Efficient time reversal strategy for MISO-OFDM systems

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Article Info	ABSTRACT
	In this work, we are interested in implementing, developing, and evaluating a time reversal strategy for a multiple-input single-output orthogonal frequency division multiplexing system. This strategy enjoys a good trade-off between the computational complexity and performance in terms of bit error rate where it offers a good coding gain by forming a beam in the direction of the destination at a price of channel state information available at the transmitter. In time reversal technique, a higher coding and diversity gain can be achieved by increasing the number of transmitting antennas, which focuses the formed beam to the direction of the destination antenna. By achieving this, the received signal-to-noise ratio can be maximized which makes time reversal a good candidate for multiple-input single-output systems while keeping a low complexity. The performance of the proposed system is evaluated in terms of bit error rate where our simulations show that the proposed strategy enjoys the full diversity gain, which is equal to the number of transmitting antennas. Moreover, a robust channel estimation technique is proposed to improve the overall system in terms of bit error rate.

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1. INTRODUCTION

Wireless communications have become in recent years a real phenomenon and more competitive every day. It has captured the public's imagination and the attention of media. The advance in wireless technology is affecting our daily life. Radio systems, wireless local area network, and many other systems have experienced exponential growth over the last decade and have replaced most of the wired networks. These technologies offer the mobility for the user who can access to any wide range of information from any place at any time. These new systems have enhanced the capacity, the rate and the performance [1-9]. With this success and growth, comes great demand for people with skills and knowledge to support all aspects of wireless network disposition. In the other hand, the systems complexity increases. The most competing thing is to enhance these systems in order to increase their performances and to make reliable communications, but also to decrease their complexity and their costs [10-15]. As it is known, communications in channel fading nature may demand channel estimation at the transmitter or at the receiver according to the used technology. There are many methods that have been proposed to enhance the communication systems and decrease their complexity [16-23]. One of these methods is the time reversal (TR) technique. Time Reversal is gaining the importance due to its potential to simplify the receiver's complexity and shifts it to the transmitter. For instance, in a downlink transmission, during the communication between the base station and mobile user, the scheduler that exists at the base station can minimize the mobile user complexity by using time reversal technique [24-28]. Multiple-input multiple-

output (MIMO) systems have proven the ability to improve the performance of wireless communication systems [1-3]. MIMO system has been adopted by current communication systems such LTE-A and 5G in order to enhance the data rate and the performance. However, deploying MIMO systems with N_t transmit antennas and N_r receive antennas require channel state information (CSI) at the transmitter in order to get a better performance. Thus, for $N_r \times N_t$ MIMO system, the transmitter has to perform the CSI estimation for the $N_r \times N_t$ links [9-11].

Time Reversal is a technique to compress temporally and focus spatially signals through richly scattering environment. It involves two stages: i.) The first stage is the "channel estimation" where an intended receiver emits a pilot signal, in which its response is recorded by each element array of the transmitter, ii.) The second stage is the "data transmission", where the same data is transmitted by each element. Each element filters the transmitted signal by a time reversal filter that has the form of the recorded signal but reversed in time (last in first out). In this work, we are studying a time reversal strategy for multiple-input single-output orthogonal frequency division multiplexing (MISO-OFDM) system, which enjoys a good trade-off between bit erro rate (BER) performance and the overall system complexity where it provides a good beamforming gain by forming a beam in the direction of the destination at a cost of CSI available at the transmitter side. In TR strategy, a higher coding and diversity gain can be achieved by increasing the transmitting antennas which can focus the formed beam to the direction of the destination antenna. By achieving the former, the received signal-to-noise ratio can be maximized which makes TR a good strategy for MISO systems while keeping a low complexity.

2.   PROPOSED METHOD

High data rate and strong reliability are becoming the dominant factors for a successful exploitation of the communication systems. There are many systems that can achieve these requirements, but with different complexities and costs. One of these systems is MISO-OFDM TR system. MISO-OFDM TR is a promising combination due to its capability of high data transmission, simplicity (simple equalizer) at the receiver and its robustness against multipath transmission. In this section, we are going to explain the proposed method that will be applied to OFDM systems.

