Al-Nahrain Journal for Engineering Sciences **NJES** 22(2)81-87, 2019
http://doi.org/10.29194/NJES.22020081

The Usage of Time Reverse Technology to Improve the BER Performance and Transmission Rate of IR-UWB System

Mohammad Alkhadour[1], Mazen Youssef[2*]

Authors affiliations:

1*) Faculty of Mechanical and Electrical Engineering, Electronics and Communication Department, Albaath University, Homs, Syria.
mohammad.alkhadour@gmail.com

2) Faculty of Mechanical and Electrical Engineering, Electronics and Communication Department, Albaath University, Homs, Syria.
mazyoussef74@gmail.com

Paper History:

Received: 15th Feb. 2019

Revised: 5th Mar. 2019

Accepted: 30th Apr. 2019

Abstract

Ultra-Wideband (UWB) technology has so many striking characteristics which includes low sensitivity to fading, superior performance, low interference, easy to penetrate in walls as well as in floor. The main motive of this work is to analyze the capability of UWB technology as various aspects and improve its performance, since the main drawback of this system is that the power spectral density of the transmitted signal is rather limited. The MIMO technology may provide a solution by increasing the received SNR for the same transmission power, but the problem in this case is the spatial correlation resulted. To solve the problem two technologies are integrated along with the UWB using Time Reverse (TR) by TR-MIMO and TR-SIMO. Among these integrations, the robust performance of the UWB is analyzed by comparing the transmission rates for a given outage probability. In the last step, the (SIMO/MIMO)-UWB and TR-(SIMO/MIMO)-UWB were compared in terms of BER values to create the way of applying the UWB in so many applications.

Keywords: Ultra-Wideband (UWB) Technology, Time-Reversal (TR), Spatial Correlation, Outage Probability.

استخدام تقنية الزمن المعكوس في تحسين أداء معدّل خطأ البت ومعدّل الإرسال للنظام فائق عرض الحزمة مُعتِمد على النبضات الراديوية

محمد عدنان الخضور ، مازن محمد يوسف

الخلاصة:

يمتاز النظام فائق عرض الحزمة (UWB) بالكثير من الخصائص اللافتة والتي تتضمن حساسيته المُنخفضة للخفوت، أداءه الفائق، التداخل المُنخفض وسهولة نفاذ إشاراته عبر الجدران والأرضيات. الدافع الرئيسي لإنجاز هذا البحث يتمثّل بتحليل أداء نظام (UWB) وذلك لتحديد قدراته في جوانب عدّة. العيب الأساسي في هذا النظام هو أن الكثافة الطيفيّة لاستطاعة الإرسال محدودة نسبياً، تقنية المداخل والمخارج المُتعدّدة (MIMO) قد توفّر حلاً لهذه المُشكلة عبر قدرتها على زيادة نسبة الإشارة إلى الضجيج (SNR) المُستقبلة من أجل نفس استطاعة الإرسال، ولكن المُشكلة في هذه الحالة تتمثّل بالارتباط الفراغي الناتج، وكحل لهذه المُشكلة تم دمج تقنيتين مع (UWB) بالاعتماد على تقنية الزمن المعكوس (TR) وهما (TR-MIMO) و(TR-SIMO)، وقد تم تحليل أداء معدّل بيانات هذه الأنظمة الناتجة عند احتماليات انقطاع معطاة. في الخطوة الأخيرة من البحث، تمت مقارنة أداء (BER) لأنظمة (SIMO/MIMO)-UWB و (TR-SIMO/TR-MIMO)-UWB بهدف تحديد المنهجية المُثلى لاستخدام UWB في العديد من التطبيقات.

1. Introduction

In Communication systems, Ultra-Wideband (UWB) technology has various kinds of applications in recent years [1]. The rising demand of UWB technology lead researchers to develop innovative techniques [2]. Also, UWB technology has an epitome high rate. This technology is a short-range communication mainly for a body centric communication due to its aspects which include wide bandwidth, less possibility of intercept and low-power consumption [3]. In the wireless environments, UWB derives systematically to rectify the issues in the limitation of bandwidth. To shift the complexity in designing related to the receiver as well as transmitter, Time reversal (TR) technology is considered. TR has a range of applications in under water communications and also in acoustic field. In modern era, TR is broadly used for UWB communication. It allows notably less co-channel interference in a system of multi-cell. This results in an effective utilization of bandwidth in the entire network. This technique can also improve the transmission rate and reduce the channel influences which typically lead to MU-UWB system quality reduction. This is the reason why the TR has more attention in UWB system.

