Spatial Modulation

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ABSTRACT

In this paper we have studied about Spatial Modulation (SM). Spatial modulation is a novel and recently proposed multiple–antenna transmission technique. SM provides improved data rates compared to Single–Input–Single–Output (SISO) systems and robust error performance even with a very low system complexity. This is achieved by adopting a simple 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. This paper also discusses about its advantages and disadvantages over other conventional multiple antenna techniques.

***Keywords*- Inter Antenna synchronization (IAS), Inter-Channel interference (ICI), Multiple-input Multiple –output (MIMO), Spatial modulation(SM).**

1. INTRODUCTION

Multiple antennas in wireless systems offer a practical way to extend next generation communication capabilities. Their new improvements over single antenna systems have given many ways for research in multiple-input multiple-output (MIMO) communications. One way is spatial multiplexing. It exploits multiple antennas to transmit more information. Spatial multiplexing requires synchronizing all antennas to transmit at the same time. It introduces interference from all antennas during reception which makes detection schemes complex. For adequate performance receivers require the number of receive antennas to be larger or equal to the number of transmit antennas, which is not practical for downlink transmission to small mobile devices.

Diversity transmission is the other way to exploit MIMO system. In this case, antennas are used to increase the reliability of the message. Diversity systems exploit the spatial domain as a coding mechanism to increase reliability (i.e., diversity). These type of systems also requires synchronizing all antennas to transmit at the same time. However, diversity is attained at the expense of transmission rate, which remains unchanged from a single-input multiple-output (SIMO) system. As opposed to spatial multiplexing, diversity schemes provide simpler detection due to certain transmission properties.

Finally, the third category is hybrid transmission: both spatial multiplexing and diversity concepts are integrated. The first application of hybrid transmission is multilayered space-time coding in, which exploits transmit antennas to increase both diversity and transmission rate. However, these benefits are achieved at the expense of increased detection complexity.

All of these systems provide their own sets of benefits and restraints, but are flexible enough to accommodate various requirements. However, some common pitfalls amongst MIMO systems are:

(1) Inter-channel interference (ICI): Introduced by coupling multiple symbols in time and space.

(2) Inter-antenna synchronization (IAS): The detection algorithms assume that all symbols are transmitted at the same time. Hence, IAS is necessary to avoid performance degradation, consequently increasing transmitter overhead.

(3) Radio frequency (RF) chains: Multiple antenna elements are relatively inexpensive to deploy and the digital signal processing requirements are feasible due to increased industry growth, so the necessary RF elements are not as simple to implement. These RF chains are bulky, expensive, and necessary for each antenna that is used. Although Antenna selection provides some reduction in RF chains, there is no way around avoiding the increase in RF chains compared to that of a single antenna system. As well, Antenna selection (AS) generally increases the overhead at the receiver, and is prone to feed back errors in the case of transmit AS. The above main drawback of any MIMO scheme increases the complexity and cost of the receiver [1].

Spatial Modulation has been recently proposed as a new modulation concept for MIMO systems. It reduces the complexity and cost of multiple–antenna schemes without deteriorating the system performance and still guaranteeing good data rates. The low–complexity transceiver design and high spectral efficiency are simultaneously achieved by adopting the simple modulation and coding mechanisms as follows:

1) Only 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–antennas are used to simultaneously transmit multiple data streams.

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. Even though just one antenna is active, SM can also achieve high data throughput [2].

In the upcoming sections we have discussed about spatial modulation, its advantages and disadvantages and recent results.

2. SPATIAL MODULATION

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.

2) A unique transmit–antenna index that is chosen from the set of transmit–antenna in the antenna–array (i.e. 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. An example is shown in Fig.1. for a linear antenna–array with N_t (number of transmit antennas) is 4 and a QPSK (Quadrature Phase Shift Keying) modulation .

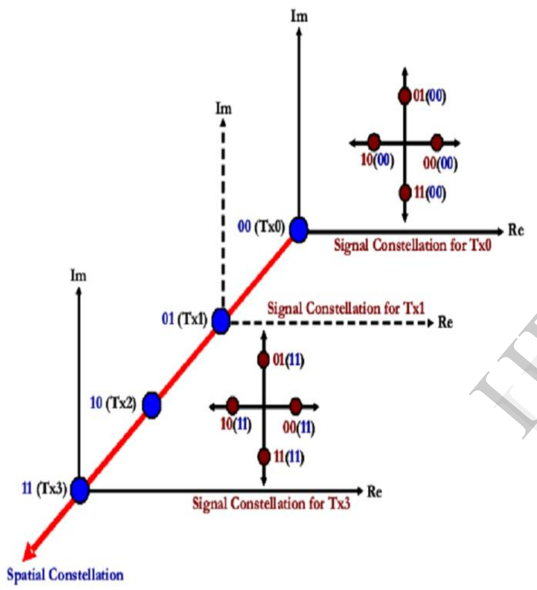

Fig.1. Tridimensional constellation diagram: each spatial–constellation point (i.e., the antenna index) defines an independent complex plane of signal–constellation points [2].

