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Time Reversal Receive Antenna Shift Keying On MIMO LOS Channel

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Abstract—Receive Antenna Shift Keying (RASK) is a Spatial Modulation (SM) transmission scheme that has recently been under study because of its low detection complexity and its ability to increase the spectral efficiency when combined with classical IQ modulation schemes. The idea is that the transmitter uses a focusing technique to target one of the receive antennas. The transmitted information is coded depending on the index of the receive antenna that have been targeted. Note that in this case, the sent signal does not contain any information, that’s why RASK can be combined with any classical IQ modulation. Different focusing techniques could be used to target a receive antenna. In this study, the Time Reversal preprocessing technique is used at the transmitter side. In this paper, theoretical performance of the Bit Error Rate and of the focusing gain are established for the RASK scheme in a MIMO Line-of-Sight configuration with two receive antennas. Also, a testbed is evaluated and used to provide RASK performance in realistic conditions.

Index Terms—Receive Antenna Shift Keying, MIMO, Spatial Modulation, Line of Sight, Time Reversal, Pre-coding, Focusing, Preprocessing

I. INTRODUCTION

Spatial Modulation (SM) has recently established itself as a promising transmission concept consisting in exploiting the index of transmit antennas to transmit additional information bits. In such techniques, location-dependent spatial information is utilized to carry additional information bits thereby boosting the overall spectral efficiency (SE) and overcoming inter-channel interference (ICI). MIMO systems employing SM, which are the so-called SM-MIMO systems, takes advantage of the whole antenna array at the transmitter, while using a limited number of RF chains [1]. The main distinguishing feature of SM-MIMOs is that they map additional information bits onto an “SM constellation diagram”, where each constellation element is constituted by either one or a subset of antenna elements [2].

One popular SM scheme at the transmitter side is Space Shift Keying (SSK) [3] whose main principle is to take advantage of the various propagation characteristics associated to the different antennas of the system [4]. Given a rich scattering environment, the receiver can utilize the distinct received signals from different antennas to discriminate between the transmitted information messages. In SM-MIMO systems, the single-stream transmission scheme is combined with the SSK scheme, which facilitates a simplified transmitter with a single RF front end. The signal processing at the receiver can also be simplified as data are transmitted through a single spatial stream in SM-MIMO systems [5].

Furthermore, a particular SM implementation case proposed in [6] and referred to as Transmitter Preprocessing Aided Spatial Modulation (TPSM), where the SM concept is applied at the receiver side, using Zero-Forcing preprocessing and joining conventional amplitude-phase modulation and preprocessing aided SSK (pre-SSK).

Another receiver SM scheme was proposed in [7] and [8] and referred to as receive antenna shift keying (RASK), where the transmitted signal carries no useful information at the level of the IQ mapping stage, and Time Reversal (TR) preprocessing is used to concentrate the signal energy towards a targeted antenna. TR enables to focus a signal in time and space, and requires a channel state information at the transmitter, and was considered suitable for Time Division Duplex (TDD) systems [9].

With RASK, a simple demodulation can be carried out based on the estimation of the index of RA that receives the maximum real part for a coherent detection, or the maximum power for incoherent detection. Since one single antenna is targeted at a time, the spectral efficiency is however limited to $\log_2 N_r$, with N_r the number of receive antennas (RAs).

In this paper, the RASK scheme with TR preprocessing technique in a MIMO Line of Sight (LOS) channel is considered, since in millimeter waves, the channel is considered as mainly LOS. The incoherent detector that compares the amount of received power on each RA is used at the receiver side, because of its simplicity, and because it doesn’t need any phase synchronization. Analytical performance of the Bit Error Rate (BER) was derived, a testbed was implemented to measure the performance in specific conditions of LOS channel, and numerical graphs are shown to evaluate the performance of the system.

The rest of the paper is organized as follows. In Section II, the system model and the block diagram of the RASK scheme are detailed. This is followed, in Section III, by analytic study of the BER performance using incoherent detection. Testbed and numerical results are provided in Section IV, and a conclusion is drawn in Section V.

