Performance Evaluation of Reconfigurable MIMO Systems in Spatially Correlated Frequency-Selective Fading Channels

Vida Vakilian and Jean-François Frigon
Dept. of Electrical Engineering
École Polytechnique de Montréal
Montréal, QC, Canada
Emails: {vida.vakilian,j-f.frigon}@polymtl.ca

Sébastien Roy
Dept. of Elec. and Comp. Engineering
Université Laval
Québec, QC, Canada
Email: sebastien.roy@gel.ulaval.ca

***Abstract*—In this paper, we study the performance of a reconfigurable multiple-input multiple-output (RE-MIMO) system in spatially correlated frequency-selective fading channels. In particular, we propose to use a RE-MIMO system to overcome the inter symbol interference (ISI) problem caused by multipath propagation. In the proposed system, we use a 3-dimensional coding scheme to obtain the same diversity order as in MIMO-OFDM systems over frequency-selective channels, and achieving better bit error rate performance by using directive reconfigurable antennas. To demonstrate the superiority of the proposed system, we compare the performance of the RE-MIMO with MIMO-OFDM system over frequency-selective channels. Simulation results show that the coded RE-MIMO system outperforms the coded MIMO-OFDM systems for small angular spread. However, for larger angular spread, the performance of the RE-MIMO system degrades due to much stronger contribution of undesired multipath components.**

I. Introduction

Multiple-input multiple-output (MIMO) systems with multiple antennas at both transmitter and receiver have been shown to be a promising solution for wireless communication to provide higher reliability and throughput without the need for additional bandwidth [1]. Recently, in order to further improve the performance of MIMO systems, the use of reconfigurable antennas have been proposed in [2]–[7]. In the reconfigurable MIMO (RE-MIMO) system, antennas at the transmitter and/or receiver are capable of changing their radiation properties such as frequency, polarization, and radiation pattern. In [6], it has been shown that the maximum achievable diversity offered by RE-MIMO systems employing reconfigurable antennas at the receiver only over flat fading channels, is equal to the product of number of transmit antennas, number of receive antennas and the number of states that reconfigurable antennas can be configured. Moreover, in [7], a novel transmission scheme called space-time-state block code (STS-BC) was proposed to exploit maximum diversity gain offered by a RE-MIMO system. However, these previous works have not addressed the frequency-selectivity problem of fading channels in a MIMO system equipped with reconfigurable antennas.

One conventional solution to frequency-selectivity problem of the wireless channel in MIMO systems is to use orthogonal frequency-division multiplexing (OFDM) modulation which transforms the frequency-selective channel into a set of flat-fading channels. However, OFDM modulation generally requires an accurate synchronization, has high peak-to-average power ratio (PAPR), and demands high computational power due to multiple inverse fast Fourier transform (IFFT) and fast Fourier transform (FFT) operations.

In this paper, we propose a lower complexity MIMO system employing reconfigurable antennas with electronically controllable radiation patterns over the frequency-selective channels to mitigate multipath effects and therefore remove inter symbol interference (ISI) without using OFDM modulation technique. In the proposed system, we assume that each element in the MIMO array is able to dynamically change its beam direction in a continuous manner from backfire to endfire. As an example of such element, we can refer to the composite right/left-handed (CRLH) leaky-wave antenna (LWA) which can provide electronically controllable dynamic radiation patterns with high directivity [8]. By integration of these elements in an array, we can have a system in which the elements steer their beams toward the selected clusters and neglect the signals coming from the undesired ones in each scan-step. As a result, the ISI can be effectively suppressed. Moreover, the STS-BC transmission scheme can be used in the RE-MIMO systems to achieve the same diversity order as space-time block coded (STBC) MIMO-OFDM systems. To show the superiority of the proposed system, the bit-error rate performance of the coded RE-MIMO is compared with the performance of STBC-MIMO-OFDM system in the spatial clustered channel model that takes into account the impact of most of the physical parameters of wireless channels.

The rest of this paper is organized as follows. Section II introduces the spatial channel model used in this work. Section III presents the proposed space-time-state block coded RE-MIMO system in frequency-selective channels. Section IV describes the signal model for space-time block coded MIMO-OFDM system. The simulation results are presented in Section V, and conclusions are drawn in Section VI.