2.1. System model

We describe the operation of TR system with M transmit antennas and one receiver, (MISO system). We denote $h_m(t)$ as the channel impulse response between the mth transmit antenna and the intended receiver as shown in Figure 1. Before starting analysis, there are some assumptions given below that must be taken into consideration:
a) The environment is static between the sounding step and the data transmission step
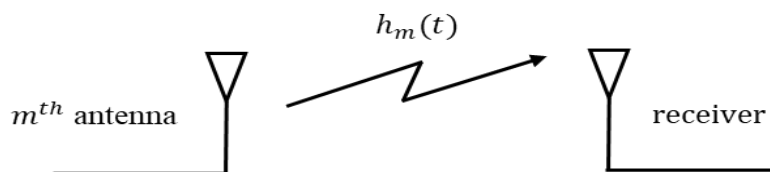b) The channel is perfectly estimated at the transmitting array

Figure 1. Channel impulse response

2.2. OFDM with TR technique

OFDM system with TR technique is presented in this section. Figure 2 shows the block diagram of OFDM TR system where S/P, IFFT and P/S respresent the serial to parallel, inverse fast fourier transform and parallel to serial, respectively. $h^*(-t)$ denotes the TR filter applied in the time domain. Moreover, an equalizer is needed for the case of multilevel modulation.
The channel model of this system in time domain is given as follows:

$$H(t) = h^*(-t) \otimes h(t) \tag{1}$$

The channel model in frequency domain is given:
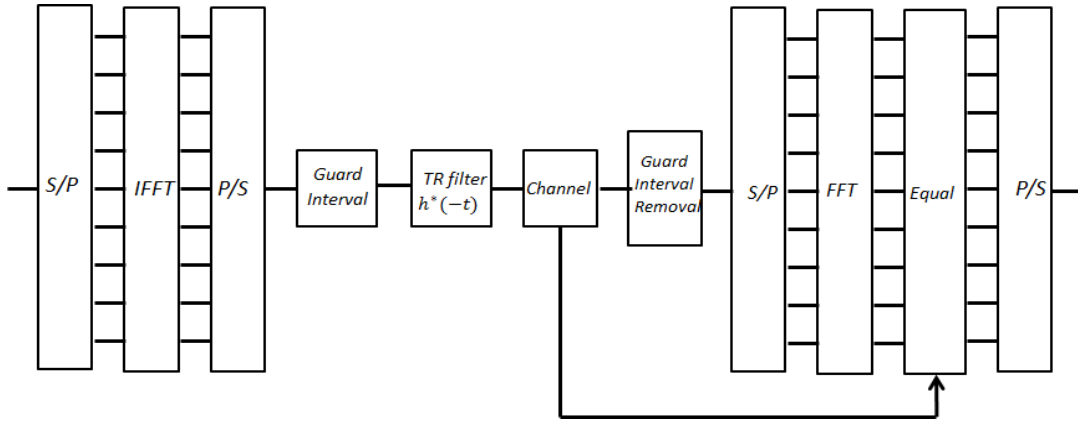
$$H(f) = |h(f)|^2 \tag{2}$$

Figure 2. OFDM TR block diagram

Since $H(f)$ is real, the equalizer at the receiver can be eliminated for one level modulation. $H(t)$ is twice the channel size without TR technique due to the convolutional operation. Thus, the elimination of inter-symbol interference (ISI) can be done by two ways, either by doubling the cyclic prefix (CP) or by adding cyclic suffix (CS) and prefix. CS and CP must be sufficiently greater than the channel size in order to avoid ISI. Figure 3 shows an OFDM symbol with TR technique in time domain, where the cyclic prefix is doubled. Instead of doubling the CP, adding cyclic prefix and suffix to OFDM TR symbol is investigated. An OFDM symbol with CP and CS is depicted in Figure 4. The linear convolution presented in (1) can be turned to circular one. Thus, TR technique is applied to OFDM system in order to have a spatial focusing and to decrease the complexity of the system.
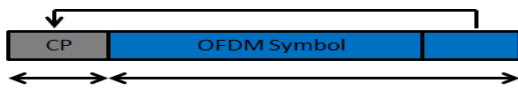

