Antenna Subset Selection for Spatial Modulation: A Novel and Energy Efficient Single RF Technique

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Abstract—In this paper, we propose a closed-loop and single RF multiple-input-multiple-output (MIMO) method, particularly suitable for the Uplink of cellular systems, which is based on the low-complexity and recently devised method of Spatial Modulation. By selecting a subset of the available transmit antennas to implement Spatial Modulation based on the instantaneous Bit Error Rate (BER), the proposed method achieves both multiplexing and transmit-diversity gains by utilizing only one RF chain. By taking into account the total power consumption at the transmit side, we numerically show that our proposed method is more energy efficient than the single RF transmit antenna selection method for the same target performance and several MIMO configurations and correlation values among the transmit antennas.

I. INTRODUCTION

The upsurge of high-rate applications in wireless networks over the recent years has brought an immense research interest in the area of MIMO systems. Although these systems achieve a significant increase in capacity and spectral efficiency (SE) compared to single-antenna systems, the energy consumption at the transceivers also increases due to the multiple RF chains required to power the multiple antennas [1]. Furthermore, the RF chains take up too much space and they are expensive in contrast to multiple-antenna elements, which are relatively inexpensive. Consequently, keeping the number of RF chains as small as possible has a profound importance for energy savings, especially for battery-driven mobile terminals in which their size and power capabilities can only allow the utilization of a limited number of RF chains.

The simplest approach for reducing the complexity and energy consumption of MIMO systems is the utilization of a single RF chain [2]. The most well-known single RF method that exploits the presence of multiple antennas at the transmitter is the transmit antenna selection method, which improves the performance of single-antenna systems by selecting for transmission the antenna branch that has the largest instantaneous Signal-to-Noise Ratio (SNR) [3]. Hence, feedback information is needed to be sent from the receive side to the transmit side that corresponds to the antenna index that has the largest instantaneous SNR. This way, the system achieves a transmit-diversity gain that enhances its performance at the high-SNR region.

Apart from the transmit antenna selection method, the last few years the so-called Spatial Modulation method has been introduced as a single-stream MIMO approach that utilizes multiple antennas with only one RF chain [4]. It explores the spatial domain of the spatially separated multiple antennas as an additional way of conveying information bits, apart from the signal-constellation diagram, thus providing a multiplexing gain. However, it cannot provide transmit-diversity gains, which means that it relies only on the existence of multiple antennas at the receive side to provide increased performance at the high-SNR region. Open-loop transmit-diversity techniques for enhancing the performance of Spatial Modulation have been proposed in [5], [6], which are based on the Space-Time Block Codes (STBCs) technology [7], but come with the disadvantage of requiring at least two active antennas and therefore two RF chains. Another performance enhancing technique for Spatial Modulation that retains its conventional distinct feature of requiring only one RF chain is presented in [8].

Contribution: In this paper, we introduce a feedback-based Spatial Modulation technique in which a subset of the available transmit antennas is selected to implement the Spatial Modulation paradigm. The selected subset satisfies the lowest instantaneous BER criterion, as it will be presented in Section III-B. This way, our Spatial Modulation-based proposed scheme achieves both multiplexing and transmit-diversity gains with only one RF chain, which results in a significantly better performance than the one of the open-loop Spatial Modulation [4], as it will be shown in Section IV-A. Furthermore, we compare the energy efficiency of our proposed scheme with the energy efficiency of the single RF transmit antenna selection for the same target average bit error probability (ABEP) and MIMO configuration. We numerically show that depending on the MIMO configuration and the correlation coefficient among the transmit antennas, the proposed scheme achieves various energy gains over the conventional transmit antenna selection method for mobile terminals equipped with a single RF.

Organization: This paper is organized as follows: In Section II, the system and energy consumption model are introduced.
In Section III, a brief description of the open-loop Spatial Modulation along with the description of the Spatial Modulation-based proposed method are given. In Section IV, Monte Carlo simulations of the ABEP curves of the proposed scheme and the transmit antenna selection method are shown for different MIMO setups. Furthermore, for these configurations the relative efficiency energy gain that the proposed method achieves over the transmit antenna selection method for a specific target ABEP is presented. Finally, Section V concludes this paper and gives some ideas for future work.

