Enhancing the Performance of MIMO Space Time Coding Systems Using a Rake Receiver Based on Continuoues Wavelet Transform

Said E. El-Khamy
Department of Electrical Engineering
Faculty of Engineering, Alexandria University
Alexandria, Egypt
elkhamy@ieee.org

Ehab F. Badran, Amira I. Zaki
Department of Electronics and Communication Engineering
Arab Academy for Science and Technology
Alexandria, Egypt
ebadran@aast.edu, amzak10@yahoo.com

Abstract— **A new maximum ratio combining (MRC) Wavelet Rake (WR) receiver is presented in this paper. The WR receiver makes use of the huge bandwidth accompanied with the Ultra-Wideband (UWB) system. The proposed WR receiver uses the continuous wavelet transform (CWT) of the transmitted pulse at different scales (frequency resolutions) as the Rake fingers template pulses. Where, the Rake fingers delays are the group delays equivalent to the template pulses center frequency. Thus, the WR does not only capture the signal energy in the different multipath components at different delays (in conventional Rake (CR)) but also at different frequency components too. The WR is presented with UWB single-input single-output (SISO) and multi-input multi-output (MIMO) with analog space time coding (STC) systems. Its performance is compared to these systems with the conventional MRC-Rake receiver and Genetic Algorithm (GA) Rake presented in [1] and showed a great enhancement in performance with less receiver complexity.**

Keywords- UWB; Space time coding; Genetic algorithm; Rake receiver; Wavelet transform; and MRC.

I. Introduction

The demand for low cost, high-speed, wireless links for short range (<10 m) communication is greatly increasing every day. The UWB system is a promising candidate that provides a high data rate which makes it suitable to be used in many fields. The UWB transmission allows it to be used with systems and in many fields like PAN (Personal Area Network), WLAN (Wireless Local Area Network) and multimedia transmission systems and in the biomedical and military fields [1], [2].

An UWB system is based on the transmission of a train of ultra-short pulses over a very wide bandwidth. According to the FCC (Federal Communication Committee) regulations, the UWB systems are allowed to transmit over the frequency band between 3.1 and 10.6 GHz. The large bandwidth covered by UWB systems, increases its possibility of interfering with other narrowband and wideband systems using the low Gigahertz frequency bands. Thus, the FCC regulations restrict the UWB transmission. Where, the UWB systems can transmit only using very low power. These strict regulations on UWB systems in addition to the channel effect which is extremely frequency selective, limit the achievable data rates, and transmission range [2], [3].

Since UWB transmits information using ultra-short pulses in nanosecond, the UWB channel is enriched with resolvable multipath components (i.e. it has a dense multipath environment). Thus, the received waveform contains many delayed and scaled replicas of the transmitted pulses.

Most of the energy of the multipath components can be captured and thus enhance the performance by using a Rake receiver that introduces multipath diversity. In order to capture most of the signal energy spread over the multipath components a large number of Rake fingers (correlators with delayed versions of the transmitted pulse as template waveforms) are needed. This is in addition to the large number of channel parameters that need to be estimated [2], [4].

Many research papers were introduced on the Rake receiver including the study of the performance of fractional, chip, or symbol delays spacing Rake with channel estimator [5]. Its performance was also studied with two combining techniques the MRC and SLC (Square Law Combiner) in [3]. Also a Selective Rake (SRake) receiver which tracks the strongest L multipath components is proposed in [6] with its performance presented.

The Rake receiver is also studied with a MISO space–time coding using MRC Rake receiver in [7] and [8], to make use of multipath diversity in addition to spatial diversity and thus increase channel performance and/or capacity.

In [1] a smart UWB system depends on the use of analog STC scheme I (STC-I) (that will be illustrated lately) with a GA Rake receiver that adaptively selects the fingers delays to capture multipath components with maximum gain. The smart UWB scheme showed a great enhancement in BER (bit error rate) for a single user scheme. Its performance is also studied in combating interference from other UWB systems using Time Reversal (TR) pre-coding technique [9].