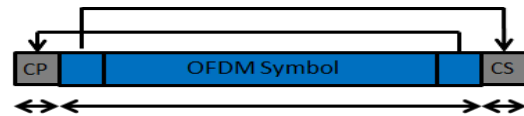
Figure 3. Double cyclic prefix OFDM TR symbol

Figure 4. Cyclic prefix + suffix OFDM TR symbol

3. RESEARCH METHOD

The major challenge in TR technique is to estimate the channel accurately. In this section, we will explain the suggested method to estimate the channel and data transmission of OFDM-TR systems.

3.1. Channel estimation

Channel estimation is carried out by transmitting known pilots by the intended receiver to the transmitter side that applies the TR filter after estimating the channel. Therefore, in the first stage of MISO-TR system, channel estimation is done by a feedback of CSI from the intended receiver where the receiver sends a pilot signal $p(t)$ to the transmitter array. $p(t)$ can be a Dirac signal $\delta(t)$ or $\varphi(t)e^{i2\pi f_0 t}$, where $\varphi(t)$ is a band limited low pass signal assuming that its power is normalized to one [22]. At the transmitter side, a recorded signal $b_m(t)$ is received by the mth antenna, where $b_m(t)$ is given as follows:

$$b_m(t) = p(t) \otimes h_m(t) \tag{3}$$

where $\otimes$ denotes the convolutional operation and $h(t)$ represents the channel impulse response between the mth antenna and the receiver. Representing $b_m(t)$ in frequency domain is given as follows:

$$B_m(f) = H_m(f)\, P(f) \tag{4}$$

where $H_m(f)$ and $P(f)$ denote the Fourier transform of $h_m(t)$ and $p(t)$, respectively. If $p(t) = \delta(t)$, then $B_m(f) = H_m(f)$. When the intended receiver sends the pilot signal to the transmitter array, the transmitter acquires the channel estimation. The next sections describe a simple and efficient channel estimation method for single input single output (SISO) and MISO-OFDM TR system by applying zero forcing (ZF) estimator.

Channel estimation for SISO-OFDM and MISO-OFDM TR systems based on pilot symbols using ZF estimator are investigated over a Rayleigh channel, where a comparison between these systems is done. Theoretical results are compared to simulation ones in order to validate our work.

3.1.1. SISO-OFDM TR channel estimation

Channel estimation is started by sending pilot symbols, drawn from binary phase shift keying (BPSK) in our case, from the intended receiver to the transmitter. The transmitter estimates the channel ($\hat{h}$) as follows:

$$\hat{h} = h + \frac{n}{N} \tag{5}$$

where h is the channel impulse response between the transmitter and the receiver, N is the number of pilot symbols and n is the white Gaussian noise. The received signal is given by:

$$y = \hat{h}^* h x + n' \tag{6}$$

Thus,

$$y = \left(h + \frac{n}{N}\right)^* h x + n' \tag{7}$$

where x is the transmitted symbol, n and n' are white Gaussian noise and y is the received signal. Then the received signal can be written as follows:

$$y = |h|^2 x + \frac{n^*}{N} h x + n \tag{8}$$

where $|h|^2 x$ is the useful part of the signal and $(\frac{n^*}{N} h x + n')$ is considered as a noise. The output signal to noise ratio (SNR_{output}) is expressed as:

$$SNR_{output} = \frac{|h|^4 P_x}{P_{n'} + \frac{P_{n^*}|h|^2 P_x}{N}} \tag{9}$$

For the same noise power and for $P_x = 1$, SNR_{output} can be written:

$$SNR_{output} = SNR_{input} \frac{|h|^4}{1 + \frac{|h|^2}{N}} \tag{10}$$

For perfect estimation:

$$SNR_{output} = SNR_{input} \, |h|^4 \tag{11}$$

where the input signal to noise ratio $SNR_{input} = \frac{P_x}{P_n} = \frac{1}{P_n} = \frac{1}{\sigma^2}$ and σ^2 is the noise variance. The theoretical BER (BER_{theo}) of this system is calculated numerically according to the following (12):

$$BER_{theo} = \int_0^\infty pdf(x) \frac{1}{2} \text{erf}\left(\sqrt{\frac{E_b x}{N_0}}\right) dx \tag{12}$$

where E_b is the bit energy, N_0 is the spectral noise density, $\frac{E_b}{N_0}$ denotes the average energy per bit (E_b) relative to the spectral noise density (N_0).

3.1.2. MISO-OFDM TR channel estimation

In this part, the channel estimation for MISO-OFDM system with the presence of TR technique is investigated. We studied the effect of ZF estimator to this system analytically. Starting by the calculation of the output SNR as a function of the input SNR. Let h_i be the channel impulse response between the *i-th* transmit antenna and the receiver for a considered subcarrier. Thus, the estimated $\hat{h}$ can be written as:

$$\hat{h} = \left(\sum_{k=1}^{N_T} h + \frac{n}{\sqrt{P_p}}\right)\frac{1}{N} \tag{13}$$

where N and P_p are the number and the power of pilots, respectively. N_T is the number of antennas at the transmitter and n is a white Gaussian noise. The received signal at the intended receiver is:

$$y = \frac{1}{\sqrt{N_T}}\left(\sum_{k=1}^{N_T} \hat{h}_k^* h_k x + n'\right) \tag{14}$$

Thus SNR_{output} expressed in terms of SNR_{input} as follows

$$SNR_{output} = SNR_{input} \frac{\sum_{k=1}^{N_T}|h_k|^4}{N_T + \frac{\sum_{k=1}^{N_T}|h_k|^2}{NP_p}} \tag{15}$$

For 2x1 MISO-OFDM TR system with $N_T = 2$, the output SNR is:

$$SNR_{output} = SNR_{input} \frac{|h_1|^4 + |h_2|^4}{2 + \frac{|h_1|^2 + |h_2|^2}{NP_p}} \tag{16}$$

where h_1 and h_2 are the channel impulse responses between the first and the second antenna and the intended receiver, respectively.

The performance of 8x1 MISO-TR has been studied in this work. The following (17)shows the output SNR as a function of the input SNR:

$$SNR_{output} = SNR_{input} \frac{\sum_{i=1}^{8}|h_i|^4}{8 + \frac{\sum_{i=1}^{8}|h_i|^2}{NP_p}} \tag{17}$$

where h_i is the channel impulse response between the *i-th* antenna and the intended receiver.

3.2. Data transmission

The 2nd stage in MISO TR is the data transmission. Let $x(t)$ be the signal to be transmitted. In this stage, the same data is transmitted simultaneously to the intended receiver by each antenna by filtering $x(t)$ through the time reversal filter as shown in Figure 5.
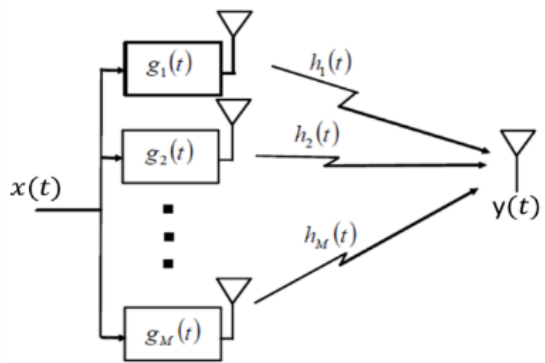