Notation: The following notation is used throughout this paper: i) $E_s$ is the average energy per transmitted symbol; ii) $n$ is the $N_r$-dimensional-where $N_r$ is the number of receive antennas- Additive White Gaussian Noise (AWGN) at the receiver input, with both real and imaginary parts of each of the $N_r$ elements having a power spectral density (PSD) equal to $N_0/2$; iii) $Q(x) = (1/\sqrt{2\pi}) \int_{-\infty}^{x} \exp(-u^2/2) du$ denotes the Q-function; iv) $\binom{N_r}{i}$ denotes the binomial coefficient; and v) vectors are denoted in boldface.

II. SYSTEM AND ENERGY CONSUMPTION MODEL

A. System Model

As we are interested in this paper in saving energy at the terminal side during the Uplink phase, we consider the Uplink of a single-carrier MIMO communication system with a mobile terminal having $N_t$ transmit antennas, but only one RF chain, and a single Base Station having $N_r$ receive antennas. We assume a slow fading channel and that the receiver uses a Maximum-Likelihood (ML) detector [9]. Moreover, the receiver input, with both real and imaginary parts of each of the $N_r$ elements having a power spectral density (PSD) equal to $N_0/2$.

![Fig. 1. Transmit RF chain.](image)

According to [10], the total power consumption at a transceiver consists of two components: i) the power that is consumed at the power amplifier, denoted as $P_{amp}$, and ii) the power consumed at all the other circuit blocks, denoted as $P_{circuit}$. A common approximate model used assumes a linear relationship between $P_{amp}$ and the transmit power $P_t$ [10, Eq. (2)]: $P_{amp} = (1 + \alpha) P_t$, where $\alpha = \xi/\eta - 1$ with $\eta$ being the drain efficiency of the power amplifier and $\xi$ being the peak-to-average-power ratio (PAPR) that is dependent on the modulation type and the size of the constellation diagram. For single-carrier systems and assuming a set of complex and equally likely symbols $s_q$, $q = 1, 2, ..., Q$, where $Q$ is the modulation order, $\xi$ is defined as the ratio between the maximum squared amplitude of $s_q$ and the average of all the squared amplitudes.

If the channel path loss follows the square-law, $P_t$ can be calculated as [10, Eq. (1)]

$$P_t = E_b R_b \times \frac{(4\pi d)^2}{G_i G_r \lambda^2 M_t N_f}$$

where $E_b$ is the required energy per bit at the receiver to achieve a target ABEP, $R_b$ is the bit rate, $d$ is the distance between the transmitter and the receiver, $G_i$ and $G_r$ are the transmit and receive antenna gains, respectively, $\lambda$ is the carrier wavelength, $M_t$ is the link margin, and $N_f$ is the noise figure of the receiver. Although (2) presupposes the existence of a line-of-sight component in the radio path, which questions the validity of Kronecker’s model, the interest in this paper is in the comparative study between two different single RF transmission schemes. Therefore, the use of (2) can be justified.

The circuit power consumption of the single RF transceiver chain is calculated as $P_{circuit} = P_{DAC} + P_{mix} + P_{filt} + P_{syn}$ [10, Eq. (3)], where $P_{DAC}$, $P_{mix}$, $P_{filt}$, $P_{syn}$ denote the power consumption of the digital-to-analog converter, the mixer, the filter, and the frequency synthesizer, respectively.

The total energy consumption per bit $E_{tot}$ at the transmit RF chain can be obtained as $E_{tot} = (P_{amp} + P_{circuit})/R_b$ [10, Eq. (4)].

By using (2) and $P_{amp} = (\xi/\eta) P_t$, we get

$$E_{tot} = \xi E_b \times \frac{(4\pi d)^2}{\eta G_i G_r \lambda^2 M_t N_f} + \frac{P_{circuit}}{R_b}$$
III. BACKGROUND AND PROPOSED METHOD

A. Open-loop Spatial Modulation

Let us first give a brief description of the open-loop Spatial Modulation principle. Assuming that \( N_t \) is a power of two and \( Q \) is the size of the signal-constellation diagram, a block of \( \log_2 (N_t) + \log_2 (Q) \) information bits at the transmitter is divided into two sub-blocks of \( \log_2 (N_t) \) and \( \log_2 (Q) \) bits each. The bits in the first sub-block are used to select the transmit antenna that is activated for transmission, while the other antennas are kept silent. The bits in the second sub-block are used to select the symbol \( s_q \) that is transmitted from it. Hence, the total \( \log_2 (N_t) + \log_2 (Q) \) bits are recovered. As it was proven, the open-loop Spatial Modulation offers only receive-diversity gains [12].

