In this paper, the effect of channel imperfections on the performance of spatial modulation (SM) and V-BLAST (vertical-Bell Labs layered space-time) combined with OFDM (orthogonal frequency division multiplexing) transmission is presented. Channel imperfections include Rician fading, spatial correlation and mutual antenna coupling. Recently, SM-OFDM is proposed as a multi antenna transmission approach that results in an increase in spectral efficiency by systematically mapping a block of information bits to a single transmit antenna (out of a set of antennas) and an information symbol. This principle is applied to each subchannel, i.e. for an entire OFDM symbol at any given subchannel and time instant only one antenna is transmitting. For each subchannel this might be a different antenna, though, depending on the sequence of incoming bits. Consequently, inter-channel interference (ICI) at the receiver input is entirely avoided while high spectral efficiency is maintained. In this paper, the effect of channel imperfections on SM-OFDM and V-BLAST-OFDM for coded and uncoded systems are studied. For the same spectral efficiency and a BER of $10^{-3}$, SM-OFDM is shown to perform 4 dB better than V-BLAST-OFDM in the presence of Rician fading and by 7 dB in the presence of all channel imperfections.

I. INTRODUCTION

The main challenges of future wireless communication systems are the increase of spectral efficiency and the catering for QoS (Quality of Service). It has been shown that multiple-input multiple-output (MIMO) wireless transmission can significantly enhance spectral efficiency [1]. As a consequence of the required high data rates and the need for simple receivers, OFDM attracts high attention. The main advantage of OFDM is that it converts a frequency-selective channel into several parallel frequency-flat subchannels. Hence, the combination of MIMO and OFDM is a very promising broadband wireless access scheme [2].

A well known MIMO transmission technique is the V-BLAST algorithm [3]. V-BLAST breaks the original data stream into substreams to be transmitted on different antennas. The receiver decodes the substreams using optimum ordering (OR), nulling and successive interference cancellation (SIC).

In this paper, an alternative MIMO technique, namely SM-OFDM is analysed [4]. The BER performance for coded and uncoded transmission in the presence of Rician fading and the combined effect of spatial correlation (SC), mutual antenna coupling (MC) and Rician fading are considered and compared to the performance of V-BLAST-OFDM.

SM-OFDM maps the incoming bits per subchannel to a combination of transmit symbol and a transmit antenna number. The transmission is only carried out at the selected antenna and no transmission is done at the other antennas for that particular subchannel and time instant. The receiver estimates the transmit antenna number and the received symbol and uses these two information to de-map the transmitted binary data block. Therefore, ICI at the receiver input is completely avoided. However, the transmitting antenna has to be known at the receiver. This requires an antenna detection algorithm. In this paper, maximum ratio combining (MRC) is used. It is analysed in this paper to what extent channel and antenna imperfections such as SC and MC hamper the performance of the joint antenna detection and symbol detection processes in SM.

SC depends on the antenna element spacing, angle of arrival (AoA) and the power azimuth spectrum (PAS). Besides, the presence of a line of sight (LOS) path (Rician fading) is shown to increase the correlation. It is demonstrated in [5] that increasing the Rician $K$ factor results in a significant degradation in V-BLAST performance when applying the SIC detection. MC is a further imperfection caused by the signal re-radiations among the closely spaced antennas that influences the correlation of the elements and affects the system performance. MC is shown to deteriorate the channel, to increase the correlation and to reduce the achievable capacity [6]. However it is also shown that MC can enhance the channel capacity of MIMO system but that is only valid for strong channel correlation [7].

The rest of the paper is organized as follows. Section II presents the SM-OFDM system model. Rician fading, SC and MC channel models are discussed in Section III. Simulation results are presented in Section IV. Finally, conclusions are given in Section V.

II. SM-OFDM SYSTEM MODEL

The following notations are considered throughout the paper. Vectors are underlined once, whereas matrices are underlined twice. Lower and upper case letters label signals in the time and the frequency domain respectively. The notations, $(\cdot)^T$, $(\cdot)^H$ and $(\cdot)^T$ denote pseudo-inverse, Hermitian and transpose of a vector or matrix respectively and $(\cdot)^{-1}$ denotes the inverse of a matrix. Finally, $\circ$ represents the Schur-Hadamard product.