978-1-4577-1180-0/11/$26.00 ©2011 IEEE

In this paper a new WR receiver is introduced depending on the CWT. The wavelet transform has been extensively used in the wireless communication field especially in UWB communications [10]. Wavelet transform (WT) was introduced in [11] as a new modulation scheme WSK (Wavelet Shift Keying) which is considered as a generalization of "Wavelet based OFDM (Orthogonal Frequency Division Multiplexing)". Also the OFDM scheme characteristics are enhanced by using OWDM (Orthogonal Wavelet Division Multiplexing) in a Rayleigh fading channel as illustrated in [12]. On the other hand the OFDM system is studied with DWT (Discrete Wavelet Transform) and DMWT (Discrete Multi-Wavelet Transform) to reduce the level of interference and increase spectral efficiency in [13]. It is shown in [13] that DMWT–OFDM proposes much lower bit error rate (BER), increases the signal to noise ratio (SNR), and thus can be used as an alternative to the conventional OFDM.

The WT is also used recently in the UWB communication field. The WT is used in analysing the UWB signal to detect it in the presence of background noise in [14]. Also the WT is used as an UWB pulse shaper as illustrated in [15] and [16] to satisfy the FCC limits in addition to enhancing the spectral efficiency. The WT is also used in UWB pulse shaping in order to cancel interference and allow the coexistence of the UWB systems with other narrowband and wideband ones in [17] and [18].

The proposed WR receiver takes the advantage of the large bandwidth covered by the UWB pulse. Where, the template references in the Rake fingers are the CWT of the transmitted pulse at different scales (i.e. at different central frequencies). While, the delay of each finger is the group delay of the channel impulse response (CIR) corresponding to such centre frequency (assuming that the CIR is known at the receiver and the channel is constant for a block of symbols). The WR receiver is introduced with analog STC and its performance is compared to the conventional and GA Rake receivers.

This paper is organized as follows: In Section II, the channel model used in simulation is introduced. Section III discusses the system model for a single transmitting and receiving antenna, the analysis and the receiver structure. This is in addition to defining the STCI scheme for UWB introduced in [7]. Section IV presents a brief discussion of Continuous Wavelet Transform (CWT). Section V presents the proposed Wavelet Rake (WR) receiver. Section VI introduces the simulations and results. Finally, the conclusions are shown in Section VII.

II. CHANNEL MODEL

The channel models used is the modified Saleh-Valenzuela (SV) model [19]. It has an impulse response mathematical model given by:

$$h(t) = \sum_{m=0}^{M-1} \alpha(m)\delta(t-\tau(m)) \tag{1}$$

Where, M is the number of multipath components, while, $\alpha(m)$ *and* $\tau(m)$ are the gain and the delay of the m^{th} path respectively. The gain of the channel due to measurements as states in [19] follows the log-normal distribution, while the arrival times of the clusters and the rays included follow the Poisson one.

The channel can be considered as a filter with a time impulse response $h(t)$, which has a frequency impulse response H(w).

$$\begin{aligned} H(\omega) &= \int_{-\infty}^{\infty} h(t)e^{-j\omega t}dt \\ &= a(\omega)e^{-j\beta(\omega)} \end{aligned} \tag{2}$$

Where,

- $H(\omega)$is the Fourier transform of $h(t)$
- ω is the angular frequency
- $a(\omega)$ is the amplitude response depending on ω
- $\beta(\omega)$ is the phase factor depending on ω

Thus, the signal frequency components when passing in the channel experience not only different attenuation but also different delays [20]. And thus, has the so-called the group delay that is give by [20]:

$$\tau_g(\omega) = \frac{d}{d\omega}(\beta(\omega)) \tag{3}$$

The group delay is, inversely proportional to frequency (the highest frequency component is the first arriving one).

Note that, it is assumed that the first path and the first frequency components are arriving at zero delay.

III. SYSTEM MODEL

This section, presents the system model used in this paper for an UWB SISO and MISO systems for pear-to-pear communication. In the UWB communications binary symbols $s = \pm 1$ are transmitted over a train of ultra-short pulses. The system has N_t transmit and N_r receives antennas. The binary symbol is pulse shaped by monocycle pulse (Gaussian pulse 2[nd] derivative). Then the symbols are modulated by Pulse amplitude modulation (PAM) modulation and transmitted repeatedly over N_f frames each of time duration T_f ($T_s = N_f T_f$, where T_s is the symbol duration). The pulse repetition, distribute the symbol energy over multiple frames of pulses to satisfy the FCC power regulations [7]. The pulse waveform $w(t)$ has typical duration T_w between 0.2–2ns, resulting in transmission over an ultra-wide bandwidth.