978-1-4673-1881-5/12/$31.00 ©2012 IEEE

II. Spatial Channel Model

In this paper, we consider a spatial channel model (SCM) which is a statistical-based model developed by 3GPP for evaluating MIMO system performance in urban micro-cell, urban macro-cell and suburban macro-cell fading environments [9]. This model takes into account the impact of several physical parameters of wireless channels such as angle of arrival (AoA), angle of departure (AoD), path power, antenna radiation patterns, angular and delay spread. The channel coefficient between transmitter antenna i and receiver antenna j for the l-th cluster, $l \in \{1, 2, \cdots, L\}$, is given by

$$\begin{aligned} h_{i,j}(l) &= \sqrt{\frac{P_l}{M}} \sum_{m=1}^{M} \alpha_l^m \\ &\times \sqrt{g_i^t(\theta_l^m)} e^{\boldsymbol{j} k_0 d_t (i-1) \sin(\theta_l^m)} \\ &\times \sqrt{g_j^r(\phi_l^m)} e^{\boldsymbol{j} k_0 d_r (j-1) \sin(\phi_l^m)}, \end{aligned} \tag{1}$$

where $\boldsymbol{j} = \sqrt{-1}$ is the imaginary unit, P_l is the power of the l-th cluster which is normalized so that the total average power for all clusters is equal to one, M is the number of unresolvable multipaths per cluster that have similar characteristics, $k_0 = 2\pi/\lambda$ is the free space wavenumber, where λ is the free-space wavelength, d_t and d_r are the antenna spacing between two elements at the transmitter and receiver side, respectively, α_l^m is the complex gain of the m-th multipath of the l-th path (the α_l^m are zero mean unit variance independent identically-distributed (i.i.d) complex random variables), $g_i^t(\theta_l^m)$ is the gains of i-th transmit antenna, and $g_j^r(\phi_l^m)$ is the gain of j-th receive antenna. θ_l^m and ϕ_l^m are the AoD and AoA for the m-th multipath of the l-th cluster, respectively, and can be given by

$$\theta_l^m = \theta_{l,AoD} + \vartheta_{l,AoD}^m, \tag{2}$$
$$\phi_l^m = \phi_{l,AoA} + \vartheta_{l,AoA}^m, \tag{3}$$

where $\theta_{l,AoD}$ and $\phi_{l,AoA}$ are the mean AoD and the mean AoA of the l^{th} cluster, respectively. The $\vartheta_{l,AoD}^m$ and $\vartheta_{l,AoA}^m$ are the deviation of the paths from mean AoD and AoA, respectively. The $\vartheta_{l,AoD}^m$ and $\vartheta_{l,AoA}^m$ are modeled as i.i.d. Gaussian random variables, with zero mean and variance σ_{AoD}^2 and σ_{AoA}^2, respectively.

The channel impulse response between transmit antenna i and receive antenna j can be modeled as

$$h_{i,j}(\tau) = \sum_{l=1}^{L} h_{i,j}(l) \delta(\tau - \tau_l), \tag{4}$$

where τ_l is the l-th cluster delay, and $h_{i,j}(l)$ is the complex amplitude of the l-th cluster defined in Eq.(1).

III. Space-Time-State coded RE-MIMO System in Frequency-Selective Channels

In this section, we consider a RE-MIMO system equipped with M_t omni-directional antenna elements at the transmitter

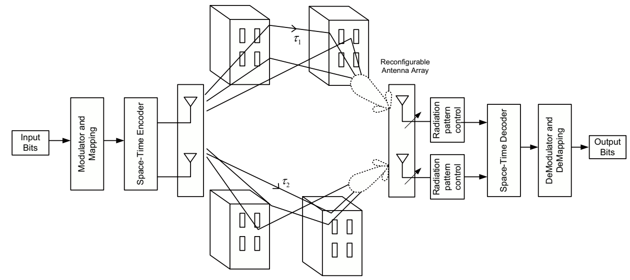

Fig. 1: RE-MIMO system with $M_t = 2$, $M_r = 2$ and $L = 2$ clusters.

and M_r directive reconfigurable antenna elements with P radiation pattern scan-step at the receiver. We assume that the mean AoA of the clusters are known at the receiver and in each radiation pattern scan-step, the reconfigurable antenna element steers toward a cluster as shown in Fig.1.