The SM-OFDM system model with BPSK (binary phase shift keying) per subchannel and $N_T=4$ is shown in Figure I. The number of transmit and receive antennas are given by $N_T$ and $N_R$ respectively. The binary matrix to be transmitted is denoted as $q(k)$. Each column vector in $q(k)$ corresponds to
the data to be transmitted in one subchannel. The SM mapping table maps the column vectors of $\tilde{g}(k)$ to the column vectors of another matrix $\tilde{x}(k)$ of size $N_T \times N_{FFT}$, where $N_{FFT}$ is the total number of subchannels. Each combination of input data bits are uniquely mapped to a set of transmit antenna position and a symbol. Even though BPSK modulation is considered, it is shown in Figure 1 that actually three bits are transmitted per OFDM subchannel. In general, the number of bits that can be transmitted using SM is [4]:

$$\tilde{m} = \log_2 (N_T) + m,$$

(1)

where $m$ is the number of bits/symbol from the signal modulation. The column vectors of $\tilde{g}(k)$ correspond to the symbols transmitted per subchannel from all the antennas. Each column vector contains one non-zero element at the position of the mapped transmit antenna number. The row vectors in $\tilde{g}(k)$ are modulated using OFDM modulators and transmitted from each antenna in an OFDM symbol duration.

In Figure 1, the input data sequence that will be transmitted in the first subchannel (highlighted column vector in $q(k)$) is $[0 \ 1 \ 0]^T$. From the SM look-up table this corresponds to the transmission of the symbol -1 from the second transmit antenna while all other antennas transmit zero power in that subchannel and this particular time instant. Thus, the transmit symbol vector for the first subchannel is $[0 \ -1 \ 0]^T$. The output vectors from $N_T$ OFDM modulators are simultaneously transmitted over the MIMO channel $h(k)$. At the receiver, the received vectors are demodulated using $N_R$ OFDM demodulators resulting in the matrix $\tilde{y}(k)$ of size $N_R \times N_{FFT}$. Each column vector in $\tilde{y}(k)$ corresponds to the received data in each OFDM subchannel from $N_R$ receive antennas.

At the receiver, SM-OFDM employs MRC in each subchannel (columns of $\tilde{y}(k)$) to estimate the transmit antenna position. The equations below illustrate the detection process in subchannel $l$:

$$\tilde{p}_l(k) = \text{arg \ max} \ |Q(G_l^l(\tilde{p}_l))|$$

(3)

$$\tilde{s}_l = Q(G_l^l(\tilde{p}_l))$$

(4)

where $Q(\cdot)$ is the constellation quantization (slicing) function, $H_l^l(k)$ is the frequency response channel matrix seen at subchannel $l$ and $Y_l^l(k)$ is the received signal vector in the $l$th subchannel. Assuming correct estimates of the transmit antenna number $\tilde{p}_l(k)$ and the transmitted symbol $\tilde{s}_l(k)$ for subchannel $l$ at discrete time instant $k$, the SM-OFDM uses the de-mapping table shown in Figure 1 to retrieve the block of information bits. In the previous scenario, SM-OFDM uses BPSK and four transmit antennas to transmit 3 bits/symbol/subchannel. Instead, SM can use 4QAM (quadrature amplitude modulation) constellation and two transmit antennas to achieve the same spectral efficiency as seen in Table II.

![Figure 1: Spatial Modulation OFDM - system model for the transmission of 3bits/symbol/subchannel](image)

<table>
<thead>
<tr>
<th>Table 1: SM look-up table - 3bits/symbol/subchannel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input bits</td>
</tr>
<tr>
<td>------------</td>
</tr>
<tr>
<td>Antenna number</td>
</tr>
<tr>
<td>000</td>
</tr>
<tr>
<td>001</td>
</tr>
<tr>
<td>010</td>
</tr>
<tr>
<td>011</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>101</td>
</tr>
<tr>
<td>110</td>
</tr>
<tr>
<td>111</td>
</tr>
</tbody>
</table>

## III. CHANNEL IMPERFECTION MODELS

The channel models with imperfections – Rician fading, SC and MC are explained below.