A. SISO Scheme

If a single transmit and receive antennas are assumed (SISO), and PAM modulation is considered, the transmitted waveform for the binary symbol s is given by:

$$S(t) = s\sqrt{\frac{E}{N_f}}\sum_{n_f=0}^{N_f-1} w(t - n_f T_f) \quad (4)$$

Where, E is the symbol energy, and pulse shape $w(t)$ is of unit energy. The multipath channel can be expressed in terms of multipath delays and gains as in (1). Note that, $\tau(m) > \tau(m-1)$, and $T_m = \tau(M-1)$ is the maximum delay spread of the dense multipath channel. To avoid the ISI simply choose $T_f \geq T_m + T_w$. The modeled multipath fading channel is assumed to be quasi-static (i.e. constant during a block of symbols).

A Rake receiver is used at the receiver to collect multipath diversity. It uses L finger (matched filters), where $L \leq M$, and uses $w(t)$ as the correlator reference template with an autocorrelation function $R_w(\tau)$. The Rake receiver with L fingers correlates the received waveform with L delayed versions of the reference waveform $\{w(t - \tau_r(l))\}_{l=0}^{L-1}$. To ensure that the Rake fingers outputs are uncorrelated $\tau_r(l)$-$\tau_r(l-1)$ must be greater than T_w, for simplicity $\tau_r(l)$ is taken by $2lT_w$ [7].

To maximize the signal-to-noise ratio (SNR), MRC is used to collect the multipath diversity in two levels: The first level is to combine the fingers output of the Rake receiver for each frame. The second one is to combine the frames corresponding to the same symbol.

When a maximum-likelihood (ML) detector is used, the conditional bit error rate (BER) is given by [7], [8]:

$$P(e / \{\alpha_r(l)\}_{l=0}^{L-1}) = Q(\sqrt{SNR_t E_m}) \quad (5)$$

Where, SNR_t is the transmitted SNR and E_m is the energy captured by the L fingers Rake receiver which is given by:

$$E_m = \sum_{l=0}^{L-1} \alpha_r^2(l) \quad (6)$$

and

$$\alpha_r(l) = \sum_{m=0}^{M-1} \alpha(m) R_w(\tau_r(l) - \tau(m)) \quad (7)$$

B. Analog STC-I MIMO Scheme

For a MISO system the impulse response of the multipath fading channel between the i^{th} transmit antenna and the j^{th} receive antenna which is denoted by:

$$h_{ij}(t) = \sum_{m=0}^{M_{ij}-1} \alpha_{ij}(m)\delta(t - \tau_{ij}(m)), \quad (8)$$

Where $\alpha_{ij}(m)$ and $\tau_{ij}(m)$ are the gain and delay of the m^{th} path of the channel between the i^{th} transmit antenna and the j^{th} receive antenna, and M_{ij} is the number of multipath components. $\{h_{ij}(t)\}_{i=0, j=0}^{N_t-1, N_r-1}$ are assumed to be mutually independent. The maximum delay spreads are given by $\{T_{hij}\}_{i=0, j=0}^{N_t-1, N_r-1}$. The overall maximum delay spread can be written as $T_h = \max\{T_{h_{ij}}\}$. Consider an UWB system with $N_t = 2$ and arbitrary N_r receiving antenna. The output of the first transmit antenna during each symbol $T_s = N_f T_f$ is given by [8]:

$$S_0(t) = s\sqrt{\frac{E}{2N_f}}\sum_{n_f=0}^{N_f-1} (-1)^{n_f} w(t - n_f T_f) \quad (9)$$

and the output of the second transmit antenna is:

$$S_1(t) = s\sqrt{\frac{E}{2N_f}}\sum_{n_f=0}^{N_f-1} w(t - n_f T_f) \quad (10)$$

The codeword of the STC per symbol and $N_f = 2$ is shown in fig. 1.

IV. CONTIUOUS WAVELET TRANSORM (CWT)

Wavelets are defined as small waveforms with different oscillatory structure that is non-zero for a limited period of time (or space). The wavelet transform is a multi-resolution analysis scheme where a signal is decomposed into different frequency components (i.e. at different scales) [10].

The wavelet transform basis functions are derived with various continuous scaling and shift parameters, a and b respectively, from the mother wavelet (MW) function $\psi(t)$ as follows [21]:

$$\psi_{ab}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \quad (11)$$

There are various MW like, Daubechies wavelets family, Morlet and Mexican Hat [22].