In the RE-MIMO system, the radiation pattern of received reconfigurable antenna at p-th scan-step is approximated by a parabolic function that can be expressed as [10]

$$g_j^r(\phi_l^m, \psi_j^p) = \frac{2\pi}{B_{3dB}} 10^{0.1 A(\phi_l^m, \psi_j^p)}, \tag{5}$$

where $A(\phi_l^m, \psi_j^p) = -\eta \left(\frac{\phi_l^m - \psi_j^p}{B_{3dB}} \right)^2$ in dB, η is a constant (set to 12 in [9]), B_{3dB} is the 3dB reconfigurable antenna beamwidth in radians, and ψ_j^p is the j-th received antenna pointing angle during p-th step.Therefore, the channel coefficient defined in Eq.(1) becomes as a function of antenna pointing angle and can be rewritten as

$$\begin{aligned} h_{i,j}^p(l, \psi_j^p) = \sqrt{\frac{P_l}{M}} \sum_{m=1}^{M} \alpha_l^m \\ \times \sqrt{g_i^t(\theta_l^m)} e^{\boldsymbol{j} k_0 d_t (i-1) \sin(\theta_l^m)} \\ \times \sqrt{g_j^r(\phi_l^m, \psi_j^p)} e^{\boldsymbol{j} k_0 d_r (j-1) \sin(\phi_l^m)}. \end{aligned} \tag{6}$$

We assume a block fading channel, where the fading coefficients are time-invariant over each scan-step, and change independently from one scan-step to another. Each scan-step is composed of K blocks of T time slots. To have a fair comparison with MIMO-OFDM, we consider $K = N_c/T$, where N_c is the number of OFDM subcarriers. At each scan-step p and time slots t in the k-th data block, the transmit codeword vector by M_t antennas can be defined as,

$$\mathbf{c}^p(t,k) = [\mathbf{c}_1^p(t,k), \mathbf{c}_2^p(t,k), \cdots, \mathbf{c}_{M_t}^p(t,k)] \in \mathcal{C}^{1 \times M_t} \tag{7}$$

where, $\mathbf{c}_i^p(t,k)$, for $i = 1, \cdots, M_t$, is the transmitted symbol at the p-th scan-step from i-th transmit antenna during t-th time slot of k-th block. At time t and scan-step p, the received antenna j is pointing to the mean AoA of a cluster such that $\psi_j^p = \phi_{l',AoA}$, where $l' \in \{1, 2, \cdots, L\}$. In this scenario, the received signal by antenna j within k-th block is given by

$$\begin{bmatrix} y_1^1(1,k) & y_2^1(1,k) \\ y_1^1(2,k) & y_2^1(2,k) \\ y_1^2(1,k) & y_2^2(1,k) \\ y_1^2(2,k) & y_2^2(2,k) \end{bmatrix} = \overbrace{\sqrt{E_s} \begin{bmatrix} s_1^k+\tilde{s}_3^k & s_2^k+\tilde{s}_4^k & 0 & 0 \\ -s_2^{k^*}-\tilde{s}_4^{k^*} & s_1^{k^*}+\tilde{s}_3^{k^*} & 0 & 0 \\ 0 & 0 & s_1^k-\tilde{s}_3^k & s_2^k-\tilde{s}_4^k \\ 0 & 0 & -s_2^{k^*}+\tilde{s}_4^{k^*} & s_1^{k^*}-\tilde{s}_3^{k^*} \end{bmatrix} \begin{bmatrix} h_{1,1}^1(1,\psi_1^1) & h_{1,2}^1(2,\psi_2^1) \\ h_{2,1}^1(1,\psi_1^1) & h_{2,2}^1(2,\psi_2^1) \\ h_{1,1}^2(2,\psi_1^2) & h_{1,2}^2(1,\psi_2^2) \\ h_{2,1}^2(2,\psi_1^2) & h_{2,2}^2(1,\psi_2^2) \end{bmatrix}}^{mainlobe}$$
$$+ \underbrace{\sqrt{E_s} \begin{bmatrix} s_1^k+\tilde{s}_3^k & s_2^k+\tilde{s}_4^k & 0 & 0 \\ -s_2^{k^*}-\tilde{s}_4^{k^*} & s_1^{k^*}+\tilde{s}_3^{k^*} & 0 & 0 \\ 0 & 0 & s_1^k-\tilde{s}_3^k & s_2^k-\tilde{s}_4^k \\ 0 & 0 & -s_2^{k^*}+\tilde{s}_4^{k^*} & s_1^{k^*}-\tilde{s}_3^{k^*} \end{bmatrix} \begin{bmatrix} h_{1,1}^1(2,\psi_1^1) & h_{1,2}^1(1,\psi_2^1) \\ h_{2,1}^1(2,\psi_1^1) & h_{2,2}^1(1,\psi_2^1) \\ h_{1,1}^2(1,\psi_1^2) & h_{1,2}^2(2,\psi_2^2) \\ h_{2,1}^2(1,\psi_1^2) & h_{2,2}^2(2,\psi_2^2) \end{bmatrix}}_{sidelobe} + \begin{bmatrix} z_1^1(1,k) & z_2^1(1,k) \\ z_1^1(2,k) & z_2^1(2,k) \\ z_1^2(1,k) & z_2^2(1,k) \\ z_1^2(2,k) & z_2^2(2,k) \end{bmatrix} \tag{24}$$