In case of a single-input, single-output (SISO-TR) scheme [4], the channel impulse response (CIR), which is time reversed, is utilized as a transmitter pre-filter. The received signal significantly intended in the temporal and spatial domains which has a major role in shifting the complexity.

The second case is the single-input multiple-outputs (SIMO) [5]. One of the motivations to use this technique is the usage of a single transmitting antenna. Hence, the effect of transmit spatial correlation will be clearly reduced, but with a loss in transmission diversity. In this case, from one antenna many contracted pulses are transferred towards numerous receiving antennas. Thus, the CIRs aimed at only one communicating antenna. The numerous received antennas are dignified and combined together. The resultant signal is then reversed and transmitted again from a particular antenna which is initially transmitting [6]. It is transmitted towards a certain multiple antenna set. From these multiple antennas, the received signals are again combined together.

The third case is the multiple-inputs, multiple-outputs (MIMO) technique which is famous along with its tremendous capability by utilizing numerous transmit and receive antennas to develop the diversity. The MIMO-UWB technique assists the entire system to develop its transmission rate considerably. Actually, the UWB originates by means to solve the limitation of bandwidth. It is clearly understood that in reality, the channels are typically multi-path fading channels. Hence, the problem of the transmission quality arises when we aid multi-user in UWB system. One solution to solve these kinds of issues is the integration of MU-MIMO-UWB system with the TR technique. This can effectively reduce the channel influences and the BER.

The organization of this paper is divided into five sections. After the introduction in Section 1, we explain the literature related to this proposed research in Section 2. Section 3 clearly elucidates the proposed work with neat sketches. Section 4 depicts the results of the research work. Finally, in Section 5 we conclude this work with the statements which are observed from the outcomes, and the future works are also included in this section.

2. Related Works

In research [7] the author has compared TR based system performances with state–of-art- non filtered scheme. This work has proposed uncoordinated IR-UWB network with a distributed context including ISI/IFI and the dispersion of multi-path with more assumptions. The outcomes have shown that the non-pre-filtered and TR system performances were affected by the power control lack and defective channel knowledge.

In research [10] the author has presented the complete examination of MU-MISO UWB systems engaged with TR pre-filter. In this model, the channel estimation errors (CEE) and spatial correlation have been considered. To classify the impact of the propagation situations, an innovative expression in closed method for the regular SINR has been affecting performance metrics of TR. The CEE and high spatial correlation have been the reason for considerable decrement in the effectiveness of the bandwidth. Through the numerical simulations, all the theoretical results have been verified.

In research [14] The author has developed a model for energy consumption. This model has been used to estimate consumption of electrical energy corresponds to the systems of impulse radio ultra-wideband (IR-UWB). The comparative study also has been done depending on SISO as well as MISO. At the same time, the comparison made with the TR-MISO configuration and MISO alone configuration. The outcomes have shown the unique behaviors based on the condition of propagation, considered number of antennas. By utilizing this model, a radio frequency designer has easily acquired the noteworthy inputs by means to select optimum configuration to frame a system of IR-UWB with adaptive energy awareness.

In research [15] the author has deliberated the SIMO system communication. When the aspects of hardware device have been considered, the antenna spacing restriction has caused system performance scaling down because of the correlation among the antennas. The novel pre-filtering vector has been proposed to resolve the interference which was produced by correlation's poor effects. The proposed pre-filtering vector was for the replacement of existing TR system. Exactly, this approach depends on the correlation matrix among the receive antenna. Through the Monte-Carlo simulation, the innovated pre-coder's effectiveness was assured and confirmed.

In research [16] the author has proposed a MIMO band notched antenna for the application of portable UWB. The mutual coupling has been reduced by proposing an antenna that comprises two square monopole-antenna elements. The first one is the T-shaped ground stub and the second one on that ground stub is a vertical slot cut. The simulation as well as various parameter measurements were carried out to investigate the performance of antennas. The outcomes have shown that the proposed MIMO antenna has a noble entrant for the application of portable UWB.

3. Proposed Work

Our proposed work focuses on the transmitter side, which transmits IR-UWB waves to the receiver via UWB channel model four (CM4). The IR-UWB waveform and CM4 parameters according to IEEE

802.15.3a standard are available in [1]. For channel correlation, we used a fixed correlation model because of its simplicity and its immediate application to the existing IEEE 802.15.3a standard.

