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Applying Time-Reversal Technique for MU MIMO UWB Communication Systems

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[1] ***Abstract*—Time Reversal (TR) is a technique to focus broadband signals tightly in time and space. Previously, this technique has been used in acoustics, medical and especially in underwater communication applications. It is capable of reducing noises, such as: Inter-Symbol Interference (ISI), Inter-User Interference (IUI). . . , while the used equipments are more simple than complex Equalizers at the transmitter and receiver . TR technique is combined with Ultra Wideband (UWB) to offer a new solution for reducing the cost and complexity of UWB receiver. In this paper, we focus on presenting the operational mechanism of TR technique and giving some specific results which concern with applying TR technique for UWB system.**

I. INTRODUCTION

Ultra Wideband (UWB) is an attractive research direction in recent years because of its capability of high-speed communication in a short distance [1]–[4]. UWB solved effectively the problems of bandwidth limit in wireless environments [5]. However, it is realized that channels in reality are multi-path fading channels, so problems affecting quality of transmission in UWB systems serving multi-user (MU) are really complex. We can resolve these problems by combining UWB systems and TR technique to improve transmission rate and minimize the influences of channels which decrease the quality of UWB systems [3], [6], [7].

In UWB systems, the dense multi-path components can be used for the purpose of both data communications and correct positioning. However, in order to harvest even half of the energy distributed in the entire impulse responses, Rake receivers with at least 20 taps, may be potentially much more, must be constructed [8]. For many UWB wireless devices, the dense multi-path causes the great difficulty and complexity for the UWB synchronizer and equalizer. The time-reversal (TR) technique combined with UWB offers a new possibility for decreasing the cost and complexity of the UWB receiver. It may also provide a solution to multi-user and secure communications. TR technique has been extensively used in acoustic, medical applications and underwater communications [9], [10]. Its advantage is decreasing bad effects caused by environments, such as: Inter-Symbol Interference (ISI), Inter-User Interference (IUI),. . . without the need of using complex equalizers at transmitters and receivers. In the TR systems, multi-access mechanism is based on the unique of channel impulse responses of the environments where a base station (BS) is forwarded to any users.

In [2], Vu Tran-Ha and the co-authors presented the results related to the channel capacity of MU MIMO UWB TR system in environment conditions when the correlation between antennas is considered. In this paper, we focus on introducing TR technique and simulating its operational mechanism. Besides, we collapse the problem in [2] when the correlation between antennas is not considered and show a number of specific results related to the comparison of capacity of UWB systems when they are applied and not applied TR technique. From the simulation results obtained, applying TR technique for UWB systems has highly effective in increasing the channel capacity significantly.

The rest of this article is organized as follow: part II is time reversal technique description, channel capacities of UWB systems are described in part III, part IV is channel capacity comparison between the UWB system and UWB TR system, and in part V we conclude our discussion.

II. TIME REVERSAL TECHNIQUE

TR is a technique to focus broadband signals tightly in space and time where the multi-path channel with rich scattering is exploited by active modulating the signal at the transmitter side using the state channel information, instead of being processed at the receiver by equalizers or Rake combiners as in the traditional communication systems [8]. This technique has been extensively used in acoustic, medical applications and underwater communications.

The main advantages of the TR technique are:

- Temporal focusing: The received signal is compressed in the time domain. Owing to this property, the inter-symbol interference (ISI) caused by the original multi-path channel is greatly reduced.
- Spatial focusing: The received signal is focused on the intended user at some specific position in space. This is very useful in realistic environments where the interference from co-channel users limits the capacity of each user. If the transmitter is able to focus precisely, an ideal space-division multiple access (SDMA) technique and the location-based security might be enabled.

Because of the simplicity in principle and aforementioned advantages of TR technology, the idea of applying TR technique in wireless communication has gained much attention recently.

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The principle of TR technique is to use state channel information to create waveform used to transmit signals. Suppose that we have a structure similar to the above example includes one transmit station and two receive stations. System is simplified only one antenna at each station, as Figure 1.