2.1 THE TRANSMITTER

At the transmitter, the bit stream emitted by a binary source is divided into blocks containing log2 (N_t)+$\log_2(M)$ bits each. 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 which is switched on for data transmission while all other transmit antennas is 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. For example in Fig. 2.1 Tx2 will be activated for data transmission by the first two bits ("10") and a -1 binary signal will be sent out corresponding to the third bit ("1").

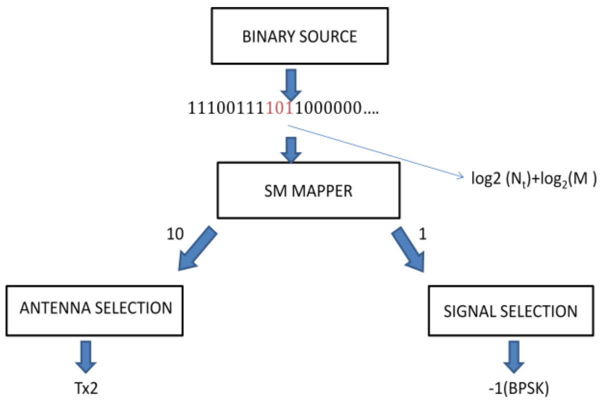

Fig.2. The Transmitter

2.2 THE WIRELESS CHANNEL AS A MODULATION UNIT

The signal emitted by the active antenna then goes through a wireless channel. Due 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. Because 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.

2.3 THE RECEIVER

The receiver detects the signal which is coming from the transmitter. Channel impulse responses (N_tN_r) need to be estimated which depends upon the number of transmitting and receiving antennas. If ML detector is used at the receiver then according to the ML principle, the receiver will compute the Euclidean distance(MN_tN_r) between the received signal and the set of possible signals modulated by the wireless channel and chooses the closest one. In this way all the bits in the transmitted block can be decoded and the original bit stream recovered.

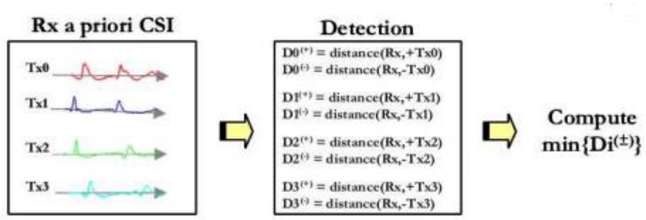

Fig.3. The Receiver[2]

3. SM TRANSMISSION AND RECEPTION

3.1 SM Transmission

The general system model is shown in Fig.4.which consists of a MIMO wireless link with N_t transmit and Nr receive antennas. A random sequence of independent bits b enters the SM mapper, which groups $m=\log_2(MN_t)$ bits and maps them to a constellation vector x=[x1 x2 ⋯ xN_t] where we assume a power constraint of unity (i.e. Ex [$x^H x$]=1). In SM, only one antenna remains active during transmission and hence, only one of the x_i in x is nonzero. The signal is transmitted over an $N_r \times N_t$ wireless channel H and experiences an Nr –dim additive white Gaussian (AWGN) noise η =[η1 η2 ⋯ηNr]^T. The received signal is given by

$$y=\sqrt{\rho}\mathrm{H}x+\eta$$

here ρ is the average signal to noise ratio (SNR) at each receive antenna, and H and η have independent and identically distributed (i.i.d) entries according to CN(0,1). As mentioned earlier, SM exploits the antenna index as an additional means to transmit information. The antenna combined with the symbol index make up the SM mapper which outputs a constellation vector of the following form:

$$x^{jq} \triangleq \begin{bmatrix} 0 & 0 & \dots & x_q & 0 & 0 \\ & & & \uparrow & & \\ & & & jth\ position & & \end{bmatrix}^T$$

,where j represents the activated antenna, and x_q is the q^{th} symbol from the M-ary constellation X. Hence, only the j^{th} antenna remains active during symbol transmission. For example, in 3 bits/s/Hz transmission with N_t =4 antennas, the information bits are mapped to a ±1 binary PSK (BPSK) symbol, and transmitted on one of the four available antennas. The output of the channel when transmitted from the antenna is expressed as

$$y = \sqrt{\rho}h_j\ x_q +\ \eta\ \ ,$$

where h_j denotes the j^{th} column of H[3].