The main motive of our work is to analyze the performance of UWB channel with different numbers of inputs and outputs, as a step in the way to find the best scheme dealing with transmit spatial correlation's effects. The proposed work consists of various modeling technologies with diagrams.

3.1 TR Methodology

In TR, time reversed channel impulse responses (CIR) is utilized as a transmitter pre-filter. After the process of pre-filtering, the signal circulates through an invariant channel ensuing the similar lanes. In the time and spatial domains [5]. Typically, it is a scheme of pre-Rake. Consider the general MIMO-UWB system illustrated in Figure 1, Let $h_{i_1 i_2}(t)$ be the CIR of the channel from the $i_2{}^{\text{th}}$ transmit antenna to the $i_1{}^{\text{th}}$ receive antenna, which can be typically modeled as [6]:

$$h_{i_1 i_2}(t) = \sum_{k=1}^{K}\sum_{l=1}^{L} \alpha_{k,l}^{(i_1 i_2)} \delta\left(t - T_k^{(i_1 i_2)} - \tau_{k,l}^{(i_1 i_2)}\right), \qquad (1)$$

Where $\alpha_{k,l}^{(i_1 i_2)}, T_k^{(i_1 i_2)}$ and $\tau_{k,l}^{(i_1 i_2)}$ are the amplitude fading, cluster delay and ray delay respectively.

The CIR matrix $G(t)$ for the MIMO channel is:

$$G(t) = \begin{bmatrix} h_{11}(t) & h_{12}(t) & \cdots & h_{1N_T}(t) \\ h_{21}(t) & h_{22}(t) & \cdots & h_{2N_T}(-t) \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_R 1}(t) & h_{N_R 2}(t) & \cdots & h_{N_R N_T}(t) \end{bmatrix}, (2)$$

Then the TR filter matrix which is based on the original CIR matrix reversed in the time domain and transposed in the spatial domain, denoted as $\breve{G}(t) = [G(-t)]^T$ will be:

$$\breve{G}(t) = \begin{bmatrix} \frac{h_{11}(-t)}{\|h_{11}\|} & \frac{h_{21}(-t)}{\|h_{21}\|} & \cdots & \frac{h_{N_R 1}(-t)}{\|h_{N_R 1}\|} \\ \frac{h_{12}(-t)}{\|h_{12}\|} & \frac{h_{22}(-t)}{\|h_{22}\|} & \cdots & \frac{h_{N_R 2}(-t)}{\|h_{N_R 2}\|} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{h_{1N_T}(-t)}{\|h_{1N_T}\|} & \frac{h_{2N_T}(-t)}{\|h_{2N_T}\|} & \cdots & \frac{h_{N_R N_T}(-t)}{\|h_{N_R N_T}\|} \end{bmatrix}, (3)$$

Where $\|.\|$ denotes the 2-norm defined by:

$$\|h\| = \sqrt{\int_{-\infty}^{+\infty} h^2(t)dt},$$

The CIR matrix of the equivalent composite channel is:

$$\dot{G}(t) = G(t) * \breve{G}(t), \qquad (4)$$

Denote by $x(t)$ and $y(t)$ (both are of dimensions N_R) the transmit and receive signals of the TR system at time t respectively. Then we have [5]:

$$y_i(t) = \sum_{k=1}^{N_T} h_{ik}(t) * \frac{h_{ik}(-t)}{\|h_{ik}\|} * x_i(t)$$
$$+ \sum_{\substack{j=1 \\ j\neq i}}^{N_R}\sum_{k=1}^{N_T} h_{ik}(t) * \frac{h_{jk}(-t)}{\|h_{jk}\|} * x_j(t) + n_i(t), \quad (5)$$

With $i = 1, \dots, N_R$, n is the receiver noise and x_i, y_i and n_i denote the i th entry of x, y and n respectively.

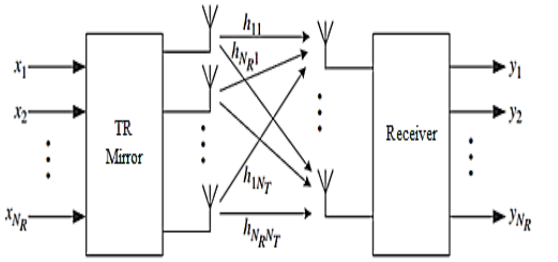

Figure (1): Block diagram of the TR system

3.1.1 Modeling of TR-SIMO-UWB transmitter:

The SIMO-UWB transmitter with the implementation of TR technology is illustrated in figure 2.