Figure 5. Data transmission for MISO TR System

where $g_m(t)$ denotes the time reversal filter between the mth transmit antenna and the intended receiver that is estimated from the CSI. $g_m(t)$ is given as follows:

$$g_m(t) = A_m h^*{}_m(-t) \tag{18}$$

Applying one-bit TR leads to a simplified form of the time reversal filter $g_m(t)$ [23]:

$$g_m(t) = sgn\{Re(h_m^*(-t)\} - j\, sgn\{Im(h_m^*(-t)\} \tag{19}$$

where A_m denotes the scaling factors that describe different power allocation situations. One-bit TR filters preserve only the sign of the real and imaginary part of the channel impulse response. The advantages of this filter is that it is simpler to implement, less sensitive to channel estimation and the transmit power is strictly controlled. The signal received by the user is given below [24], where we consider that the pilot signal is $p(t) = \delta(t)$ (Dirac signal).

$$y(t) = \left(\sum_{m=1}^M h_m(t) \otimes g_m(t)\right) \otimes x(t) + n(t) \tag{20}$$

The first term is the useful signal, while the second term is the receiver noise, which is considered as a white Gaussian noise. The equivalent channel impulse response of the system $h_{eq}(t)$ is the sum of the autocorrelation of the channel impulse responses $h_m(t)$ that is given by:

$$h_{eq}(t) = \sum_{m=1}^M h_m(t) \otimes g_m(t) = \sum_{m=1}^M A_m R_{h_m h_m}(t) \tag{21}$$

where $R_{h_m h_m}(t)$ is the autocorrelation of the impulse responses $h_m(t)$. As shown in (22) represents $h_{eq}(t)$ in the frequency.

$$H_{eq}(f) = \sum_{m=1}^M A_m |H_m(f)|^2 \tag{22}$$

Our assumption is that TR transmission filter introduces a unity gain. As a result, the transmitted power depends only on the power of the transmitted signal $x(t)$. We introduce two situations that correspond to different power allocations:

a)   Simple time reversal: The factors A_m normalize the total filter gain as follows:

$$A_m^{simple\ TR} = \frac{1}{\sqrt{\sum_{m=1}^M \|h_m\|^2}} \tag{23}$$

b)   Equal power allocation: This scheme has a simple complexity since the scaling factors are individually fitted at each transmitter without the knowledge of other channel impulse responses. The factors A_m are given as follows:

$$A_m^{equal\ power} = \frac{1}{\sqrt{M\|h_m\|^2}} \tag{24}$$

4.   RESULTS AND ANALYSIS

The performance of the SISO-OFDM system with TR technique is given in Figure 6. This figure shows the BER as a function of SNR-per-bit ($\frac{E_b}{N_0}$) for SISO-OFDM TR system. The simulation results match perfectly the theoretical ones. For low $\frac{E_b}{N_0}$, there is a loss of 2.5 dB (max. loss) between the prefect estimation and 1-pilot ZF estimator. This loss is decreased to be negligible at high $\frac{E_b}{N_0}$ (25 dB). The loss can be decreased to 1.5 dB by increasing the pilot symbols to two. Furthermore, ZF is considered as a simple estimator in terms of complexity. The loss of spectral efficiency was decreased enormously since the number of used pilots is relatively small. Figure 7 shows the BER vs. $\frac{E_b}{N_0}$ for 2x1 MISO-OFDM TR system. A gain of 13 dB is achieved by passing from SISO system to MISO one. With respect to ZF estimator, for low $\frac{E_b}{N_0}$, the loss between perfect estimation and 1-pilot ZF estimator is 2.5 dB. For high $\frac{E_b}{N_0}$, this loss is decreased to be negligible. The loss can be decreased to 1 dB and to 0.7 dB, by increasing the number of pilots to 2 and 4, respectively. These results were compared to theoretical ones that match perfectly.

Figure 8 shows the performance the BER versus $\frac{E_b}{N_0}$ for 8x1 MISO-OFDN TR system. A ZF estimator has been adopted for one, two and four pilots. For one pilot estimator, there is a loss of 2.5 dB compared to the perfect estimator. This loss can be decreased to 0.7 dB by using four pilots estimator. However, a gain in terms of complexity is achieved. Once again our simulation results match the theoretical ones with a slight difference (0.06 dB) due to simulation precisions.