II. SYSTEM MODEL FOR RASK

A. System Model

A MIMO system with N_t transmit antennas (TAs) and N_r RAs is considered. Assuming a deterministic MIMO LOS channel taking into account the free space propagation effect on the signal, $\mathbf{H} = (h_{j,i})_{1 \leq i \leq N_t, 1 \leq j \leq N_r}$ where $\mathbf{H} \in \mathbb{C}^{N_r \times N_t}$ and $h_{j,i}$ represents the complex channel coefficient between

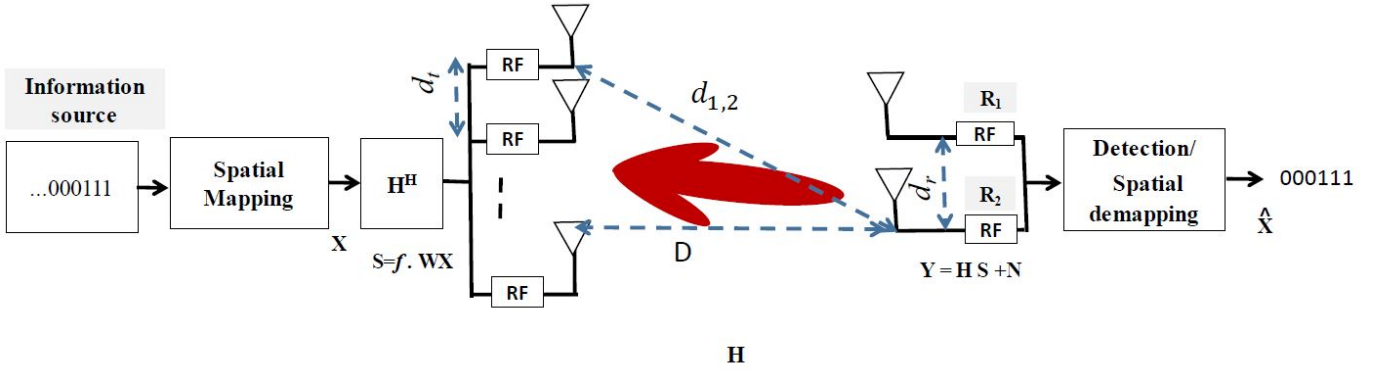


Figure 1. Block diagram of RASK

the i -th TA, denoted by Tx_i , and the j -th RA, denoted by Rx_j . Let:

$$\tilde{h}_{j,i} = \left(\frac{\lambda}{2\pi d_{i,j}} \right)^2 e^{j\theta} \quad (1)$$

with $\theta = 2\pi d_{i,j}/\lambda$, λ is the wavelength of the wave used, and $d_{i,j}$ the euclidean distance between Tx_i and Rx_j , be the complex non normalized channel coefficient. Let also:

$$\beta = \left(\frac{\lambda}{2\pi D} \right)^2 e^{j\theta_0} \quad (2)$$

where $\theta_0 = 2\pi D/\lambda$, and D the distance between the transmitter and the receiver, be the normalization factor. The normalized MIMO-LOS coefficients are then given by $h_{j,i} = \tilde{h}_{j,i}/\beta$. The received signal vector can be written as

$$\mathbf{Y} = \mathbf{H}\mathbf{S} + \mathbf{N} \quad (3)$$

$\mathbf{Y} \in \mathbb{C}^{N_r \times 1}$ is the vector of the received signals on all RAs, $\mathbf{S} \in \mathbb{C}^{N_t \times 1}$ is the vector of the transmitted signals by all emitting antennas, and $\mathbf{N} \in \mathbb{C}^{N_r \times 1}$ is the vector of additive white Gaussian noise (AWGN) samples η_j at the such that $\eta_j \sim \mathcal{N}(0, \sigma_n^2)$. An incoherent detection is used in this system, so the additive noise is assumed to be real, as well as the received signal.