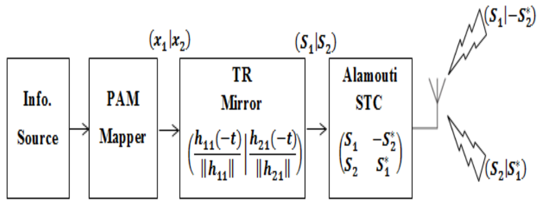

Figure (2): TR-SIMO-UWB transmitter for 1*2 case.

In this technology, a single IR-UWB pulse is transferred from one antenna towards multiple receiving antennas using Alamouti Space-Time Coding (STC) scheme, since we transmit N_R data streams via the single transmit antenna. So, the CIR should be available in both transmitter and receiver sides. The final signals are reversed and again transferred commencing from the particular antenna towards the multiple antennas. At the receiver side, the multiple antennas add the received signals together again using maximum-Ratio Combiner (MRC).

3.1.2 Modeling of TR-MIMO-UWB transmitter:

In this case, multiple signals are transmitted via multiple antennas also using IR-UWB with the appropriate STC scheme, towards multiple antennas which use MRC followed by Maximum Likelihood (ML) detector since we only use real orthogonal designs (ROD) for STC. This system operates only if it anticipates CIR information. This information is then sent to every user. Initially, the user sends an impulse to base station. The base station's Time-Reversal Mirror (TRM) records as well as stores the information which is received to be utilized to carry out the process of transmitting the signals. Figure 3 shows the transmitter for this case.

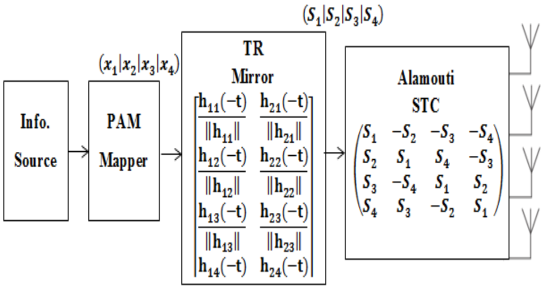

Figure (3): TR-MIMO-UWB transmitter for 4*4 case

Subsequently, the decoding process will use the following companion of the real orthogonal design (CROD) matrix [8]:

$$G_c(t) = \begin{bmatrix} \alpha_1 & \alpha_2 & \alpha_3 & \alpha_4 \\ \alpha_2 & -\alpha_1 & -\alpha_4 & \alpha_3 \\ \alpha_3 & \alpha_4 & -\alpha_1 & -\alpha_2 \\ \alpha_4 & -\alpha_3 & \alpha_2 & -\alpha_1 \end{bmatrix}, \quad (6)$$

Where the $G_c(t)$ CROD is a matrix satisfying the following equation:

$$[\alpha_1, \alpha_2, .., \alpha_m] G(S_1, S_2, .., S_k) = [S_1, S_2, .., S_k] G_c(\alpha_1, \alpha_2, .., \alpha_m), \quad (7)$$

4. Performance Analysis

The performance of the considered technologies will be discussed in this section and subsections.

The Bit Error Ratio is measured as the number of bit errors occurred per unit of time. It is used to describe the quality and the performance.

Signal to Noise Ratio is distinct as the ratio between signal power and noise power. This is uttered in decibels. If the ratio is higher than 1:1, this designates that the signal power is higher than that of noise.

Transmission Rate is the speed at which data is transmitted between marginal devices defined in bytes per second when the channel capacity is calculated using base 2 logarithm, or in nats per second if the natural logarithm is used.

Channel Capacity is a foremost used metric for supreme amount of signal or traffic which has the capability to move above a specific arrangement.

Outage Probability:

First, if the fading changes so quickly that a transmitted codeword experiences many independently fading blocks, the ergodic capacity is defined as [8]:

$$C_e = B.\mathrm{E}\left\{\log(1 + \frac{S}{N})\right\}, \quad (8)$$

Where B is the channel bandwidth, E denotes the conditional expectation, S and N are the transmitted signal and receiver noise respectively. It gives a characterization for the transmission rates supportable by the channel.