$$y_j^p(t,k) = \overbrace{\sqrt{E_s}\mathbf{c}^p(t,k)\ \mathbf{h}_j^p(l',\psi_j^p)}^{\text{mainlobe}} + \underbrace{\sum_{l\neq l'} \sqrt{E_s}\mathbf{c}^p(t,k)\ \mathbf{h}_j^p(l,\psi_j^p)}_{\text{sidelobe}} + z_j^p(t,k), \tag{8}$$

where E_s is the average energy per symbol at each transmit antenna, $z_j(t,k)$ is a zero mean complex AWGN at receive antenna j and time instant t with variance $\sigma_n^2/2$ per dimension. In Eq.(8), $\mathbf{h}_j^p(l,\psi_j^p) \in \mathcal{C}^{M_t\times 1}$ is the channel vector given by

$$\mathbf{h}_j^p(l,\psi_j^p) \triangleq [h_{1,j}^p(l,\psi_j^p), h_{2,j}^p(l,\psi_j^p), \cdots, h_{M_t,j}^p(l,\psi_j^p)]^T. \tag{9}$$

After T time slots, the overall received signal during p-th scan-step and k-th block can be defined as $T\times M_r$ matrix, as below

$$\mathbf{Y}^p(k) \triangleq [\mathbf{y}_1^p(k), \mathbf{y}_2^p(k), \cdots, \mathbf{y}_{M_r}^p(k)], \tag{10}$$

where

$$\mathbf{y}_j^p(k) \triangleq [y_j^p(1,k), y_j^p(2,k), \cdots, y_j^p(T,k)]^T. \tag{11}$$

Eq.(10) can be computed as

$$\mathbf{Y}^p(k) = \sum_{l=1}^{L} \sqrt{E_s}\mathbf{C}^p(k)\ \mathbf{H}^p(l,\boldsymbol{\psi}^p) + \mathbf{Z}^p(k), \tag{12}$$

where

$$\mathbf{H}^p(l,\boldsymbol{\psi}^p) \triangleq [\mathbf{h}_1^p(l,\psi_1^p), \mathbf{h}_2^p(l,\psi_2^p), \cdots, \mathbf{h}_{M_r}^p(l,\psi_{M_r}^p)], \tag{13}$$
$$\boldsymbol{\psi}^p \triangleq [\psi_1^p, \psi_2^p, \cdots, \psi_{M_r}^p], \tag{14}$$
$$\mathbf{C}^p(k) \triangleq [\mathbf{c}(1,k)^T, \mathbf{c}(2,k)^T, \cdots, \mathbf{c}(T,k)^T]^T, \tag{15}$$
$$\mathbf{Z}^p(k) \triangleq [\mathbf{z}_1^p(k), \mathbf{z}_2^p(k), \cdots, \mathbf{z}_{M_r}^p(k)]. \tag{16}$$