B. Proposed Method

The block diagram description of the proposed method is shown in Fig. 2. The receiver uses the estimated CSI to select a subset \( \ell \), \( \ell = 1, 2, ..., N_s \), of \( M \) transmit antennas out of the possible \( N_s = \binom{N_t}{M} \) subsets to implement the Spatial Modulation principle. We note that in this case \( M \) should be a power of two, not \( N_t \). After the selection of the subset is performed, the receiver sends the index of the selected subset to the transmitter through the feedback channel.

Antenna subset selection based on the Union Bound of the instantaneous BER:

By selecting a subset of \( M \) antennas, the total number of bits that are conveyed is equal to \( \log_2 (M) + \log_2 (Q) \). For a particular subset \( \ell \), if the symbol \( s_q \) is transmitted from the \( m^{th} \) antenna, \( m = 1, 2, ..., M \), the received signal vector is given by

\[
y = \sqrt{E_s} x^{(\ell)}_{mq} + n
\]

where \( x^{(\ell)}_{mq} = h^{(\ell)}_{mq} s_q \) is the constellation vector to be conveyed and \( h^{(\ell)}_{mq} \in \mathbb{C}^{N_t \times 1} \) is the channel vector with elements that correspond to the channel paths from the \( m^{th} \) antenna of the \( \ell^{th} \) subset to all the receive antennas.

According to [4] and based on the ML detection principle, the instantaneous Pairwise Error Probability (PEP) for the \( \ell^{th} \) subset conditioned on the channel realization of deciding on the constellation vector \( x^{(\ell)}_{mq} = h^{(\ell)}_{mq} s_q \) given that the vector \( x^{(\ell)}_{mq} = h^{(\ell)}_{mq} s_q \) is conveyed is given by

\[
P_r \left( x^{(\ell)}_{mq} \rightarrow x^{(\ell)}_{mq} | \mathbf{H} \right) = Q \left( \sqrt{\frac{E_s}{2N_0}} \left\| x^{(\ell)}_{mq} - x^{(\ell)}_{mq} \right\|_F \right)
\]

For calculating the Union Bound of the instantaneous BER of the \( \ell^{th} \) subset, we rely on the Codeword-based Union Bound (CUB) [11], which was shown to be a tight bound in the high-SNR region. The CUB is given by

\[
BER^{(\ell)} | \mathbf{H} \leq A \sum_{m=1}^{M} \sum_{q=1}^{Q} \sum_{\tilde{m}=1}^{M} \sum_{\tilde{q}=1}^{Q} F \left( x^{(\ell)}_{\tilde{m}\tilde{q}} \rightarrow x^{(\ell)}_{mq} | \mathbf{H} \right)
\]

where

\[
F \left( x^{(\ell)}_{mq} \rightarrow x^{(\ell)}_{mq} | \mathbf{H} \right) = N_{bmq-mq} P_r \left( x^{(\ell)}_{mq} \rightarrow x^{(\ell)}_{mq} | \mathbf{H} \right)
\]

with \( A = 1/(M2^{\log_2 (Q)}) \) is the Hamming distance (number of bits in error) between the constellation vectors \( x^{(\ell)}_{mq} \) and \( x^{(\ell)}_{\tilde{m}\tilde{q}} \), \( N_{bmq-mq} \) depends on bit-to-constellation vectors mapping, which we assume to be fixed. After the CUBs of the instantaneous BERs of the \( N_s \) candidate subsets are calculated, the subset that is selected, which is denoted as \( \ell_{\text{selected}} \), is the one that corresponds to the minimum among them. Consequently,

\[
\ell_{\text{selected}} = \arg \min_{\ell=1,2,...,N_s} \left[ \min \left( BER^{(\ell)} | \mathbf{H} \right) \right]
\]

where \( BER^{(\ell)} | \mathbf{H} \) is given by the right-side term of (6).