Second, if the fading changes so slowly that a transmitted codeword spans only a single fading block (in other words, the fading is almost constant in one codeword which is the case of CM4), the outage capacity (or probability) is defined as:

$$P_{out} = C_e(R), \quad (9)$$

Where R is the data rate. The so defined P_{out} means that if some codewords are transmitted across the channel with the rate R, it cannot be correctly decoded with a probability of P_{out}, then the channel can only support the rate R with a probability of $1 - P_{out}$.

The modeling is done using MATLAB and the following table represents the main parameters' values.

Table (1): Parameters of the used channel

Parameter	Value
Length of CIRs	403
Sampling time of the system (T_S)	1×10^{-9}
Delay spread of channel (σ_T)	$125\ T_S$
Pulse width (τ_P)	0.1225 ns
Number of transmit antennas (N_T)	[1 2 4]
Number of receive antennas (N_R)	[2 4]
Modulation	PAM
Channel Model	CM4
Correlation Model	Fixed
Number of multi-paths (rays in each cluster)	[2 7 50]

4.1 "1*2" SIMO UWB without TR transmission rate:

First, the outage probability versus the transmit rate is plotted for three cases 2, 7 and 50 multi-paths.

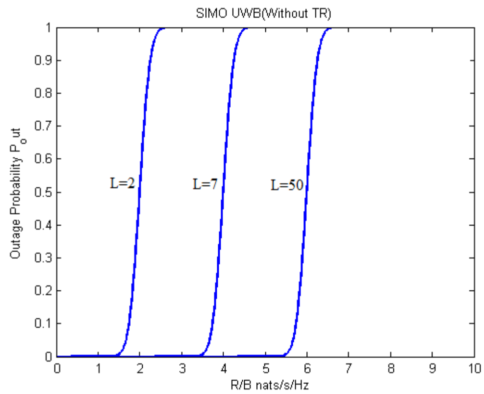

Figure (4): Plot between Outage probability VS. R/B for 1*2 SIMO-UWB without TR technology.

Figure 4 shows that with more paths in the channel, more rate is gained, that is because of UWB ability of employing the frequency diversity. For $L = 7$ with 10% outage probability the achievable transmission rate is about $3.7\ nats/s/Hz$, However, it becomes around $6\ nats/s/Hz$ when $L = 50$ for the same outage probability.

4.2 "1*2" SIMO UWB with TR transmission rate:

Now, the outage probability versus the transmission rate is re-plotted for the SIMO case, but with the use of TR technology.

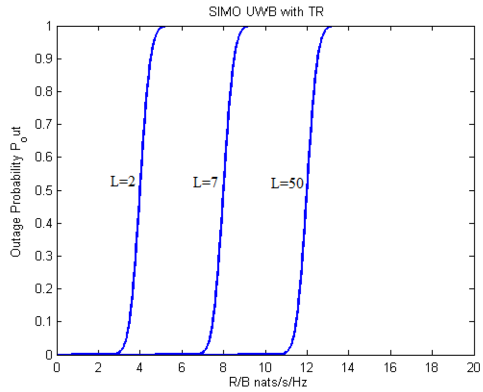

Figure (5): Plot between Outage probabilities vs. R/B for 1*2 SIMO UWB with TR technology.

Figure 5 shows that the outage curve slope remained the same as in the previous case, but with a significant increase in achievable rate for the same outage probability, i.e., without the use of TR and for $L = 7$, the achievable rate is about $3.7\ nats/s/Hz$ for 10% outage probability. However, with the use of TR, the achievable rate almost doubled and became around $7.3\ nats/s/HZ$ under the same conditions.

4.3 "4*4" MIMO UWB without TR transmission rate:

MIMO's theoretical principles indicate that the transmission rate will increase with the greater number of antennas. This is what we have achieved with the use of MIMO in the UWB system as figure 6 shows.

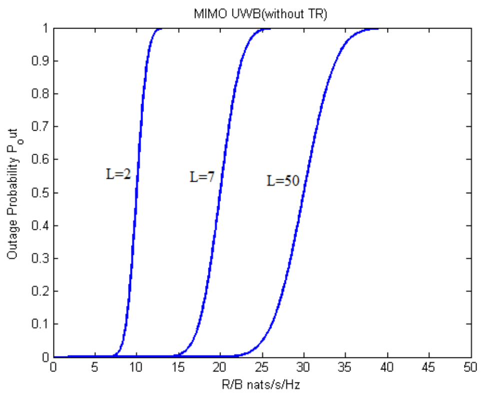

Figure (6): Plot between outage probabilities vs. R/B for 4*4 MIMO UWB (without TR).