The codeword transmitted over all P scan-steps can be expressed as

$$\mathbf{C} \triangleq \mathrm{diag}\{\mathbf{C}^1, \mathbf{C}^2, \cdots, \mathbf{C}^P\}, \tag{17}$$

where $\mathbf{C}^p \triangleq [\mathbf{C}^{p^T}(1), \mathbf{C}^{p^T}(2), \cdots, \mathbf{C}^{p^T}(K)]^T$ is the transmitted codeword during one scan-step. In this case, the received signal over over all P scan-steps $\mathbf{Y} \in \mathcal{C}^{PKT\times M_r}$ is given by

$$\mathbf{Y} = \sum_{l=1}^{L} \sqrt{E_s}\mathbf{C}\ \mathbf{H}(l,\boldsymbol{\psi}) + \mathbf{Z}, \tag{18}$$

where

$$\mathbf{H}(l,\boldsymbol{\psi}) \triangleq [\mathbf{H}^1(l,\boldsymbol{\psi}^1)^T, \mathbf{H}^2(l,\boldsymbol{\psi}^2)^T, \cdots, \mathbf{H}^P(l,\boldsymbol{\psi}^P)^T]^T, \tag{19}$$
$$\boldsymbol{\psi} \triangleq [\boldsymbol{\psi}^1, \boldsymbol{\psi}^2, \cdots, \boldsymbol{\psi}^P], \tag{20}$$
$$\mathbf{Z} \triangleq [\mathbf{Z}^1, \mathbf{Z}^2, \cdots, \mathbf{Z}^P]. \tag{21}$$

Now, as an example, consider a 2×2 RE-MIMO system in a two-cluster channel model with STS-BC scheme at the transmitter and reconfigurable antennas with $P=2$ scan-steps at the receiver which is equal to the number of the clusters. In this scenario, in the first scan-step, the pointing angle of the first and second reconfigurable antenna elements at the receiver are $\psi_1^1 = \phi_{1,AoA}$ and $\psi_2^1 = \phi_{2,AoA}$, respectively, and in the next step, they will be $\psi_1^2 = \phi_{2,AoA}$ and $\psi_2^2 = \phi_{1,AoA}$. In this case, we define a vector containing the received signals at two consecutive scan-steps over the k-th block that can be expressed as

$$\begin{bmatrix} \mathbf{Y}^1(k) \\ \mathbf{Y}^2(k) \end{bmatrix} = \begin{bmatrix} \mathbf{C}^1(k) & \mathbf{0} \\ \mathbf{0} & \mathbf{C}^2(k) \end{bmatrix} \begin{bmatrix} \mathbf{H}^1(l,\boldsymbol{\psi}^1) \\ \mathbf{H}^2(l,\boldsymbol{\psi}^2) \end{bmatrix} + \begin{bmatrix} \mathbf{Z}^1(k) \\ \mathbf{Z}^2(k) \end{bmatrix}, \tag{22}$$

where $\mathbf{C}^p(k)$ is quasi-orthogonal space-time-state block code given by [7] which can be represented as

$$\mathbf{C}^1(k) = \begin{bmatrix} s_1^k+\tilde{s}_3^k & s_2^k+\tilde{s}_4^k \\ -\left(s_2^k+\tilde{s}_4^k\right)^* & \left(s_1^k+\tilde{s}_3^k\right)^* \end{bmatrix},$$
$$\mathbf{C}^2(k) = \begin{bmatrix} s_1^k-\tilde{s}_3^k & s_2^k-\tilde{s}_4^k \\ -\left(s_2^k-\tilde{s}_4^k\right)^* & \left(s_1^k-\tilde{s}_3^k\right)^* \end{bmatrix}, \tag{23}$$

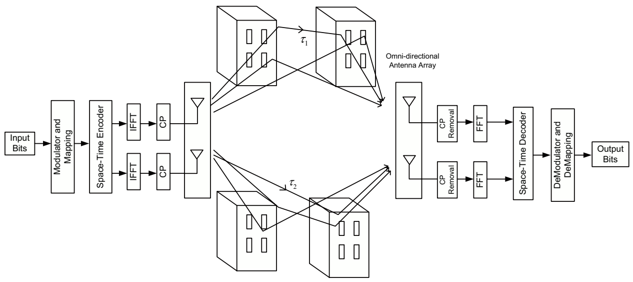

Fig. 2: MIMO-OFDM system with $M_t = 2$, $M_r = 2$ and $L = 2$ clusters.

where s_1^k and s_2^k belong to a constellation $\mathcal{A}$ and $\tilde{s}_3^k$ and $\tilde{s}_4^k$ belong to the rotated constellation $e^{\boldsymbol{j}\theta}\mathcal{A}$, which θ is the optimal rotation angle and equal to $\pi/2$ for BPSK. Eq.(22) can be decoupled into received signals from mainlobe and sidelobe given in Eq.(24), shown at the top of the previous page. If we have more than two clusters and we to use the codeword built based on two scan-steps, then at the receiver, we configure the antenna to receive the signal from the two strongest cluster.

