = 4$, and ii) $M = 4$. Legend: i) Re = real axis of the signal–constellation diagram, and ii) Im = imaginary axis of the signal–constellation diagram.

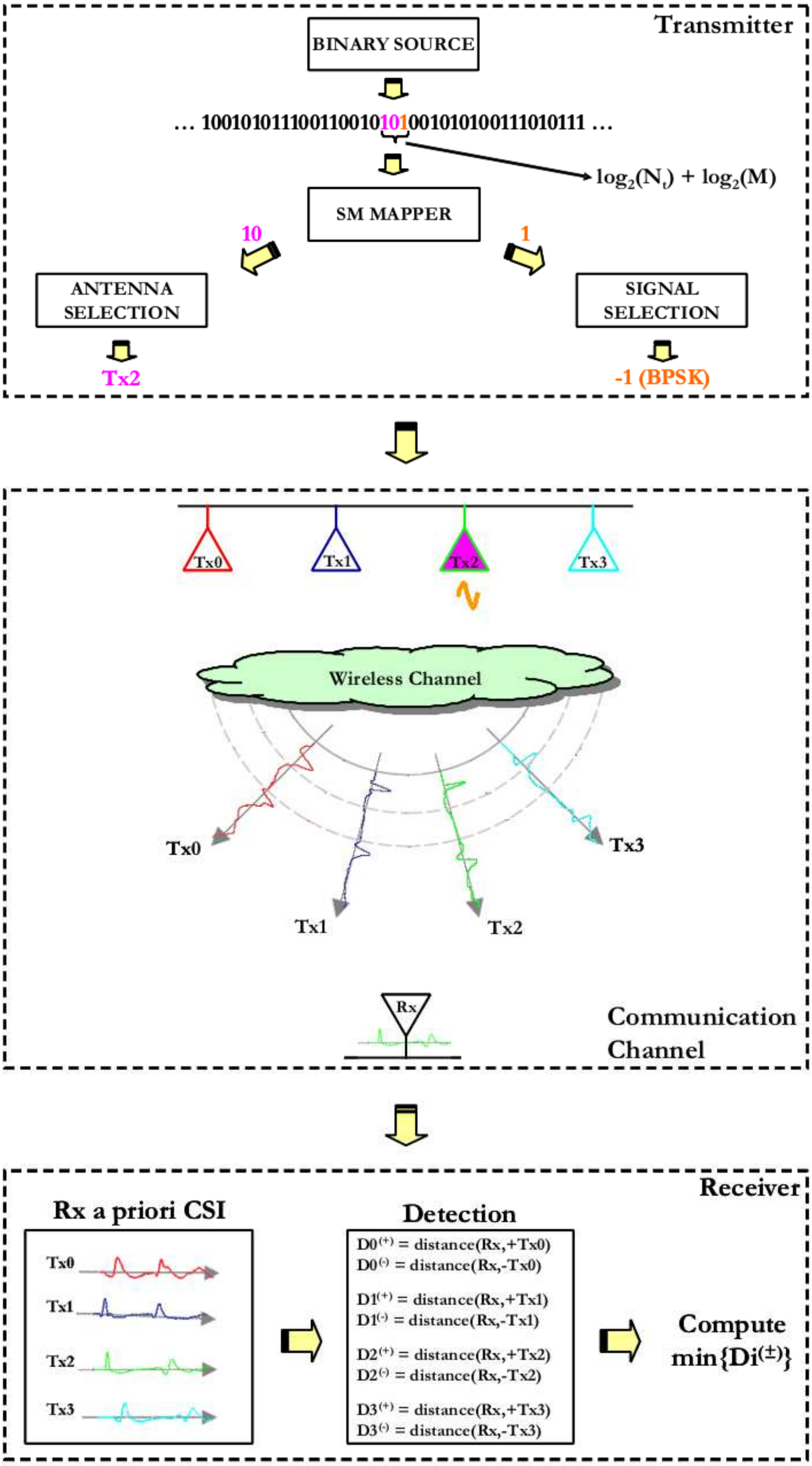

Fig. 2. SM: How it works. Setup: i) $N_t = 4$, ii) $N_r = 1$, and ii) $M = 2$. Legend: i) BPSK = Binary Phase Shift Keying, ii) CSI = Channel State Information, and iii) distance (x, y) = Euclidean distance between signals x and y [7, Ref. [7]].