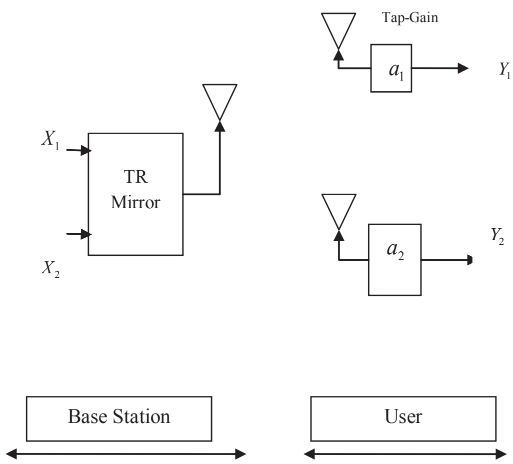

Figure 1. UWB TR System

In order to use TR technique, the state channel information needs to be known in advance. Therefore, first of all, receive station has to send to transmit station an impulse. When the impulse is transmitted through environment to transmit station, received signal is the channel impulse response (CIR). The received signal at transmit station (is called X1) look like the Figure 2.

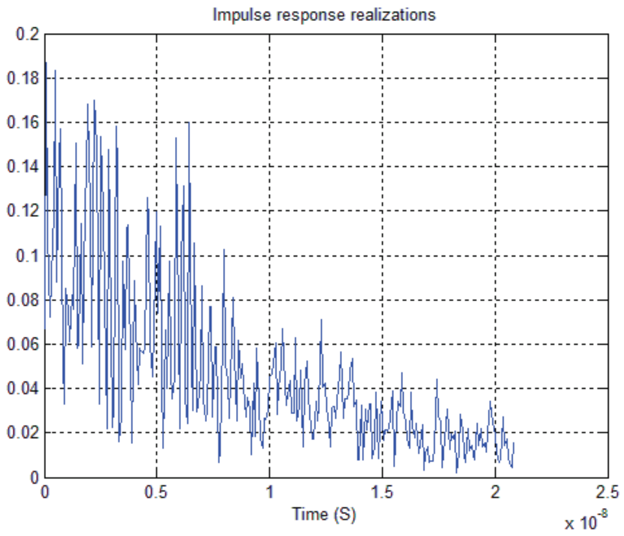

Figure 2. X1 signal

At this time, the transmit station store the received signal and reverse it in time axis. The time-reversed signal will be used to transfer data between the transmitter and receiver. The time-reversed signal (is called X2) look like the Figure 3.

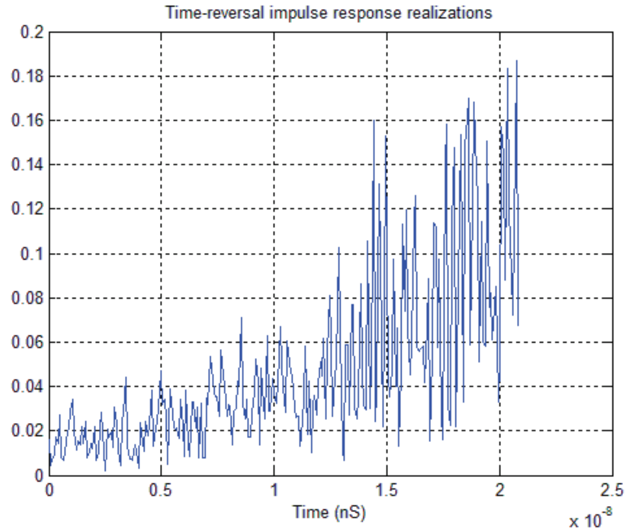

Figure 3. X2 signal

Thus, we have identified signal waveforms that will be used to transmit data based on state channel information. When X2 is used for communication, the received signal at receive station (is called X3) will have the waveform as Figure 4.