B. Transmission Block Diagram

The block diagram of the RASK system is depicted in Figure 1. A group of $m = \log_2(N_r)$ bits is mapped to a spatial symbol $\mathbf{X}_k \in \mathbb{R}^{N_r \times 1}$ which is written as:

$$\mathbf{X}_k = \left[0 \quad \dots \quad \underbrace{x}_{k_{th}position} \quad \dots \quad 0 \right]^T \quad (4)$$

where k is the position of the targeted antenna. Then, the preprocessing block transforms the vector of spatial symbols \mathbf{X} into a vector of transmitted signals denoted as $\mathbf{S} \in \mathbb{C}^{N_t \times 1}$ using the preprocessing matrix $\mathbf{W} \in \mathbb{C}^{N_t \times N_r}$. In this paper, the Time-Reversal (TR) technique is employed, where the trans-conjugate of the channel matrix is used as a pre-filter:

$$\mathbf{W} = \mathbf{H}^H \quad (5)$$

Consequently, the transmitted signal is written as:

$$\mathbf{S} = f.\mathbf{W}\mathbf{X} \quad (6)$$

where $f = 1/\sqrt{\sigma_x^2 \text{Tr}(\mathbf{H}^H.\mathbf{H})}$ is a normalization factor used to guarantee that the average total transmit power \bar{P}_t is equal to 1, $\text{Tr}(\cdot)$ holds for the trace of matrix and \mathbb{E}_x stands for the expectation over x . Since \mathbf{X} has i.i.d. entries, the variance $\sigma_x^2 = \mathbb{E}_x [x_j x_j^*]$ is independent of j and comes in factor of the trace computation. Then, only one of N_r entry of \mathbf{X} is of amplitude $\sqrt{E_S}$ with a probability that can be easily verified to be of $\frac{1}{N_r}$, leading to $\sigma_x^2 = \frac{E_S}{N_r}$.

C. Received Signal

At the level of the RA Rx_j , the received signal then simply writes:

$$y_j = f \times \sum_{i=1}^{N_t} h_{j,i} h_{k,i}^* \times x + \eta_j. \quad (7)$$

and for $j = k$, we have:

$$\begin{aligned} y_k &= f \times \sum_{i=1}^{N_t} h_{k,i}^2 \times x + \eta_k \\ &\approx f \times N_t x + \eta_k \end{aligned} \quad (8)$$

Or, for the non targeted antennas, the received amplitude is the interference amplitude, which can be given after mathematical derivation by:

$$y_{j,j \neq k} \approx f \left(\frac{\sin(\pi N_t G)}{\sin(\pi G)} \right) x + \eta_j \quad \text{where } G = \frac{d_t d_r}{D\lambda} \quad (9)$$

Let $A_S = f.N_t$ and $A_I = f \left(\frac{\sin(\pi N_t G)}{\sin(\pi G)} \right)$, and define SIR the signal to interference ratio, which is the ratio of the useful received power on the targeted antenna and the interference received power on the non targeted antenna. We have:

$$SIR = \left(\frac{A_S}{A_I} \right)^2 = \left(\frac{\sin(\pi G) \times N_t}{\sin(\pi N_t G)} \right)^2 \quad (10)$$

III. ANALYTICAL STUDY

In this paper, a non coherent detector is used, where the index of the targeted antenna is estimated as:

$$\hat{k} = \underset{j}{\text{Arg max}} \|y_j\|^2 \quad (11)$$

$$\forall j \in [1; N_r], \|y_j\|^2 \leq \|y_{\hat{k}}\|^2$$

The BER of a two receive antenna RT-RASK scheme using the above receiver is given by:

$$\mathcal{P}_e = \frac{1}{2}(\mathcal{P}(\mathbf{X}_1 \rightarrow \mathbf{X}_2) + \mathcal{P}(\mathbf{X}_2 \rightarrow \mathbf{X}_1)) \quad (12)$$

where $\mathcal{P}(\mathbf{X}_i \rightarrow \mathbf{X}_j)$ is the probability to detect X_j such that X_i was transmitted. Let $\mathcal{X}_{i,j} = |y_j/X_i|$ which is the square root of the measured power at the j th RA such that the i th antenna was targeted.

$$\mathcal{P}_e = \frac{1}{2}(\mathcal{P}(\mathcal{X}_{1,1} < \mathcal{X}_{2,1}) + \mathcal{P}(\mathcal{X}_{2,2} < \mathcal{X}_{1,2})) \quad (13)$$