MIMO deploys numerous antennas both in transmitting as well as receiving ends by means of developing the transmission rate. So, without utilizing additional transmit power, the quality of communication is improved. For the case of $L = 7$, the achievable rate became about $18\ nats/s/Hz$ with 10% outage probability which represents 79% improvement in transmission rate comparing to SIMO-UWB case.

4.4 "4*4" MIMO UWB with TR transmission rate:

The TR technology is used to avoid the spatial correlation's effects. The diversity is preserved by using 4 transmit antennas.

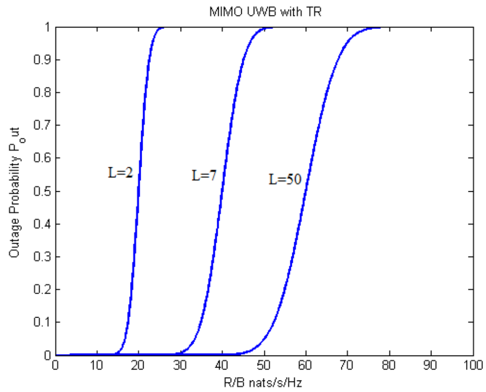

Figure (7): Plot between outage probabilities vs. R/B for 4*4 MIMO UWB (with TR).

The combining of TR with a MIMO-UWB antenna framework is greatly developing the UWB system capacity. This combination permits enormously robust transmission rates which is used to locate the target notes in the wireless networks accurately. As it is shown in figure 7, with the use of TR, the transmission rate is increased significantly for the same discussed case the achievable rate became about $34\ nats/s/Hz$ which represents 49% improvement comparing to the MIMO-UWB case without TR.

4.5 Performance comparison:

After making sure that the use of MIMO with UWB has increased the transmission rates and that the use of TR technology has further improved this high rate. To evaluate the benefit of integrating TR technology in terms of reducing the effect of spatial correlation between the transmitted signals, we will compare the cases of using and not using TR technology in terms of BER. Later, we will identify cases in which the best performance of BER is achieved for two different scenarios of spatial correlation coefficient values ($\rho_{T_x} > 0.5\ and\ \rho_{T_x} \leq 0.5$) which is related to completely different types of applications.

4.5.1 BER performance without TR:

Figure 8 illustrates the average BER versus the transmit correlation coefficient, which varies depending on the spacing between transmit antennas and the number of multi-paths. Here the antennas' spacing vary from 6 cm to 1 cm, and the case of 7 multi-paths was considered with SNR=10 dB.

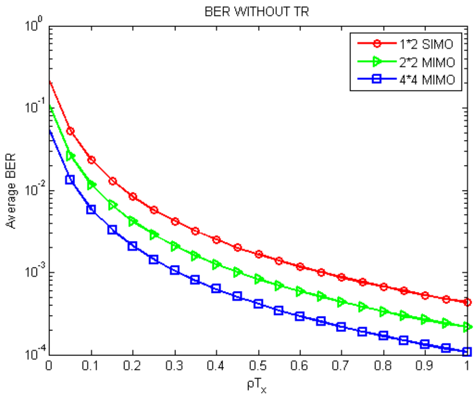

Figure (8): Plot between Averages BER VS. transmitting correlation without TR.

Figure 8 shows the comparison of BER for 1*2 SIMO, 2*2 MIMO, and 4*4 MIMO with the color variation without TR technology. It is noted that the BER decreases with the increase of the transmit correlation coefficient values. The reason for this phenomenon is that, without using TR and while using STC, the spatial diversity is fully exploited and therefore, the increasing spatial correlation which increases the amount of spatial multiplexed signals in the channel, gives a greater opportunity to reduce the BER. We can note that the BER is relatively high for correlation coefficient values below 0.5 which weakens the system performance, so this case is not effective for channels with low spatial correlation. Another finding from figure 8 is that the performance of MIMO outweighs SIMO due to the increased transmit diversity which is proportional to the number of transmit antennas. It is clear that with the increasing number of antennas in both transmit and receive sides, system performance improves.