At the receiver, due to the independence of different blocks of data corresponding to different values of k, the maximum-likelihood (ML) decoding is reduced into independent ML decoding per block. In this case, ML decoding is performed to estimate the transmitted symbol by solving the following optimization problem

$$\arg\min \sum_{p=1}^{P} ||\mathbf{Y}^p(k) - \mathbf{C}^p(k)\mathbf{H}^p(l, \boldsymbol{\psi})||_F^2, \tag{25}$$

where $||.||_F$ denotes the Frobenius norm.

IV. Space-Time Coded MIMO-OFDM System

In this section, we consider a MIMO-OFDM system with M_t omni-directional transmit antennas, M_r omni-directional receive antennas, and N_c subcarriers. The frequency response of the channel impulse response defined in Eq.(4), is given

$$H_{i,j}(e^{\boldsymbol{j}\frac{2\pi}{N_c}n}) = \sum_{l=1}^{L} h_{i,j}(l)e^{-\boldsymbol{j}\frac{2\pi}{N_c}\tau_l n}, n = 0, 1, \cdots, N_c - 1 \tag{26}$$

At the transmitter, we consider STBC scheme to encode information and produce the codeword $\mathbf{c}^b(n) \triangleq [c_1^b(n), c_2^b(n), \cdots, c_{M_t}^b(n)]$, where $c_i^b(n)$ is the coded symbol transmitted from the i-th antenna on the b-th OFDM symbols and n-th subchannel. At the receiver, after the cyclic prefix removal and FFT, the frequency domain of the received signal at the j-th receive antenna and n-th subcarrier, where $n = 0, 1, \cdots, N_c - 1$ and $b = 1, 2, \cdots, B$, can be written as

$$y_j^b(n) = \sum_{i=1}^{M_t} \sqrt{E_s} c_i^b(n) H_{i,j}^b(e^{\boldsymbol{j}\frac{2\pi}{N_c}n}) + z_j^b(n), \tag{27}$$

where $z_j^b(n)$ is the additive white Gaussian noise (AWGN) at the n-th subcarrier and the b-th OFDM symbol duration with variance $\sigma_n^2/2$ per dimension. We assume that the channel is quasi-static and remains constant for B OFDM symbols $\mathbf{H}^b(n) = \mathbf{H}(n) \in \mathcal{C}^{M_t \times M_r}$. Therefore, the received signal during b-th OFDM symbol duration $\mathbf{Y}^b \in \mathcal{C}^{N_c \times M_r}$ can be given as

$$\mathbf{Y}^b = \sqrt{E_s}\mathbf{C}^b\mathbf{H} + \mathbf{Z}^b, \tag{28}$$

where

$$\mathbf{C}^b \triangleq \text{diag}\{\mathbf{c}^b(0), \mathbf{c}^b(1), \cdots, \mathbf{c}^b(N_c - 1)\}, \tag{29}$$

$$\mathbf{H} \triangleq [\mathbf{H}^T(0), \mathbf{H}^T(1), \cdots, \mathbf{H}(N_c - 1)]^T. \tag{30}$$

Using Alamouti code [11], the transmission codeword for $M_t = 2$ transmit antenna and $B = 2$ OFDM symbols can be expressed as

$$\mathbf{C}^1 = \text{diag}\big\{[s_1, s_2], \cdots, [s_{2N_c-1}, s_{2N_c}]\big\}, \tag{31}$$

$$\mathbf{C}^2 = \text{diag}\big\{[-s_2^*, s_1^*], \cdots, [-s_{2N_c}^*, s_{2N_c-1}^*]\big\}. \tag{32}$$