The CWT of the signal $s(t)$ is defined by the wavelet coefficients [21] given by:

$$W_f(a,b) = \int_{-\infty}^{\infty} s(t)\psi_{ab}(t)\,dt \quad (12)$$

Where $W_f(a,b)$ represents the similarity between the signal $s(t)$ and the MR at the scale a and dilation b (i.e. like the correlation between $s(t)$ and $\psi_{ab}(t)$). The scale a is physically defined as an inverse proportional to the frequency [22].

$$\text{Codeword/symbol} = \begin{bmatrix} w(t) & -w(t) \\ w(t) & w(t) \end{bmatrix} \quad \xrightarrow{\text{Time}} \quad \downarrow \text{Space}$$

Figure 1. STC Codeword per symbol for N_f=2

V. PROPOSED WAVELET RAKE RECEIVER

This section illustrates the proposed Wavelet Rake (WR) receiver shown in fig. 2. The WR receiver is similar to the conventional one, where it is composed of number of correlator fingers. The conventional Rake uses delayed versions of the transmitted pulse as the reference waveform, where, the delays are equivalent to the delays of the multipath components (i.e. makes use of the CIR in the time domain). While, the WT makes uses of the huge bandwidth of the UWB transmitted signal and the CIR in the frequency domain. In the WR the template waveforms of the correlators are the CWT of the transmitted pulse $w(t)$ at a different scale (thus different center frequency f_c) for each finger $W_{a(l)}(t)$.

For the reference waveform $W_{a(l)}(t)$, $a(l)$ is the scale at the l^{th} Rake finger, where l=0,1,2 …L-1 and $a(l)>a(l-1)$. At each finger the reference waveform $W_{a(l)}(t)$ at scale al (or center frequency $f_{c(l)}$) is delayed by $\tau_{g(l)}$. Where, $\tau_{g(l)}$ is the group delay corresponding to the center frequency $f_{c(l)}$.

The mother wavelet (MW) transform function used is chosen to be with high similarity with the transmitted pulse and poor similarity with the noise. Thus, at the correlators, high correlation is obtained with the transmitted pulse and low correlation with the background noise.

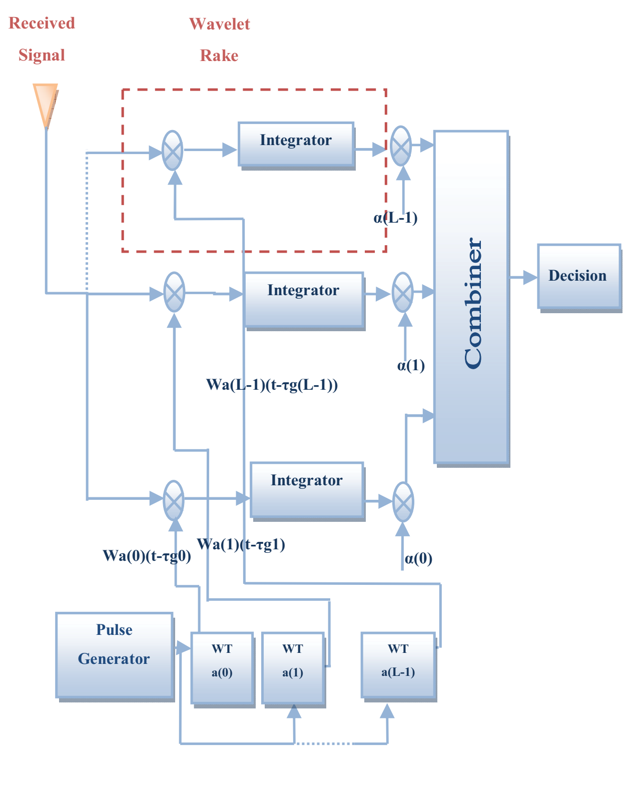

Figure 2. Wavelet Rake (WR) receiver

VI. SIMULATION AND RESULTS

In this section the simulation, results and comparison between different systems using conventional Rake, GA Rake, and the proposed WT Rake receivers are illustrated for SISO and STC MIMO UWB systems.

As stated in section II the channel used is the modified SV-model. The main parameters of the channel are presented in the IEEE802.15.3a proposal for the line-of-sight (LOS) channel CM1 [19]. The multipath components used are the optimum 20 paths, i.e. $M = M_{ij} = 20$ for $i = 0….N_{t\text{-}1}$ and $j = 0$ … $N_{r\text{-}1}$ [2]. The group delay of CM1 verses frequency is shown in fig. 3. The transmitted pulse is the second derivative of the Gaussian function shown in fig. 4 with pulse width 0.5ns and unit energy.