Since

$$\begin{aligned} \mathcal{X}_{1,1} \text{ and } \mathcal{X}_{2,2} &\sim |\mathcal{N}(A_S, \sigma_n^2)| \\ \mathcal{X}_{1,2} \text{ and } \mathcal{X}_{2,1} &\sim |\mathcal{N}(A_I, \sigma_n^2)| \end{aligned} \quad (14)$$

we have:

$$\begin{aligned} \mathcal{P}_e &= \mathcal{P}(|\mathcal{N}(A_S, \sigma_n^2)| < |\mathcal{N}(A_I, \sigma_n^2)|) \\ &= \int_{-\infty}^{+\infty} f_{\mathcal{X}_{1,1}}(x) \cdot (1 - F_{\mathcal{X}_{2,1}}(x)) dx \end{aligned} \quad (15)$$

where:

$$f_{\mathcal{X}_{1,1}}(x) = \frac{1}{\sqrt{2\pi\sigma_b^2}} \left(e^{-\frac{(x-A_S)^2}{2\sigma_b^2}} + e^{-\frac{(x+A_S)^2}{2\sigma_b^2}} \right) \quad (16)$$

is the probability density function of $\mathcal{X}_{1,1}$, and

$$F_{\mathcal{X}_{2,1}}(x) = \frac{1}{2} \left[\text{erf} \left(\frac{x+A_I}{\sqrt{2}\sigma_b} \right) + \text{erf} \left(\frac{x-A_I}{\sqrt{2}\sigma_b} \right) \right] \quad (17)$$

is the cumulative density function of $\mathcal{X}_{1,1}$. After some mathematical derivation, the equation 15 becomes:

$$\mathcal{P}_e = \frac{1}{2} \left[\text{erfc} \left(\frac{A_S + A_I}{\sqrt{2}\sigma_b} \right) + \text{erfc} \left(\frac{A_S - A_I}{\sqrt{2}\sigma_b} \right) \right] \quad (18)$$

IV. NUMERICAL AND EXPERIMENTAL RESULTS

A. Numerical results

The performance of the RT-RASK system on MIMO LOS channel is evaluated through the measurement of the BER versus the ratio between the average transmit power level and noise level, i.e. $\frac{\bar{P}_t}{\sigma_n^2}$ and for different number of TAs. The power for each sub-channel is normalized:

$$E[\|H_{j,i}\|^2] = 1$$

Finally, we consider that the channel response is perfectly known at the transmitter. Simulations are run by implementing a sufficient number of iterations for different channel realizations, and taking the mean value of the BER for each value of $\frac{\bar{P}_t}{\sigma_n^2}$.

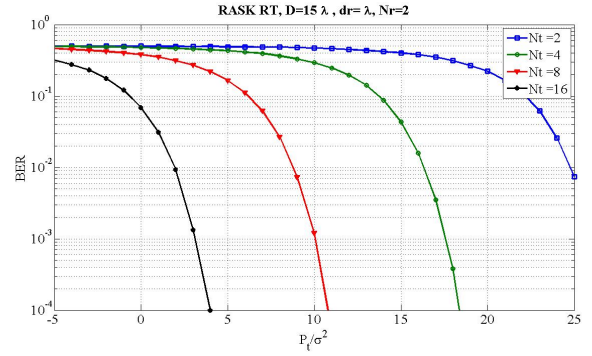


Figure 2. BER numerical result of a MIMO LOS TR-RASK transmission system, for $d_r = \lambda$, $d_t = \lambda/2$ and $D = 15\lambda$

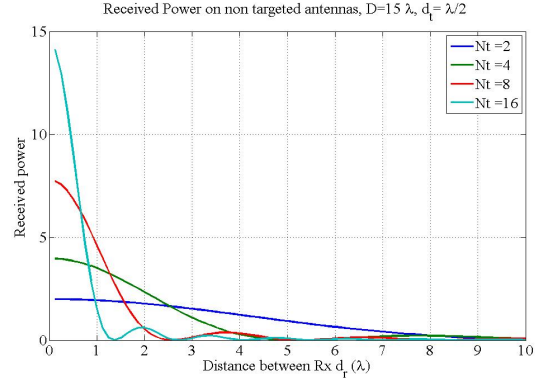


Figure 3. Received power on the non targeted antenna in terms of the distance between RAs

A MIMO RT-RASK with with $N_r = 2$ and $N_t = 2, 4, 8$ and 16 antennas is considered. The channel is assumed to be LOS, with no fading, and with $D = 15\lambda$, $d_t = \lambda/2$ and $d_r = \lambda$. In Figure 2, the incoherent maximum power detector is used, and the performance based on the analytic study is evaluated. As evident from the obtained curves, increasing the number of the transmit antennas leads to improvement of the performance, because of the increasing in the focusing gain.