Another point to mention is the complexity and energy consumption comparison at the receiver of our proposal with the conventional transmit antenna selection method regarding the required feedback operations, such as estimating the feedback variable and dispatching it to the terminal. However, in this paper we are interested in the energy consumption reduction at the terminal side during the Uplink phase, which is very important for battery-powered terminals, and therefore we do not consider this comparison study at the receiver. This is left as a topic for future research.

IV. NUMERICAL RESULTS

The aim of this Section is to provide an energy efficiency comparison of our proposed scheme with the transmit antenna selection method for various MIMO setups and antenna correlation values. For the latter method, we consider maximum ratio combining (MRC) [9] at the receiver and refer to it as transmit antenna selection/MRC. We first provide in Section IV-A a performance comparison in terms of ABEP of these two single RF methods and explain the observed trends. From the ABEP curves, the required energy per bit for a target ABEP is obtained, which is used in Section IV-B to calculate the relative energy efficiency gain between our proposal and the transmit antenna selection/MRC method.
A. Performance Comparison

We assume that the channel can support a 4 bits/symbol transmission. Fig. 3 shows the ABEP curves of our proposed scheme, the transmit antenna selection/MRC, and the open-loop Spatial Modulation [4] for $N_t = 4$ and different correlation values and number of receive antennas. A Gray code bit-mapping was used in the simulations for the transmit antenna selection/MRC case whereas a random bit-mapping was used for our proposed and the open-loop Spatial Modulation method. The curves of the open-loop Spatial Modulation and the Union Bound formula of (6) are shown in order to substantiate the expected transmit-diversity gain of our method in contrast to the open-loop Spatial Modulation and the optimallity at the high SNR region of the instantaneous Union Bound BER criterion for selecting the antenna subset, respectively. Two trends are observed in Fig. 3: i) For increasing number of receive antennas, the SNR gain difference of our scheme compared to the transmit antenna selection/MRC increases as well. A similar trend is observed in [12] in the comparison of open-loop Spatial Modulation with single-antenna systems with MRC at the receiver. Intuitively thinking, this trend is expected because the Spatial Modulation principle allows the use of a smaller modulation order than the conventional way of conveying information through only a signal-constellation diagram. Hence, a higher average minimum Euclidean Distance between constellation points is expected. ii) As the correlation coefficient $r$ among the transmit antennas increases, the proposed scheme is affected more than the transmit antenna selection/MRC. To provide an insight for this trend, let us consider the worst-case scenario of $r = 1$. Then, the transmit antenna selection/MRC becomes a single-input-multiple-output system (there is no transmit-diversity gain). For the Spatial Modulation-based proposed scheme the effect is far worse due to the identicalness of the constellation points that differ only in the spatial component. Consequently, the PEP between these constellation points is equal to 0.5. This effect is worse for higher $M$ and smaller $Q$ because more constellation points are identical.

Fig. 4 shows the $N_r = 5$ case, which offers the flexibility of either choosing $M = 2$ or $M = 4$ for the proposed method. Two trends are observed: i) For $N_r = 3$, the ABEP curves of the proposed method for $M = 2$ have a steeper slope at the high-SNR region than the ones for $M = 4$, which indicates a higher diversity order of the former case. This behavior can be explained by considering the well-known diversity and multiplexing trade-off [13]. While for $M = 4$ we gain in multiplexing gain compared to the $M = 2$ case since one more bit is conveyed from the spatial constellation diagram, we lose from the transmit-diversity gain. However, the $M = 4$ setup achieves a higher SNR increase as the number of receive antennas increases from three to four, which is attributed to the smaller modulation order that is used as discussed in the previous paragraph. ii) As we observe in Fig. 4 b), the SNR degradation of the $M = 4$ setup is higher than the $M = 2$ one for the high correlation case. This behavior verifies our based on insight claims made in the previous paragraph: A high correlation among the transmit antennas has a worse effect for our proposed method for higher $M$ and smaller $Q$.