The MW function used in the proposed WR receiver is the Mexican Hat wavelet due to its high similarity with the transmitted monocycle pulse. The Mexican Hat MW is presented by [22]:

$$\psi(t) = (1-t^2)e^{\frac{-t^2}{2}} \qquad (13)$$

The CWT coefficients of the transmitted pulse $w(t)$ using Mexican Hat MW is illustrated in fig. 5. The WR fingers reference waveforms are selected to be the CWT wavelets at optimum scales. The optimum scales (or frequency components) are those with highest coefficients amplitude, which indicates the highest resemblance between the MW and the transmitted pulse $w(t)$ at theses scales (or frequencies, where theses frequency components are supposed to be within the transmitted pulse bandwidth). The optimum scale can be estimated from fig.5 to be a=1.5-4. Thus, the reference waveforms of the corelator fingers are the CWT of $w(t)$, scaled with scales within that range. And so, each finger template reference is highly correlated with the transmitted pulse at different f_c and poorly correlated with the noise. The frequency response of the transmitted pulse $w(t)$ and of the CWT wavelets using Mexican Hat at different scales is shown in fig. 6.

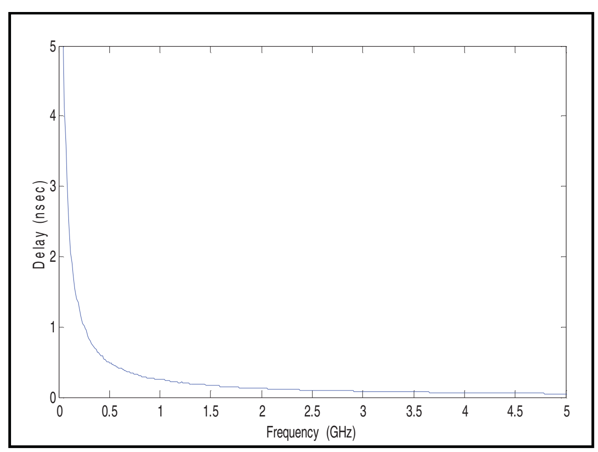

Figure 3. The group delay of CM1 channel verses frequency

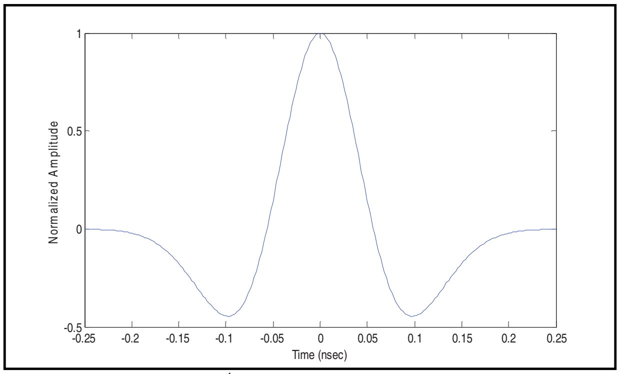

Figure 4. The 2^{nd} derivative Gaussian monocycle pulse

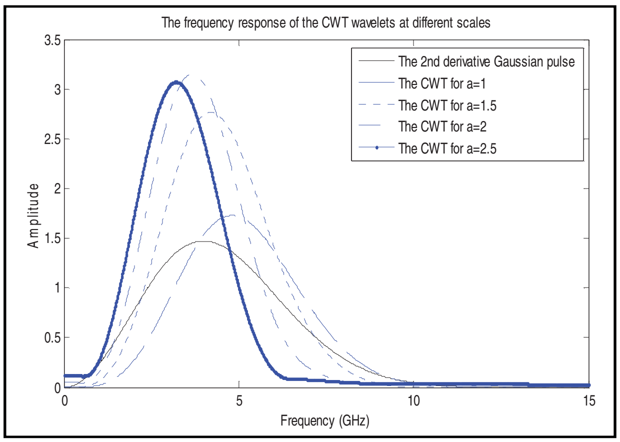

Figure 5. The CWT coefficients of the 2^{nd} derivative Gaussian Pulse at different scales

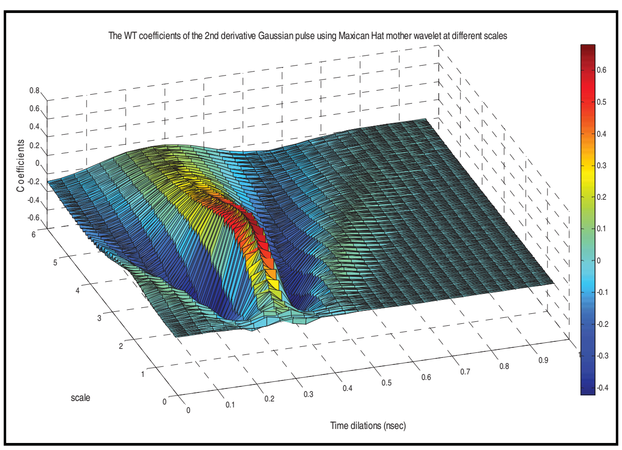

Figure 6. The frequency response of the transmitted pulse and the Mexican Hat wavelets at different scales