3.2 SM Detection (Sub-Optimal)

In [9], a sub-optimal detection rule based on MRC is given by:

$$\hat{\jmath} = \arg\max z_j$$
$$\hat{q} = \mathcal{D}(z_j)$$

$\hat{\jmath}$ and $\hat{q}$ represent the estimated antenna and symbol index, respectively, and $\mathcal{D}$is the constellation demodulator function. Since the mapping is one to one, the demapper obtains an estimate of the transmitted bits by taking $\hat{\jmath}$ and $\hat{q}$ inputs.

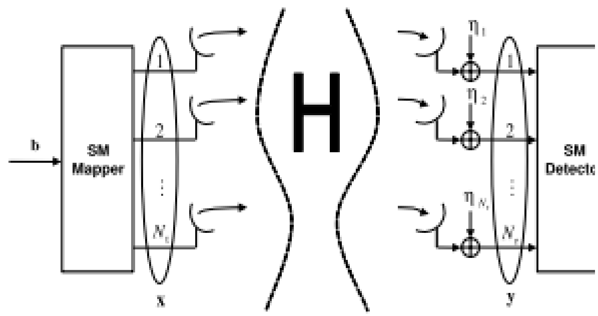

Fig.4. Spatial modulation system model [3]

4. ADVANTAGES AND DISADVANTAGES OF SM OVER CONVENTIONAL SCHEMES

4.1 Advantages

1) SM entirely avoids ICI and IAS.
2) It 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.
3) Tridimensional constellation diagram in SM introduces a multiplexing gain in the spatial domain that increases logarithmically with the number of transmit–antenna.
4) SM provides a high spectrally–efficient code with an equivalent code rate greater than one.
5) The receiver design is simple since complicated interference cancelation algorithms are not required to cope with the ICI unlike conventional spatial multiplexing methods for MIMO systems,
6) SM can attain ML decoding via a simple single–stream receiver.
7) SM can efficiently work if N_r<N_t since the receive–antenna are used to get only a diversity gain.
8) SM is able to work in multiple–access scenarios since different pairs of transmitters and receivers usually occupy different spatial positions. If each intended receiver uses the set of channel impulse responses of all the transmitters for data detection (i.e., multi–user detection), several users might share the same wireless resources for communication.
9) SM provides a larger capacity than conventional low–complexity coding methods for MIMO systems.

4.2 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 [10].
3) The receiver requires perfect channel knowledge for data detection, this may pose complexity constraints on the channel estimation unit.
4) SM offers 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.

5. SM VERSUS SSK

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. In SSK, antenna indices are used as the only means to relay information, which makes it somewhat a special case of SM. However, elimination of

APM (amplitude phase modulation) provides SSK with notable differences and advantages over SM:
1) The performance of SSK is almost identical to SM but the detection complexity is lowered.
2) Because phase and amplitude of the pulse do not convey information, transceiver requirements for SSK are less stringent than for APM.

6. LITERATURE REVIEW

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:

In [4], 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 Rayleigh fading channels and compared to conventional schemes. Furthermore, simulation results have been obtained over more realistic propagation environments that take into account Rician fading, channel correlation, and antenna coupling. The results have clearly showcased that SM can offer better error performance than conventional schemes with a lower receiver complexity, while still guaranteeing the same spectral efficiency.

In [5], the authors have proposed an improved version of the SSK modulation concept by allowing a sub–set of transmit–antenna 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 [6], 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 [7] the ML–optimum receiver based on hard–decision decoding 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.

In paper [8], 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 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.

7. CONCLUSION

SM is a technique which combines digital modulation & coding and multiple–antenna in a unique fashion to achieve high data rates.SM offers a low–complexity alternative to the design of MIMO wireless systems, which avoids multiple Radio Frequency (RF) chains at the transmitter and high–complexity interference cancelation algorithms at the receiver, but still guarantees a multiplexing gain that only depends on the number of antennas at the transmitter. This makes this technology especially suitable for the downlink with low–complexity mobile units.

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