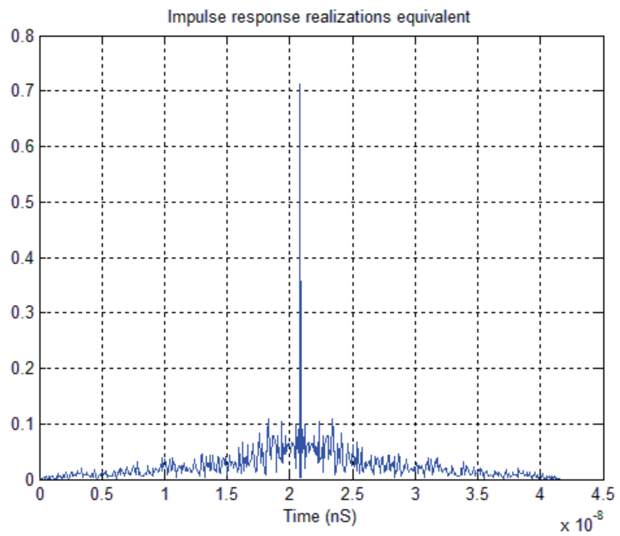

Figure 4. X3 signal

The energy of received signal is converged to a certain position in the time domain. Furthermore, if and only if, X2 signal form transmitted through environment has exactly CIR is X1 signal, then we just get X3 signal form. It means that, only receive station is forwarded just receive above signal form. For other receive stations which are not forwarded, received signal at that stations will look like the waveform (X4 form) as Figure 5.

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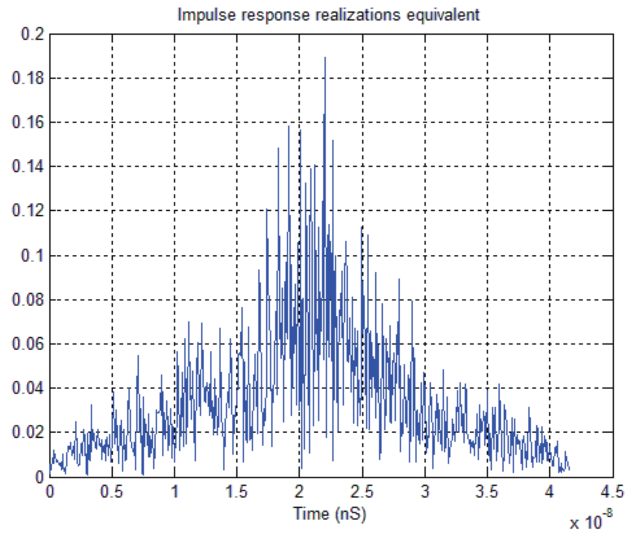