In this section, the results of research are explained and at the same time is given the comprehensive discussion. We apply TR technique to SISO and MISO OFDM systems with perfect channel knowledge at the transmitter. The transmitted symbols are experienced a Rayleigh fading channel. In these simulations, the guard interval is sufficiently greater than the channel length in order to have an ideal OFDM TR system. Moreover, the modulation type used in this simulation is 4-QAM. Note that, with TR technique there is no need for equalizer to be used at the receiver while a zero forcing equalizer should be used for 4-QAM without TR technique since the channel is a complex one. Thus, a compromise between the performance and the complexity must be taken into account. Figure 9 shows the BER versus $\frac{E_b}{N_0}$ for 4-QAM OFDM of SISO-OFDM-TR, 2x1 MISO-OFDM-TR, 3x1 MISO-OFDM-TR, 4x1 MISO-OFDM-TR and 8x1 MISO-OFDM-TR over Rayleigh fading channel. In these simulations, the channel is perfectly estimated at the transmitter.

While the number of antennas increased, the performance is also increased, which is expected. For BER of 10^{-2}, a 13 dB is needed for 2x1 MISO-TR, while more than 25 dB is needed to achieve the same performance for SISO-TR. Thus, a gain of more than 12 dB is achieved. For BER of 10^{-2}, a 7 dB is needed for 3x1 MISO-TR. A gain of 6 dB is achieved by passing from 2x1 MISO to 3x1 MISO. Furthermore, at the same performance, a 7 dB is needed for 4x1 MISO, thus a gain of 3 dB between 3x1 MISO and 4x1 MISO is achieved. A gain of 6 dB is achieved between 8x1 MISO and 4x1 MISO systems. While the number of antennas increases, the performance also increases but in a less rate.
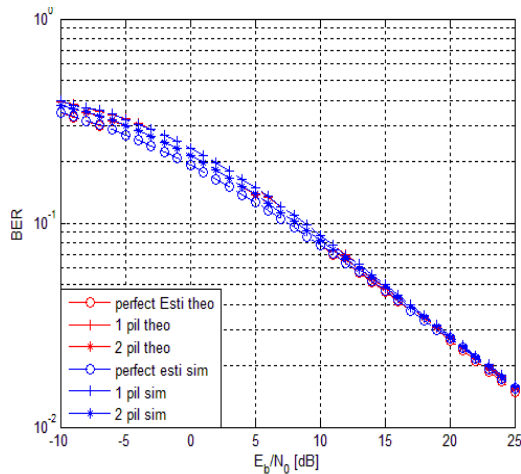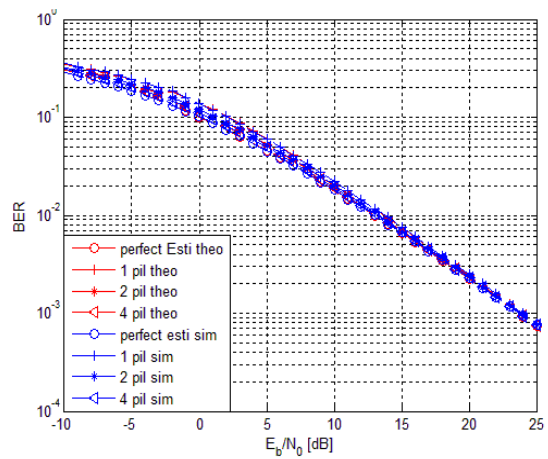