### A. Rician Fading Channel

The discrete time-variant channel between the $\nu^{th}$ transmit and $\nu^{th}$ receive antenna with $L$ multipaths is given by $h_{\nu,\nu}(l, \tau) =$
[h_{ν,κ}(t, τ_0) \ldots h(t, τ_{L-1})] and is modelled using Monte-Carlo Model (MCM) presented in [8, 9]. The time-varying MIMO channel matrix is given by

\[ h(t, τ) = \begin{bmatrix} h_{1,1}(t, τ) & h_{1,2}(t, τ) & \cdots & h_{1,N_R}(t, τ) \\ \vdots & \vdots & & \vdots \\ h_{N_R,1}(t, τ) & h_{N_R,2}(t, τ) & \cdots & h_{N_R,N_R}(t, τ) \end{bmatrix} \]

The channel impulse response (CIR) is weighted according to the power delay profile \( ρ(τ) \) [10]. In the presence of LOS component, the CIR between each transmit and receive antenna is modeled as the sum of a fixed component and a random multipath channel component [11] given by

\[ h_{ν,κ}(t, τ) = \sqrt{\frac{K}{1 + K}} h_{LO S}^{ν,κ} + \sqrt{\frac{1}{1 + K}} h_{τx}(t, τ) \]  

(5)

where \( h_{LO S}^{ν,κ} = [1 \ 0 \ \cdots \ 0] \) is an \( 1 \times L \) vector with all components except first one set to zero for all \( ν \) and \( κ \). \( K \) is the Rician \( K \)-factor and is defined as the ratio of signal power in dominant component over the scattered power. \( K/(1 + K) \) is the mean power of LOS component and \( 1/(1 + K) \) is the mean power of the random component.

B. Spatial Correlation (SC)

Signals received by two antennas are correlated due to insufficient separation or lack of a rich scattering environment. The magnitude of correlation depends on the antenna spacing, angular values of the signals, PAS and the radiation pattern [12].

The correlated channel matrix at delay time \( τ_0 \) is obtained as

\[ h_{ν,κ}^{corr}(t, τ_0) = \sqrt{\frac{1}{2}} h_{ν,κ}(t, τ_0) ρ^{1/2} \]  

(6)

The correlation matrices are calculated based on the PAS distribution and the array geometry as in [12].

C. Mutual Antenna Coupling (MC)

A radio signal impinging upon an antenna element induces a current in that element which in turn radiates a field that generates a surface current on the surrounding antenna elements. This effect is known as mutual coupling. MC influences the radiation pattern and the antenna correlation. In practical systems, antenna arrays have MC when the element spacing is less than 0.5λ. Parameters affecting MC are element separation, frequency and array geometry [7].

The modified MIMO channel in the presence of MC is given as [7]

\[ h_{ν,κ}^{coup}(t, τ_0) = \frac{z_r}{c_r} h(t, τ_0) c_t = \frac{z_t}{c_t} \]  

(7)

where \( z_r = z_t = ε_r/c_r \) and \( c_r, c_t \) are receiver and transmitter coupling matrices respectively. Where \( c_t \) is a normalization factor to guarantee that the vector of terminal voltages is the same as the vector of source voltages at the transmit array for zero MC. Similarly, \( c_r \) is the normalization factor at the receiver antenna array.

The mutual coupling matrices depend on the mutual impedance matrix \( z_r^T \) and \( z_t^T \) at the transmit and receive antenna array respectively. The impedance matrix for a multiple element array can be calculated as in [13].

IV. SIMULATION RESULTS

In the simulation, a carrier frequency of 2GHz with a system bandwidth of 20MHz, and 256 OFDM subchannels are assumed. A time-variant multi-path channel with a maximum propagation delay of 0.45µs, a Doppler frequency of 5Hz, a guard interval of 0.5µs and 20 OFDM symbols per frame are considered. The multi-path channels of different links are statistically independent of each other. The total signal power is the same for all transmissions. The noise is additive white Gaussian that is spatially and temporally white. Perfect time and frequency synchronization are assumed.

Coded and uncoded SM-OFDM and V-BLAST-OFDM systems with a transmission of 6 bits/symbol/subchannel (\( m = 6 \)) are compared in the presence of the aforementioned channel imperfections assuming perfect channel knowledge at the receiver.

Six bits/symbol/subchannel transmission can be obtained for SM-OFDM using either 2x4 32QAM or 4x4 16QAM system configurations. Alternatively, 2x4 8QAM and 3x4 4QAM configurations transmit the same number of information bits for V-BLAST-OFDM.

An interesting point to note in all previous configurations is that the number of receive antennas is always larger or equal to the number of transmit antennas. This is required to make the V-BLAST system work efficiently [3] but not really necessary for SM. Figure 2 depicts different simulation results in ideal channel conditions (assuming no channel imperfections) of SM and V-BLAST for the case that \( N_T > N_R \). V-BLAST shows an error floor while SM demonstrates a good performance and is clearly shown to be suitable for such configurations. These configurations are required in most cellular systems since the base station can usually accommodate more transmit antennas than mobile transceivers. However, for the sake of comparison between SM and V-BLAST, only the case of \( N_T \leq N_R \) is considered in the following.