Figure 5. X4 signal waveform

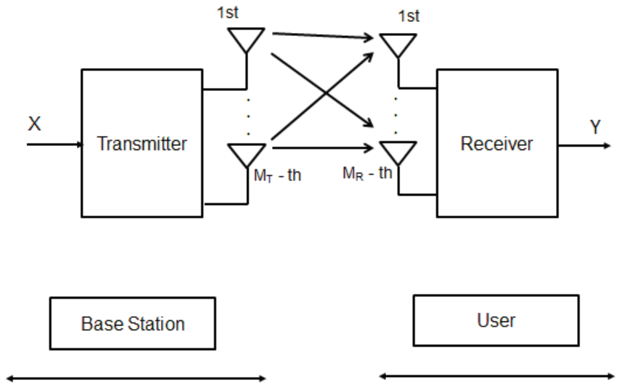

Figure 6. Block diagram of MIMO UWB system

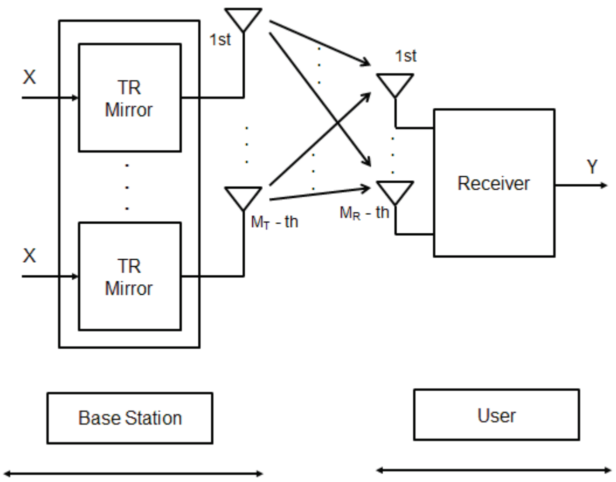

Figure 7. Block diagram of MIMO UWB TR system

Thus, the energy of X4 signal is smaller than X3 signal very much. This is also amount of interference between receive stations or inter-user interference (IUI). In summary, TR technique takes advantage of diversification and unique of CIR from Base Station (BS) is forwarded to any receive station to focus signal energy as well as supply a simple but effective multi-access mechanism. This multi-access method similar to CDMA. In which, each CIR will play a role similar to a Pseudo Noise (PN) code in CDMA [1].

III. CHANNEL CAPACITY OF MIMO UWB SYSTEM

In this part, we will describe MIMO UWB system and show the formulas to calculate its channel capacity when it is applied and not applied TR technique (UWB and UWB TR).

The difference between UWB and UWB TR systems is that, UWB TR systems only operate when it anticipates the CIRs' information forwarded each user.

Therefore, in UWB TR systems, first of all, intended users will send an impulse to Base Station (BS), the received signal form at BS is CIRs form of that environment. When the BS received CIRs information from the users, the block Time Reversal (TR) Mirror will use this information of CIRs to create waveforms which are used for communication between BS and intended users.

In this paper, we do not consider the correlation between transmit antennas and receive antennas. We suppose that the number of transmit antennas is M_T and the number of receive antennas is M_R.

MIMO (Multi Input Multi Output) system is a wireless system using multiple transmit antennas ($M_T > 1$) and multiple receive antennas ($M_R > 1$). The block diagram of MIMO UWB and MIMO UWB TR systems are shown in Figure 6 and Figure 7, respectively.

The received signal at the user has the following form:

$$\mathbf{Y} = \mathbf{H} * \mathbf{X} + \mathbf{n}, \tag{1}$$

Where $\mathbf{Y}$ is the received signal vector at the user; $\mathbf{X}$ is the transmitted signal vector; $\mathbf{H}$ is the CIRs matrix with dimension $M_R \times M_T$ from BS to the user and $\mathbf{n}$ is the white Gaussian noise at the user. $\mathbf{H}$ can be written as:

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & \dots & h_{1M_T} \\ h_{21} & h_{22} & \dots & h_{2M_T} \\ \vdots & \vdots & \ddots & \vdots \\ h_{M_R1} & h_{M_R2} & \dots & h_{M_RM_T} \end{bmatrix} \tag{2}$$

Where h_{ij} is the CIR between the j-th transmit antenna and the i-th receive antenna of the user. It is represented as:

$$h_{ij}(t) = \sum_{l=0}^{L-1} \alpha_l^{ij} \delta(t - \tau_l^{ij}),\ i = 1, ..., M_R,\ j = 1, ..., M_T \tag{3}$$

With α_l^{ij} and τ_l^{ij} are the amplitude and the delay of the l-th tap, respectively. The discrete time form of $h_{ij}(t)$ is expressed

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as:

$$h_{ij} = [h_{ij}[0]\ h_{ij}[1]\ ...\ h_{ij}[L-1]] \quad (4)$$

Where $h_{ij}[k]$, $k = 0, \ldots, L-1$ is the k-th tap of CIR with the length of L, $\delta[]$ is the Dirac pulse function. For each downlink, we assume that there are independent circular symmetric complex Gaussian (CSCG) random variables with zero mean:

$$\mathbf{E}\left[|h_{ij}[k]|^2\right] = e^{-\frac{kT_S}{\sigma_T}},\ 0 \le k \le L-1 \quad (5)$$

With T_S is the sampling time of the system; σ_T is the delay spread of the channel.