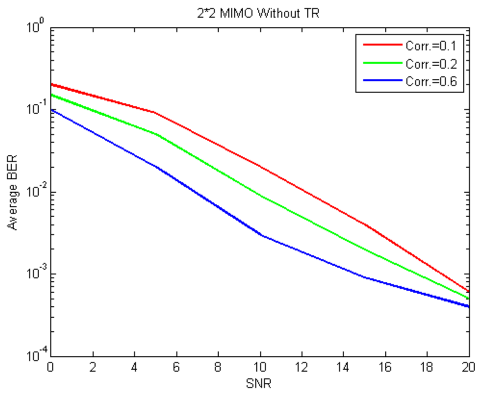

Figure (9): Plot between Average BER VS. SNR without TR

Again, from Figure 9 we notice that the performance under high correlation scenario outperform low correlation scenario for all the SNR range.

4.5.2 BER performance with TR:

Here the test was performed under the same previous conditions, but with the use of TR, Figure 10 shows these results:

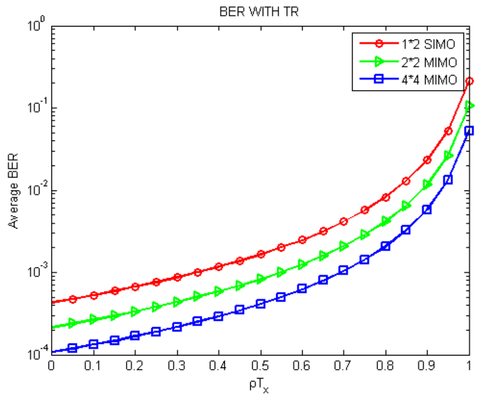

Figure (10): Plot between Average BER VS. transmitting correlation with TR.

Figure 10 shows the comparison of BER for 1*2 SIMO, 2*2 MIMO, and 4*4 MIMO using TR technology. In this case, we observe counter phenomenon to the one noticed in the previous case (here the greatest BER performance improvement is for low correlation scenarios while a performance drawback appears at high correlation scenarios), therefore, the decision of using TR or not, depends on the application's conditions, if the channel works under low correlation values ($\rho_{Tx} \leq 0.5$) then the use of TR is recommended, whereas if the channel works under high correlation values ($\rho_{Tx} > 0.5$), then using STC itself can prevent any system drawback. Another important thing to note from figure 10 is that although using TR within SIMO enables the ability of transmitting multiple data streams equal to the number of receive antennas ($= N_R$) via the single transmission antenna each time slot, its transmit diversity remains slight compared to MIMO case, so the trade-off between exploiting diversity and minimizing the effects of spatial correlation by using single transmit antenna is clear, and this trade-off result goes in favor of transmit diversity (using MIMO instead of SIMO) because TR-SIMO has performed worse than TR-MIMO on the whole range of correlation coefficient values. Table 2 represents the BER reduction percentage when we use TR-MIMO-UWB comparing to MIMO-UWB, we chose 2*2 MIMO case for comparison as an intermediate case among the studied cases.

Table 2: BER reduction percentage

Corr.	BER		Reduction percentage
	2*2 MIMO-UWB	2*2 TR MIMO-UWB	
0.1	125×10^{-4}	10.85×10^{-4}	91.32%
0.2	50×10^{-4}	6×10^{-4}	88%
0.6	8×10^{-4}	9.8×10^{-4}	No reduction achieved

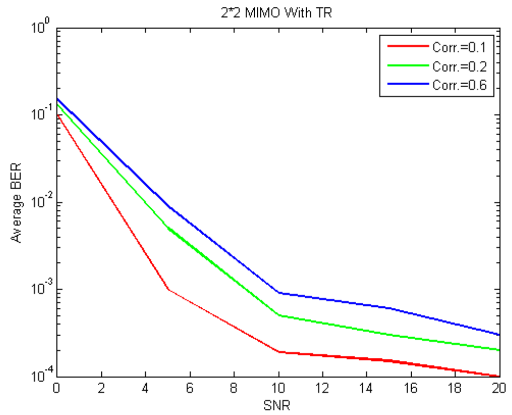

Figure 11: Plot between Average BER VS. SNR with TR.

From figure 11 we observe again that in contrast to the non-use of TR case, the performance under low correlation scenario outperform high correlation scenario for all the SNR range.

5. Conclusions

Typically, UWB system performs more efficiently in both cost and quality when it is incorporated with TR technology. This paper mainly focused on analyzing the UWB achievable transmission rates and BER measurement when integrating SIMO and MIMO technologies with and without the use of TR. The outcomes have shown that the application of TR vastly increases the UWB transmission rate and significantly reduces the BER values for spatial correlation coefficient values below 0.5, meanwhile STC itself can provide a good BER performance for spatial correlation coefficient values higher than 0.5. This work will be a base for further research works on the UWB system and its enormous applications such as Ultra Low Power Data Communications, Wi-media technology, Home Networking, Home Electronics, and Wireless Body Area Networks.