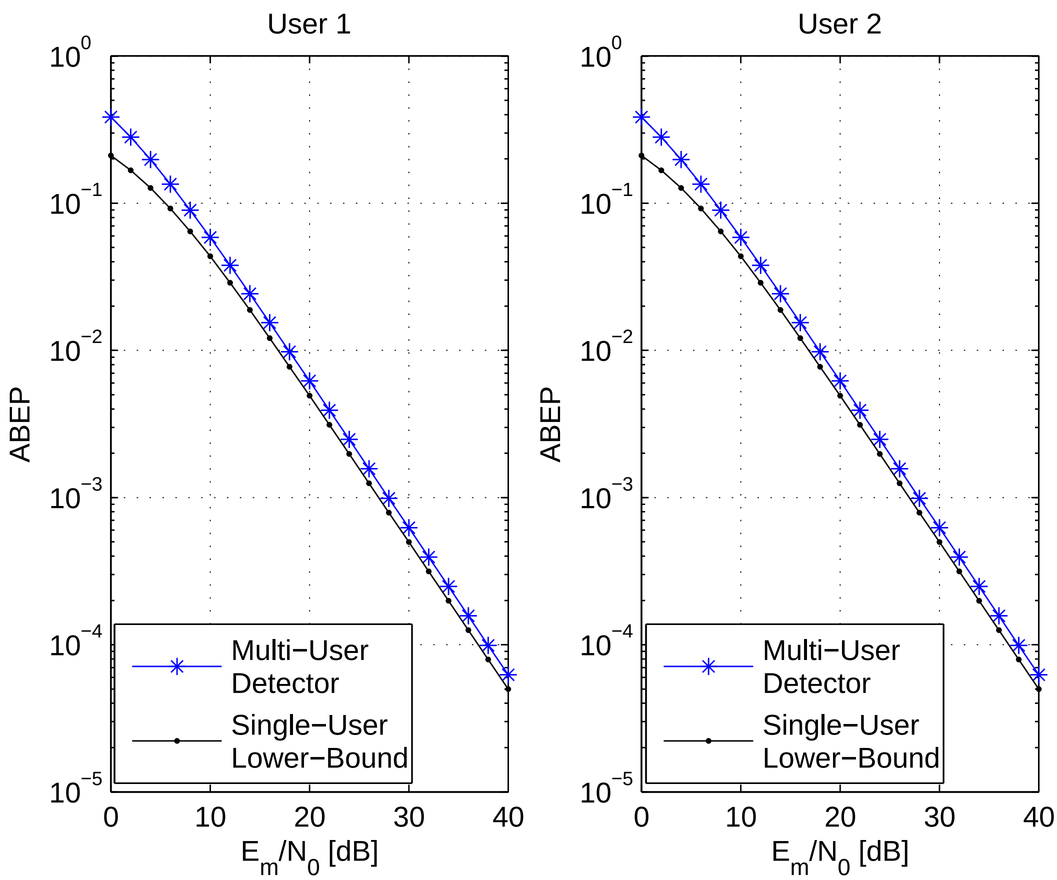

Fig. 3. Average Bit Error Probability (ABEP) against E_m/N_0 for a scenario with 2 transmitters and 1 receiver (*i.e.*, multi–user setup): i) each transmitter has $N_t = 2$, ii) the receiver has $N_r = 1$, iii) the channel of both users is uncorrelated and identically distributed according to a Nakagami–*m* distribution with parameters (Ω_1, m_1), (Ω_2, m_2) with $m_1 = m_2 = 1$ and $\Omega_1 = \Omega_2 = 1$ [7, Ref. [7]]. A multi–user ML–optimum receiver is considered [1].