Channel capacity of MIMO UWB system will be calculated by the following formula:

$$C_{No-TR} = log_2\left[det\left(\mathbf{I}_{M_R} + SNR.\mathbf{H}.\mathbf{H}^H\right)\right], \quad (6)$$

Where, $\mathbf{I}_{M_R}$ is the unit matrix with dimension $M_R \times M_R$, SNR is the signal to noise ratio and

$$\mathbf{H}^H = \begin{bmatrix} h_{11}^* & h_{21}^* & ... & h_{M_R1}^* \\ h_{12}^* & h_{22}^* & ... & h_{M_R2}^* \\ \vdots & \vdots & \ddots & \vdots \\ h_{1M_T}^* & h_{2M_T}^* & ... & h_{M_RM_T}^* \end{bmatrix} \quad (7)$$

With h_{ij}^* is complex conjugate of h_{ij}, $i = 1, \ldots, M_R$, $j = 1, \ldots, M_T$.

With aforementioned UWB TR system, the TR Mirror block of BS records and stores received information which is used for processing transmitted signal. Let $\mathbf{G}$ is TR Mirror's matrix, which is expressed as:

$$\mathbf{G} = \begin{bmatrix} g_{11} & g_{12} & ... & g_{1M_R} \\ g_{21} & g_{22} & ... & g_{2M_R} \\ \vdots & \vdots & \ddots & \vdots \\ g_{M_T1} & g_{M_T2} & ... & g_{M_TM_R} \end{bmatrix} \quad (8)$$

With $g_{ij} = \left[h_{ji}^*[L-1]\ h_{ji}^*[L-2]\ ...\ h_{ji}^*[0]\right]$, $h_{ji}^*[k]$ is complex conjugate of $h_{ji}[k]$, $i = 1, \ldots, M_T$; $j = 1, \ldots, M_R$, $k = 0, \ldots, L-1$.

Let $\hat{\mathbf{H}}$ is the equivalent CIRs matrix, which is represented as:

$$\hat{\mathbf{H}} = \mathbf{H} * \mathbf{G} = \begin{bmatrix} \hat{h}_{11} & \hat{h}_{12} & ... & \hat{h}_{1M_R} \\ \hat{h}_{21} & \hat{h}_{22} & ... & \hat{h}_{2M_R} \\ \vdots & \vdots & \ddots & \vdots \\ \hat{h}_{M_R1} & \hat{h}_{M_R2} & ... & \hat{h}_{M_RM_R} \end{bmatrix} \quad (9)$$

Where, $\hat{h}_{ij} = \sum_{m=1}^{M_T} h_{im} * g_{mj},\ i, j = 1, \ldots, M_R$.

And then, equation (1) can rewrite as the following:

$$\mathbf{Y} = \hat{\mathbf{H}} * \mathbf{X} + \mathbf{n}, \quad (10)$$

Channel capacity of MIMO UWB TR is:

$$C_{TR} = log_2\left[det\left(\mathbf{I}_{M_R} + SNR.\hat{\mathbf{H}}.\hat{\mathbf{H}}^H\right)\right], \quad (11)$$

Where, $\mathbf{I}_{M_R}$ is the unit matrix with dimension $M_R \times M_R$, SNR is the signal to noise ratio and

$$\hat{\mathbf{H}}^H = \begin{bmatrix} \hat{h}_{11}^* & \hat{h}_{21}^* & ... & \hat{h}_{M_R1}^* \\ \hat{h}_{12}^* & \hat{h}_{22}^* & ... & \hat{h}_{M_R2}^* \\ \vdots & \vdots & \ddots & \vdots \\ \hat{h}_{1M_R}^* & \hat{h}_{2M_R}^* & ... & \hat{h}_{M_RM_R}^* \end{bmatrix} \quad (12)$$

With $\hat{h}_{ij}^*$ is complex conjugate of $\hat{h}_{ij}$, $i = 1, \ldots, M_R$; $j = 1, \ldots, M_R$.