In Figure 3, we measured the received power on the non targeted antenna while targeting the other one, for different distance d_r between the two antennas. It is shown that the form of the beam change in the distance having local maximum and minimum, and that increasing the number of transmit antennas leads to more directive beam, which explain the improvement of the performance in the Figure 2. Note that because of the normalization of the transmission channel, the amplitude of the interference for $N_t = 16$ is higher than the others near the targeted antenna, but also the received amplitude at the targeted antenna is also the highest, and the beam is more directive.

B. Experimental Results

A RASK TDD MIMO transmission system between a transmitter featuring $N_t = 4$ antennas and a receiver with

	Theoretical Result	Testbed Result
<i>SIR -Targeting Rx1</i>	0.0343 [dB]	0.0380 [dB]
<i>SIR -Targeting Rx2</i>	0.0343 [dB]	0.6811 [dB]
<i>BER</i>	0.2028	0.2549

Table I

TESTBED AND THEORETICAL SIR AND BER RESULTS OF A 4X2 MIMO LOS CHANNEL WITH $\nu = 2.4$ GHz, $D = 15\lambda$, $d_r = \lambda/4$ AND $d_t = \lambda/2$.

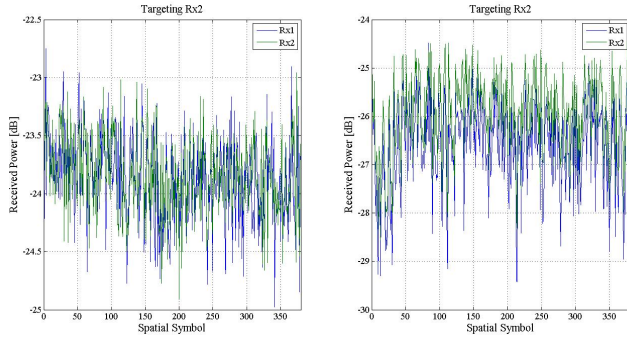


Figure 4. Received power on each antenna targeting Rx1 (Left) and Rx2 (right)

$N_r = 2$ antennas is considered. The system is implemented using two FPGA-based motherboards (WARP v3), with additional radio board (FMC-RF-2X45) and clock board (CM-MMCX) for each, configured with the WARPLab Reference Design, as described in [10]. A 125 kbps RASK transmission at $\nu = 2.4$ GHz is considered in MIMO LOS configuration with $D = 15\lambda$, $d_r = \lambda/4$ and $d_t = \lambda/2$. A Time Reversal preprocessing technique is used to target the RA. Figure 4 shows the detected power at the two RAs, the blue color for Rx_1 and the green for Rx_2 , when targeting Rx_1 (left figure), and Rx_2 (right figure). Table I shows the measurement results and their associated theoretical results for the considered environment. A BER equal to 0.2549 is obtained with the testbed, which is closed to the BER obtained with theoretical approach equal to 0.2028. Moreover, for the SIR measurement, it is shown that theoretically, a same SIR on the two RAs equal to 0,0343 dB is resulted, because of the geometry of the system. But with testbed measurement, we calculate the mean of the received power on each antenna during the transmission. Rx_1 gives a result equal to 0.0380 dB that is close to the theoretical one, while Rx_2 provides a higher SIR equal to 0.6811 dB, and that is caused by some reflections in the environment that will improve the focusing toward this RA.

V. CONCLUSION

In this paper, we evaluated the performance of a Receive Antenna Shift Keying using the Time Reversal preprocessing technique at the transmitter, and a simple incoherent power detection at the receiver, over a deterministic MIMO Line of Sight transmission channel, and for two receive antennas. We derive an analytic Bit Error Rate performance of the system, and we calculate the amount of interference on the

non targeted antenna. Numerical result have been provided for different number of transmit antennas. We demonstrate that increasing the number of transmit antennas leads to better focusing of the power over targeted antenna, and so to a better performance. Moreover, a real testbed is evaluated and used to measure the performance of the technique on the specified conditions, confirming the theoretical results.

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