![Figure 2: Performance of SM-OFDM and V-BLAST-OFDM for the case \( N_T > N_R \).](image-url)
A. Rician fading

The Rice factor $K$ is set to 2 for the simulation of CIR in (5). The presence of LOS component increases the correlation of MIMO channels which degrades the detector performance of both systems. This is clearly seen when comparing the BER results in the Rician fading channel shown in Figure 4 with the ideal channel results (assuming no channel imperfections) depicted in Figure 3. For example, a loss of 5 dB in SNR can be noticed at a BER of $10^{-3}$ in V-BLAST system. In SM and at the same BER, the loss varies from around 2 dB for the 2x4 SM system to about 5 dB for the 4x4 system. The larger loss noticed in the 4x4 SM system as compared to the 2x4 SM system indicates that Rician fading affects more the antenna number detection process. In case of Rician fading channel, SM system outperforms V-BLAST by about 4 dB at a BER of $10^{-3}$.

Another interesting point of SM can be seen in Figures 3 and 4 where the 2x4 SM BER curve crosses the 4x4 one at around 18 dB SNR in case of Rician fading and at about 23 dB SNR in ideal channel conditions. This effect can be explained by the existence of two estimation processes in SM – the antenna number and the transmitted symbol. For low SNR, the error is dominated by the estimation of the transmitted symbol. While at relatively higher SNR, the error is dominated by the estimation of the respective antenna number. The probability of detecting a wrong antenna number is higher for four transmit antennas as compared to two transmit antennas. This behavior allows for a flexible tradeoff between number of transmit antennas and size of constellation diagram in order to achieve better performance. For instance, as can be seen in Figure 3 for SNR $< 23$ dB, it is better to use lower constellation size and higher number of transmit antennas. However, for SNR $> 23$ dB a better performance is achieved if smaller number of transmit antennas are used with higher constellation size.

B. Uncoded system with all imperfections

In the following, the BER results of SM and V-BLAST systems in the presence of all channel imperfections including Rician fading, SC and MC are shown.

Antenna spacing and the angular values for the simulation of SC are taken from 3rd generation partnership project (3GPP) Spatial Channel Model [14]. The transmit array with an element spacing of $0.5\lambda$, mean AoA of $20^\circ$ and an AS of $35^\circ$ are assumed. The receive array has an element spacing of $10\lambda$, mean AoD of $20^\circ$ and an AS of $5^\circ$. The MC effect is negligible for antenna spacing beyond $\lambda$. A uniform linear array of identical dipole antennas assuming side by side configuration with each dipole having a length of $0.5\lambda$ and radius of $3.33 \times 10^{-3}\lambda$ with isotropic radiation pattern are assumed.

Figure 5 shows the BER results for the above settings. For a BER of $2 \times 10^{-3}$, SM-OFDM outperforms V-BLAST-OFDM by around 7 dB. Compared to the previous result in Figure 4 the presence of all imperfections has a more severe impact on the error performance of V-BLAST-OFDM. This can be explained due to the presence of error propagation in V-BLAST that does not exist in SM.

C. Coded system with all imperfections

A convolutional channel encoder followed by a block interleaver is considered. Each transmitted OFDM frame is independently encoded by the channel encoder and then interleaved by the block interleaver. A non-recursive rate-1/2 convolutional encoder with an overall constraint length of 4 is used. The data received after OFDM demodulation is block de-interleaved and then decoded using hard Viterbi decoder.

The performance of the two systems in the presence of all channel imperfections along with channel coding are presented in Figure 6. SM-OFDM gains around 7 dB in SNR at BER of $10^{-3}$ as compared to V-BLAST-OFDM. The gain achieved by SM over V-BLAST increases by about 3 dB as compared to the
that SM is more robust to the presence of all channel imperfections as compared to V-BLAST. These improvements can be attributed to the inherent ability of SM to avoid ICI while V-BLAST-OFDM suffers from error propagation. Another important advantage of SM is the possibility to interchange spatial constellation size and signal constellation size in order to achieve better performance according to the operating SNR. This is to be exploited in future works. In addition, it is foreseen that introducing new detection algorithms for SM technique will further enhance the performance.

ACKNOWLEDGEMENT

The authors would like to thank Samsung Advanced Institute of Technology (SAIT), Korea for supporting this work.

REFERENCES