IV. CHANNEL CAPACITY COMPARISON OF MIMO UWB AND MIMO UWB TR SYSTEMS

To carry out this comparison, we simulated the channel capacity of MIMO UWB system when TR technique is applied and not applied (MIMO UWB and MIMO UWB TR systems). The simulation parameters are shown in Table 1.

Table I
SIMULATION PARAMETERS

Parameters	System values
Number of transmit antennas (M_T)	3
Number of receive antennas (M_R)	[3 5 7]
Environment	Rayleigh
Number of users (N)	1
Sampling time of the system (T_S)	$125T_S$
Delay spread of the channel (σ_T)	$\frac{1}{6}.10^{-9}$
Length of CIRs (L)	257
SNR	-10dB – 20dB

The simulation results of channel capacity of aforementioned UWB systems is shown as Figure 8.

Figure 8 shows that, with SNR = 5dB, the channel capacity of 3x3, 3x5, 3x7 MIMO UWB systems and 3x3, 3x5, 3x7 MIMO UWB TR systems are: $C_{No-TR}^{3\times3}$ approximates 31 bps/Hz while $C_{TR}^{3\times3}$ approximates 53 bps/Hz; $C_{No-TR}^{3\times5}$ approximates 50 bps/Hz while $C_{TR}^{3\times5}$ approximates 89 bps/Hz; $C_{No-TR}^{3\times7}$ approximates 70 bps/Hz while $C_{TR}^{3\times7}$ approximates 126 bps/Hz. Thus, the channel capacity of MIMO UWB TR systems are higher than the channel capacity of MIMO UWB systems respectively.

In Figure 8 also indicates that, in MIMO UWB systems and MIMO UWB TR systems, 3x7 MIMO UWB systems and 3x7 MIMO UWB TR systems have the highest channel capacity. This means that, the more the number of antennas is used, the more increasing the channel capacity of the systems are.

The combination between UWB system and Time Reversal (TR) technique help to improve transmission rate and reduce effects decreasing the quality of UWB system using complex equalizers at transmitters and receivers. In other words, this combination has increased channel capacity of UWB system significantly and decreased the cost and the complexity of UWB receiver.

The Gain (G) of the UWB system is defined as:

$$G = \frac{C_{TR}}{C_{No-TR}} \quad (13)$$

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Where C_{TR} and C_{No-TR} are the channel capacity of UWB system with TR technique and without TR technique, respectively. The simulation results of gain G of aforementioned UWB systems is shown as Figure 9.

From Figure 9, we consider that, in the 3x3, 3x5, 3x7 MIMO systems, the 3x7 MIMO system has the highest gain and the 3x3 MIMO system has the smallest gain. At the same time, when the more increasing the SNR (dB) value, the more decreasing the gain of the UWB system. In other words, the UWB systems combined with TR technique show high performance in high noise environments (SNR is low).