Now, let $\underline{\mathbf{y}}_j(n) \triangleq [y_j^1(n)\ y_j^2(n)]^T$ and be the signal received by j-th antenna during two consecutive OFDM symbols over the n-th subcarrier. Also, assume perfect channel information at the receiver. In this case, the Maximum-Likelihood (ML) decoding can be performed by solving the following minimization problem

$$\arg\min \sum_{j=1}^{M_r} |\underline{\mathbf{y}}_j(n) - \underline{\mathbf{c}}(n)\mathbf{H}_j(n)|^2, \tag{33}$$

where

$$\underline{\mathbf{c}}(n) = \begin{bmatrix} s_{2n+1} & s_{2n+2} \\ -s_{2n+2}^* & s_{2n+1}^* \end{bmatrix}, \tag{34}$$

is the transmitted codeword during two consecutive OFDM symbols over the n-th subcarrier and $\mathbf{H}_j(n)$ is the j-th column of channel matrix $\mathbf{H}(n)$.

V. Simulation Results

In order to compare the performance of RE-MIMO with MIMO-OFDM systems, the bit error rate (BER) is computed by Monte Carlo simulations, while the same throughput and transmission power are considered for both systems. For all simulations, BPSK modulation is applied and the maximum likelihood decoding with perfect channel state information at the receiver is implemented. Furthermore, a two-cluster channel model according to Eq.(1), is considered in which each cluster is composed of $M = 20$ unresolvable multi-paths. For RE-MIMO system, we consider two reconfigurable antenna elements at the transmitter which each element has two radiation pattern scan-steps and two omni-directional antennas at the receiver ($M_t = M_r = 2$,$P = 2$). We also perform simulations using the STS-BC given by Eq.(24). For MIMO-OFDM system, we consider two omni-directional antennas at the transmitter and two omni-directional antennas

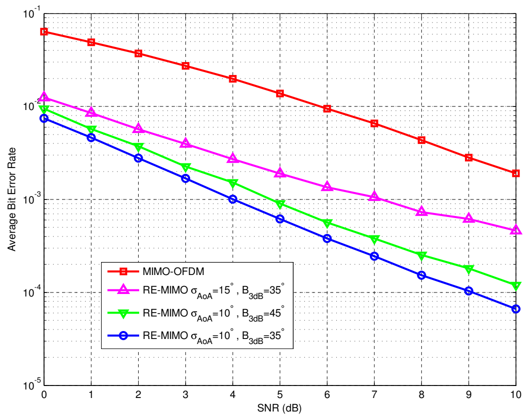

Fig. 3: Average BER vs. SNR for RE-MIMO and MIMO-OFDM systems with $M_t = 2$, $M_r = 2$, $L = 2$, and angular spread of $10°$.

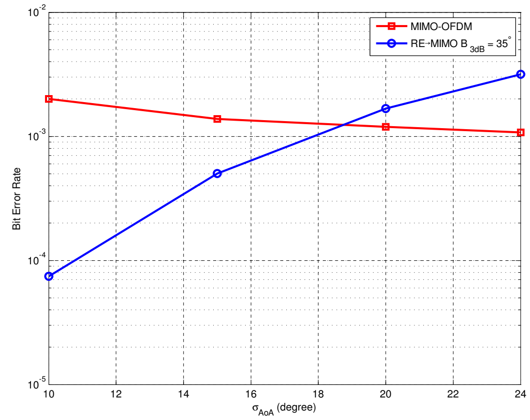

Fig. 4: Average BER vs. received angular spread for RE-MIMO and MIMO-OFDM systems with $M_t = 2$, $M_r = 2$, and $L = 2$ clusters.

at the receiver ($M_t = M_r = 2$) and $N_c = 64$ subcarriers. Moreover, we use alamouti coding scheme at the transmitter. For both RE-MIMO and MIMO-OFDM system, the inter-element spacing at the receiver and transmitter, is equal to $\lambda_c/2$, where $\lambda_c = c/f_c$ is the wavelength of the transmitted signal, f_c is the carrier frequency, and c is the light speed. The simulation parameters are listed in Table I.

Fig.3 shows the BER versus signal to noise ratio (SNR) for coded RE-MIMO and MIMO-OFDM system for various value of received angular spread (σ_{AoA}) and reconfigurable antenna beamwidth (B_{3dB}). From this figure, it can be observed that the diversity order is preserved in RE-MIMO system. Moreover, it is evident from the figure that for smaller angular spread at the receiver, the RE-MIMO systems perform extremely well, specially for narrower beamwidth, thanks to the power gain provided by directional reconfigurable antenna. However, for larger angular spread, the performance of the RE-MIMO system degrades due to much stronger contribution of undesired multipath components.