6. References

[1] S. H. Choi, J. K. Park, S. K. Kim, and J. Y. Park, "A new ultra‐wideband antenna for UWB applications," *Microwave and optical technology letters,* vol. 40, pp. 399-401, 2004.

[2] Q. H. Abbasi, H. El Sallabi, E. Serpedin, K. Qaraqe, A. Alomainy, and Y. Hao, "Ellipticity statistics of ultra wideband MIMO channels for body centric wireless communication," 2016.

[3] A. Pellegrini, A. Brizzi, L. Zhang, K. Ali, Y. Hao, X. Wu, *et al.*, "Antennas and propagation for body-centric wireless communications at millimeter-wave frequencies: A review [wireless corner]," *IEEE Antennas and Propagation Magazine,* vol. 55, pp. 262-287, 2013.

[4] D. Abbasi-Moghadam and V. T. Vakili, "A SIMO one-bit time reversal for UWB communication systems," *EURASIP Journal on Wireless Communications and Networking,* vol. 2012, p. 113, 2012.

[5] I. H. Naqvi and G. El Zein, "Time domain measurements for a time reversal SIMO system in reverberation chamber and in an indoor environment," in *Ultra-Wideband, 2008. ICUWB 2008. IEEE International Conference on*, 2008, pp. 211-214.

[6] V. Tran-Ha, D.-D. Tran, D.-B. Ha, and E.-K. Hong, "On the Performance of MU SIMO/MIMO UWB Communication Systems Applying Time-Reversal Technique," in *Transactions on Engineering Technologies*, ed: Springer, 2014, pp. 445-458.

[7] G. Caso, L. De Nardis, M. T. P. Le, F. Maschietti, J. Fiorina, and M.-G. Di Benedetto, "Performance evaluation of non-prefiltering vs. time reversal prefiltering in distributed and uncoordinated IR-UWB ad-hoc networks," *Mobile Networks and Applications,* vol. 22, pp. 796-805, 2017.

[8] A. Pitarokoilis, S. K. Mohammed, and E. G. Larsson, "Uplink performance of time-reversal MRC in massive MIMO systems subject to phase noise," *IEEE Transactions on Wireless Communications,* vol. 14, pp. 711-723, 2015.

[9] C. A. Viteri-Mera and F. L. Teixeira, "Interference-Nulling Time-Reversal Beamforming for mm-Wave Massive MIMO in Multi-User Frequency-Selective Indoor Channels," *arXiv preprint arXiv:1506.05143,* 2015.

[10] B. He, T. Sun, Z. Wang, and K. Su, "A Fine-Grained Analysis of Time Reversal MU-MISO Systems Over Correlated Multipath Channels With Imperfect CSI," *IEEE Access,* vol. 6, pp. 69516-69527, 2018.

[11] Y. Yang, B.-Z. Wang, and S. Ding, "Performance comparison with different antenna properties in time reversal ultra-wideband communications for sensor system applications," *Sensors,* vol. 18, p. 88, 2018.

[12] A. Dezfooliyan and A. M. Weiner, "Spatiotemporal focusing of phase compensation and time reversal in ultrawideband systems with limited rate feedback," *IEEE Transactions on Vehicular Technology,* vol. 65, pp. 1998-2006, 2016.

[13] E. Bogdani, D. Vouyioukas, and N. Nomikos, "Localization error modeling of hybrid fingerprint-based techniques for indoor ultra-wideband systems," *Telecommunication Systems,* vol. 63, pp. 223-241, 2016.

[14] A. El Abboubi, F. Elbahhar, M. Heddebaut, and Y. Elhillali, "Energy Consumption Models For MISO-UWB and TR-MISO-UWB Systems," *International Journal of Electronics and Telecommunications,* vol. 63, pp. 285-291, 2017.

[15] V. Tran-Ha and E.-K. Hong, "An advanced Time Reversal Precoding for SIMO Systems over Correlated Channels," *한국통신학회학술대회논문집,* pp. 1012-1014, 2015.

[16] L. Liu, S. Cheung, and T. Yuk, "Compact MIMO antenna for portable UWB applications with band-notched characteristic," *IEEE Transactions on Antennas and Propagation,* vol. 63, pp. 1917-1924, 2015.

.