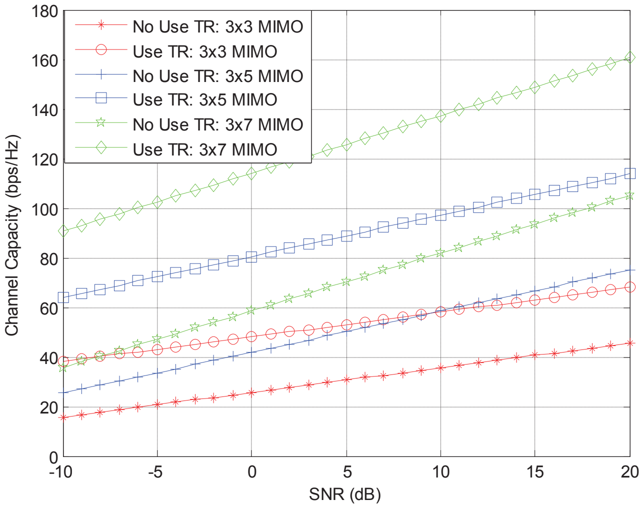

Figure 8. Channel capacity of UWB systems

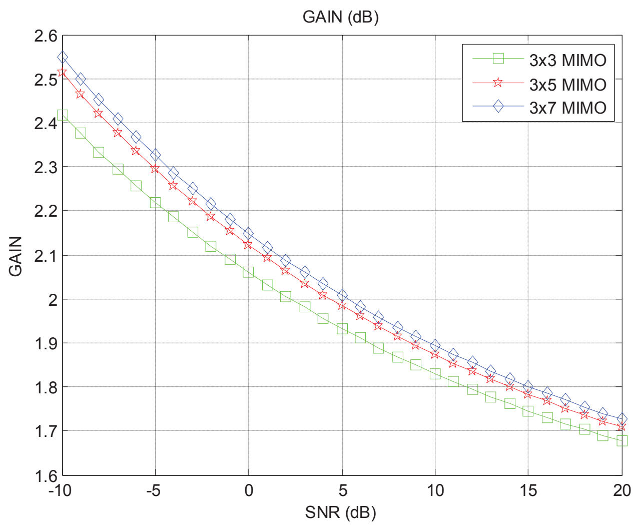

Figure 9. Gain of UWB systems

V. CONCLUSION

UWB technology has been showing its preeminence and advantages in high-speed communication in short distance. And UWB systems operate more effectively (both quality and cost) when they are combined with TR technique. In this paper, we have focused on investigating and simulating the channel capacity of MIMO UWB systems in two cases, when the TR technique is applied and not applied. And thence, we realized the advantages and efficiency of that combination. The simulation results showed that, the received channel capacity of UWB system in case of applying TR technique increased significantly than that in case of not applying TR technique. At the same time, this results also indicated that, the more the number of antennas is used, the higher the channel capacity received. And the combination of UWB system and TR technique showed high performance in high noise environments.

REFERENCES

[1] F. Han, Y.-H. Yang, B. Wang, Y. Wu, and L. K.J.R., "Time-reversal division multiple access in multi-path channels," *Global Telecommunications Conference 2011*, pp. 1–5, 2011.

[2] T. H. Vu, N. T. Hieu, H. D. T. Linh, N. T. Dung, and L. V. Tuan, "Channel capacity of multi user TR-MIMO-UWB communications system," in *International Conference on Computing, Management and Telecommunications (ComManTel)*, 2013, pp. 22–26.

[3] H. Nguyen, Z. Zhao, F. Zheng, and T. Kaiser, "Preequalizer design for spatial multiplexing simo-uwb tr systems," vol. 59, no. 8, pp. 3798–3805, 2010.

[4] N. T. Dung, N. V. Sinh, N. T. Hoa, and N. T. Hieu, "Application of compressive sensing in time hopping multi-user uwb system," in *International Conference Advanced Technologies for Communications (ATC) 2011, pp. 248-251,*, 2011.

[5] L. Y. and. Georgios B. Giannakis, "Ultra-wideband communications: an idea whose time has come," *IEEE Signal Processing Magazine*, vol. 21(6), pp. 26–54, 2004.

[6] H. T. Nguyen, I. Z. Kovacs, and P. C. F. Eggers, "A time reversal transmission approach for multiuser uwb communications," vol. 54, no. 11, pp. 3216–3224, 2006.

[7] R. C. Qiu, "A theory of time-reversed impulse multiple-input multiple-output (mimo) for ultra-wideband (uwb) communications," in *Proc. IEEE 2006 Int Ultra-Wideband Conf*, 2006, pp. 587–592.

[8] T. Kaiser and F. Zheng, *Ultra-wideband Systems With MIMO*. Wiley, 2010.

[9] M. Fink, "Time reversal of ultrasonic fields. i. basic principles," vol. 39, no. 5, pp. 555–566, 1992.

[10] P. Derode, A. Roux and M. Fink, "Robust acoustic time reversal with high-order multiple scattering," *Phys. Rev. Lett.*, vol. 75, 1995.

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