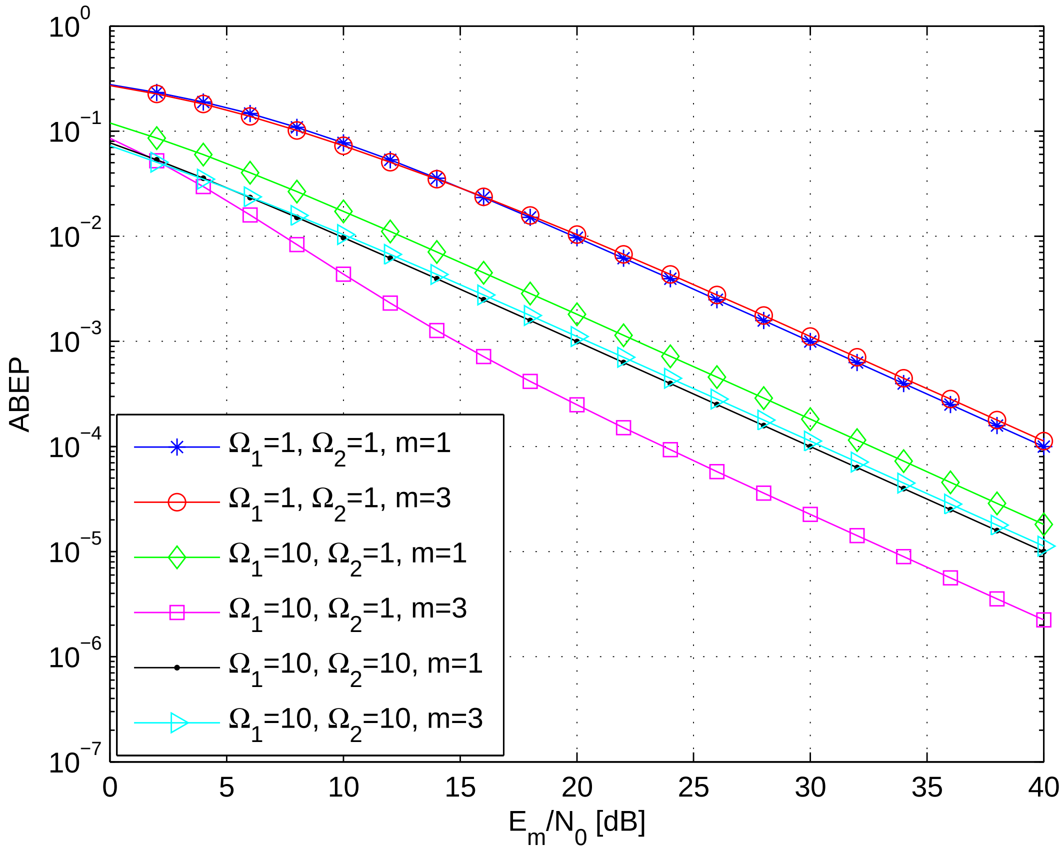

Fig. 4. Average Bit Error Probability (ABEP) against E_m/N_0 for: i) $N_t = 2$, ii) $N_r = 1$, iii) uncorrelated Nakagami–*m* fading with parameters (Ω_1, m_1), (Ω_2, m_2) [7, Ref. [7]], and iv) $m = m_1 = m_2$. The ML–optimum receiver in [7, Ref. [7]], [8] is considered.

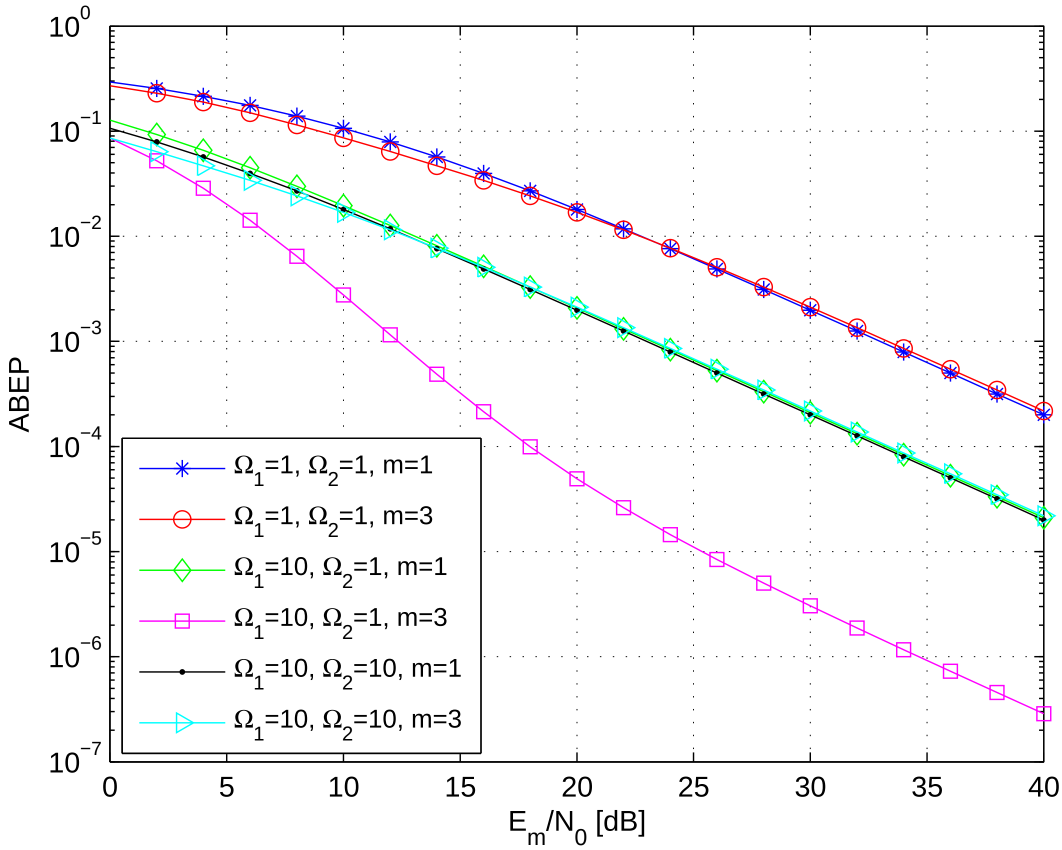

Fig. 5. Average Bit Error Probability (ABEP) against E_m/N_0 for: i) $N_t = 2$, ii) $N_r = 1$, iii) correlated Nakagami–m fading with parameters (Ω_1, m_1), (Ω_2, m_2) and correlation coefficient $\rho = \rho_{1,2} = \rho_{2,1} = 0.75$ [7, Ref. [7]], and iv) $m = m_1 = m_2$. The ML–optimum receiver in [7, Ref. [7]], [8] is considered.