Fig.4 depicts the bit error rate performance of coded RE-MIMO and MIMO-OFDM systems with different received angle spread values. In this simulation, we set the reconfigurable antenna beamwidth at $B_{3dB} = 35°$ and SNR= 10 dB. From this figure, we observe that the BER performance of RE-MIMO system highly depends on the angular spread. When the angle spread is smaller than 18 degree, the RE-MIMO system outperforms the MIMO-OFDM system.

VI. Conclusion

In this paper, we evaluated the performance of the space-time-state block-coded RE-MIMO system in the spatially correlated frequency-selective fading channels. We also studied the impact of angular spread and antenna beamwidth on the performance of the system. Moreover, we compared the BER performance of the proposed system with that of MIMO-OFDM system. Simulation results show that as the angular spread decreases, the RE-MIMO system outperforms the MIMO-OFDM system. Furthermore, we observed the same conclusion for the antenna beamwidth, i.e., the performance of the RE-MIMO system improves, as the antenna beamwidth decreases.

Simulation parameters	
Carrier frequency (f_c)	3.484 GHz
Reconfigurable antenna Beamwidth (B_{3dB})	35 & 45°
Number of Tx and Rx antennas (N_t,N_r)	(2, 2)
Number of scan-steps (P)	2
Number of subcarriers (N_c)	64
Number of clusters (L)	2
Number of multipaths per cluster (M)	20
cluster delay (τ_1, τ_2)	$(0.46, 0.89)\ \mu s$
cluster power (P_1, P_2)	$(0.53, 0.47)$

TABLE I: Simulation parameters for the proposed RE-MIMO and MIMO-OFDM systems.

References

[1] G. Foschini and M. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," *Wireless Pers. Commun.*

[2] B. Cetiner, E. Akay, E. Sengul, and E. Ayanoglu, "A MIMO system with multifunctional reconfigurable antennas," *IEEE Antennas Wireless Propag. Lett.*, vol. 5, pp. 463–466, 2006.

[3] D. Piazza, N. Kirsch, A. Forenza, R. Heath, and K. Dandekar, "Design and evaluation of a reconfigurable antenna array for MIMO systems," *IEEE Trans. Antennas Propagat.*, vol. 56, pp. 869–881, Mar. 2008.

[4] J. Frigon, C. Caloz, and Y. Zhao, "Dynamic radiation pattern diversity (DRPD) MIMO using CRLH leaky-wave antennas," in *Proc. IEEE Radio and Wireless Symp.*, 2008, pp. 635–638.

[5] X. Li and J. Frigon, "Capacity analysis of MIMO systems with dynamic radiation pattern diversity," in *Proc. IEEE VTC Spring*, 2009, pp. 1–5.

[6] A. Grau, H. Jafarkhani, and F. De Flaviis, "A reconfigurable multiple-input multiple-output communication system," *IEEE Trans. on Wireless Commun.*, vol. 7, pp. 1719–1733, May 2008.

[7] F. Fazel, A. Grau, H. Jafarkhani, and F. Flaviis, "Space-time-state block coded MIMO communication systems using reconfigurable antennas," *IEEE Trans. on Wireless Commun.*, vol. 8, pp. 6019–6029, Dec. 2009.

[8] S. Lim, C. Caloz, and T. Itoh, "Metamaterial-based electronically controlled transmission-line structure as a novel leaky-wave antenna with tunable radiation angle and beamwidth," *IEEE Trans. Microw. Theory and Tech.*, vol. 52, pp. 2678–2690, Dec. 2004.

[9] 3GPP, "Spatial channel model for multiple input multiple output (MIMO) simulations," Tech. Rep., Sept. 2003.

[10] V. Vakilian, J. Frigon, and S. Roy, "Effects of angle-of-arrival estimation errors, angular spread and antenna beamwidth on the performance of reconfigurable siso systems," in *IEEE Pacific Rim Conf. on Commun., Computers and Signal Proc. (PacRim)*, 2011, pp. 515–519.

[11] S. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE J. Sel. Areas Commun.*, vol. 16, pp. 1451–1458, Oct. 1998.