Figure 6. Performance of SISO-OFDM TR
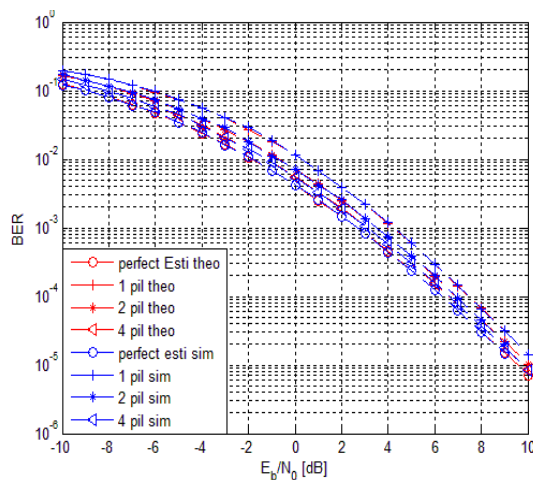

Figure 7. Performance of 2x1 MISO-OFDM TR

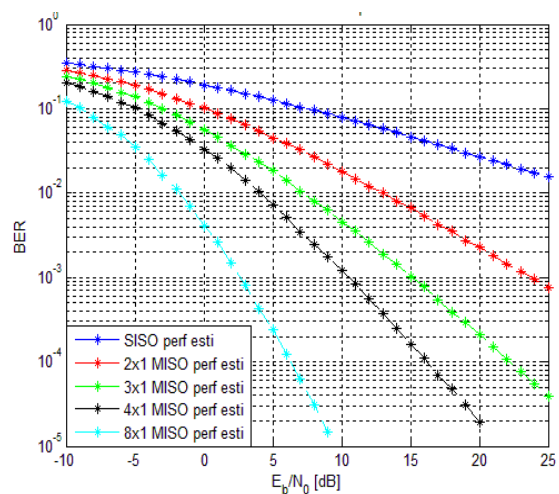Figure 8. Performance of 8x1 MISO-OFDM TR

Figure 9. Comparison between SISO and MISO TR OFDM System

5. CONCLUSION

In this paper, a TR strategy for a MISO-OFDM system, which enjoys a good trade-off between BER performance and the overall system complexity has been studied. This strategy offers a good coding gain and full diversity gain by forming a beam in the direction of the intended receiver at a cost of CSI available at the transmitter side. In this strategy, a higher coding and diversity gain can be achieved by adding more transmitting antennas in order to focus the formed beam to the direction of the destination antenna. By doing this, the received SNR can be maximized which makes TR a good strategy for large MISO systems while keeping a low complexity.

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BIOGRAPHY OF AUTHORS

Issam Maaz joined American University of the Middle East as an assistant professor of electrical and computer engineering in 2017. He received his PhD degree in electronics and communication engineering with great honor from Telecom ParisTech, Paris, France, in 2015. During the last few years, he has worked as an assistant professor, and research engineer in several companies such as Orange France and worked on several European projects such as SHARING CelticPlus. The main idea of his research is to develop new channel modeling and channel estimation for heterogeneous networks, small cells, MIMO systems, Radio Environmental Maps (REM), etc, that can be used for the new generations of communication systems such as 5G and beyond.

Samer Alabed is an associate professor of electrical engineering at the college of engineering and technology in the American University of the Middle East, Kuwait. He worked also in the communication systems group at Darmstadt University of Technology, Darmstadt, Germany from 2008 to 2015. He received his PhD degree in electrical engineering and information technology, from Darmstadt University of Technology, Darmstadt, Germany. During the last 16 years, he has worked as an associate professor, assistant professor, (post-doctoral) researcher, and lecturer in several universities in Germany and Middle East and supervised tens of master students and several PhD students. He received several awards from IEE, IEEE, DAAD ... etc., such as the best paper award from the International IEEE WSA in March, 2015 and was invited to many conferences and workshops in Europe, US, and North Africa. The main idea of his research is to develop advanced DSP algorithms in the area of wireless communications including (Massive) MIMO systems, distributed systems, co-operative communications, relay networks, space-time block and trellis coding, differential and blind techniques, channel coding, two-way relaying, baseband communications, multi-carrier transmission, modeling of channel characteristics, adaptive beamforming, sensor array processing, transceiver design, multi-user and multi-carrier systems, convex optimization, channel equalization, and other kinds of distortion and interference mitigation. Further information are available on his homepage: http://drsameralabed.wixsite.com/samer