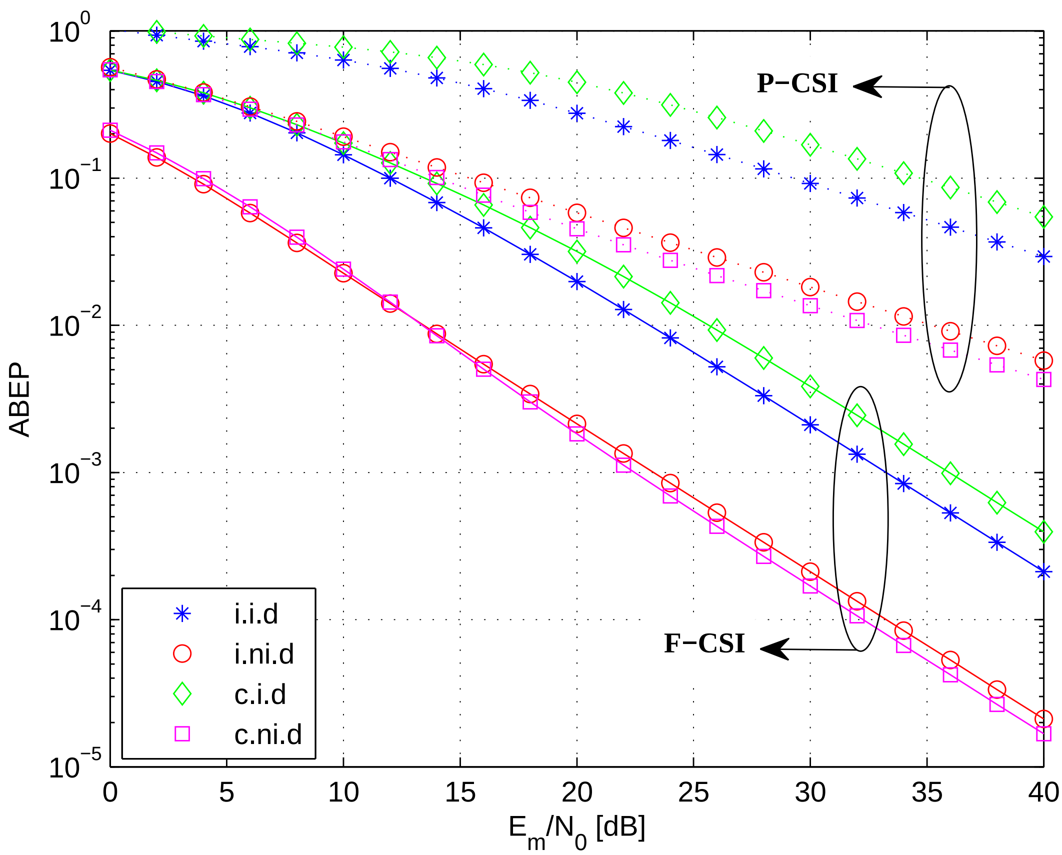

Fig. 6. Average Bit Error Probability (ABEP) against E_m/N_0 for: i) $N_t = 4$, ii) $N_r = 1$, iii) Nakagami–m fading with parameters $\{(\Omega_i, m_i)\}_{i=1}^4$ and correlation coefficient $\{\rho_{i,j}\}_{i,j=1}^4 = \exp\left(-0.22\,|i-j|\right)$ [7, Ref. [7]] if c.i.d. and c.ni.d., iv) $\{m_i\}_{i=1}^4 = 2.5$, and v) $\{\Omega_i\}_{i=1}^4 = 1$ if i.i.d. and c.i.d., and $\Omega_1 = 1$, $\{\Omega_i\}_{i=2}^4 = 4\,(i-1)$ if i.ni.d. and c.ni.d.. Legend: i) F–CSI = Full Channel State Information, ii) P–CSI = Partial Channel State Information, iii) i.i.d. = independent and identically distributed, iv) i.ni.d = independent and non–identically distributed, v) c.i.d. = correlated and identically distributed, and vi) c.ni.d = correlated and non–identically distributed.