It is important to mention that such scenarios where the number of antennas at the terminal is equal or slightly greater than the number of Base Station antennas are not unrealistic since we assume only a single RF chain at the terminal side whereas multiple RF-chains can be present at the Base Station. As technology progresses, it would be easier to place multiple antennas at a mobile terminal, while maintaining only one RF chain due to the complexity and size requirements for multiple RF chains [3].

B. Energy Efficiency Comparison

For the energy efficiency comparison of the proposed scheme with the transmit antenna selection/MRC, we use the system parameters of Table I where the power consumption values of the circuit blocks are quoted from [10]. Moreover, according to the definition of PAPR: $Q_{\text{PSK}} = 0 \text{ dB}$, $\xi_8-\text{QAM} = 1.98 \text{ dB}$, and $\xi_{16}-\text{QAM} = 2.55 \text{ dB}$.

<table>
<thead>
<tr>
<th>TABLE I</th>
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<tbody>
<tr>
<td><strong>SYSTEM PARAMETERS</strong></td>
</tr>
<tr>
<td>$f_c = 2.5 \text{ GHz}$</td>
</tr>
<tr>
<td>$d = 750 \text{ m}$</td>
</tr>
<tr>
<td>$G_{\text{yG}} = 5 \text{ dBm}$</td>
</tr>
<tr>
<td>$P_{\text{max}} = 10 \text{ mW}$</td>
</tr>
<tr>
<td>Target ABEP = $10^{-5}$</td>
</tr>
<tr>
<td>$P_{\text{idle}} = 2.5 \text{ mW}$</td>
</tr>
</tbody>
</table>
The values of the relative gain in the energy consumption are presented in Table II. The relative gain is defined as:

\[
100\% \times \left[ 1 - \frac{E_{\text{tot}}^{(\text{Proposed})}}{E_{\text{tot}}^{(TAS/MRC)}} \right]
\]

where \(E_{\text{tot}}^{(\text{Proposed})}\) and \(E_{\text{tot}}^{(TAS/MRC)}\) are the total transmit energy consumption per bit of the proposed and the transmit antenna selection/MRC method according to (3), respectively.

**TABLE II**

RELATIVE ENERGY GAIN OF THE PROPOSED METHOD OVER THE TRANSMIT ANTENNA SELECTION/MRC METHOD

<table>
<thead>
<tr>
<th>(N_t = 3)</th>
<th>(N_t = 4)</th>
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<tbody>
<tr>
<td>Energy Gain (%)</td>
<td>r = 0.5</td>
</tr>
<tr>
<td>(N_t = 4, M = 2)</td>
<td>(11.52)</td>
</tr>
<tr>
<td>(N_t = 5, M = 2)</td>
<td>(19.02)</td>
</tr>
<tr>
<td>(N_t = 5, M = 4)</td>
<td>(33.72)</td>
</tr>
</tbody>
</table>

As we see from Table II, our proposed scheme achieves various energy gains over the transmit antenna selection/MRC for the same target ABEP depending on the MIMO configuration and the correlation coefficient \(r\). Even though for some MIMO configurations and correlation values among the transmit antennas, the transmit antenna selection/MRC method requires a lower energy per symbol \(E_s\) and consequently a lower energy per bit \(E_b = E_s/k\) (where \(k = 4\) is the number of bits per transmitted symbol, which is the same for both schemes) to achieve the target ABEP according to Fig. 3 and Fig. 4, its energy efficiency is worse than the proposed scheme due to the lower PAPR of the latter scheme. This is more evident in the \(N_t = 5\) and \(M = 4\) case, which enables the use of a QPSK constellation diagram for our scheme with a 2.55 dB energy advantage over the transmit antenna selection/MRC regarding the PAPR reduction.

V. CONCLUSIONS

A Spatial Modulation based closed-loop and single RF method has been introduced, which is particularly suitable for Uplink applications. By modeling the total power consumption at the transmitter, we have shown that the proposed scheme achieves various energy gains over the transmit antenna selection method with receive MRC for the same target ABEP, which depend on the MIMO configuration and the correlation coefficient among the transmit antennas.

Future work will consider the dynamic selection of \(M\), plus the effect of imperfect CSI at the receiver and pulse-shaping filters on the achievable energy gains.

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