The wavelet analysis of the received signal containing delayed versions of the transmitted pulse is shown in fig. 7 for CM1 multipath channel. The analysis in fig. 7 shows the different frequency components (scales) of the received signal at different delays.

It is shown in [7] that enhancing the performance of a SISO or MIMO STC UWB communication system using a Rake receiver require increasing the number of fingers or increasing the delay between fingers. The adaptive GA Rake receiver presented in [1], succeeded to overcomes this problem where the optimizing GA algorithm is used to select the delays between Rake receiver fingers to enhance the performance without increasing the system complexity. The main idea is to use GA to select the delay fingers that are nearly equal to the multipath component delay. The proposed WR receiver introduces further enhancement without increasing the receiver complexity especially for low SNR (required by FCC limitations). As illustrated in this section the WR receiver outperforms both conventional and GA Rake receivers, this is in addition to, overcoming the time consumed by the GA optimization process in the GA Rake receiver.

The performance UWB SISO system using conventional Rake and WR receivers for different number of fingers L is shown in fig. 8. It can be seen that the WR receiver outperforms the conventional one for low SNR for L=4 and L=8. It is also concluded from figure that, as the number of fingers is increased the rate of enhancement is increased (the enhancement in performance for L=8 is greater than that for L=4). It is also seen that the WR performs with L=4 is better than the CR case with L=8 for SNR less than 11dB (required by FCC regulations). That is to say, it is obtaining better performance with less complexity.

The efficiency of the MISO STCI system with CR receiver presented in [7] and [8] is compared to that using WR receiver in fig. 9. It is estimated from figure that the MISO STCI system outperforms the SISO and STC systems using CR by 7.71 and 3.12dB respectively for L=4, and 8.74 and 5.05dB for L=8 (as L increases the rate of performance enhancement increases).

The performance is also examined with different non-line-of-sight (NLOS) channels CM2, CM3, and CM4 presented in the IEEE802.15.3a proposal. The channels main parameters are shown in table. I [3], [19]. This is illustrated in fig. 10 for a MISO STCI system using CR and WR receivers. Fig. 10 shows the significant enhancement in performance for highly multipath NLOS channels which is about 13dB for CM2 and CM3, and 15dB for CM4 using L=4.

Further simulations took place for the MISO STC scheme with N_r=2 for channel CM1, which increases the diversity gain. The diversity gain is shown in fig. 11, where it compares the BER of the MISO STCI and the MIMO STCI using CR and WR receivers with L=4 . It is clear from fig. 11 that the MISO system using WR receiver nearly achieves the same BER of the MIMO one with N_r=2 using CR receiver. Thus, the WR decreases the receiver complexity. The figure also shows that the MIMO STCI (N_t=N_r=2) system using WR leads in performance that using CR by 3.85dB.

Finally, the proposed WR receiver with the MISO STCI UWB system is compared to GA Rake receiver with the same system introduced in [1]. Where, the GA Rake uses the genetic algorithm process to adaptively adjust the Rake fingers delays to select optimum paths. This comparison is illustrated in fig. 12. It is obvious from fig. 12 that the WR outperforms the GA one for low SNR especially for L=8. Thus, using the WR enhances the performance of the system using GA Rake; this is in addition to avoiding the processing time consumed by GA optimization process.

TABLE I. MULTIPATH CHANNELS MODEL PARAMETERS AS PRESENTED IN THE IEEE802.15.3A REPORT.

Model Parameters	Multipath Channels			
	CM1	***CM2***	***CM3***	***CM4***
Channel Condition	LOS	NLOS	NLOS	Extreme NLOS
Range	0-4m	0-4m	1-10m	0-10m
Cluster arrival rate (Λ [1/nsec])	0.0233	0.4	0.0667	0.0667
Ray arrival rate (λ [1/nsec])	2.5	0.5	2.1	2.1
Cluster decay factor (Γ)	7.1	5.5	14	24
Ray decay factor (γ)	4.3	6.7	7.9	12

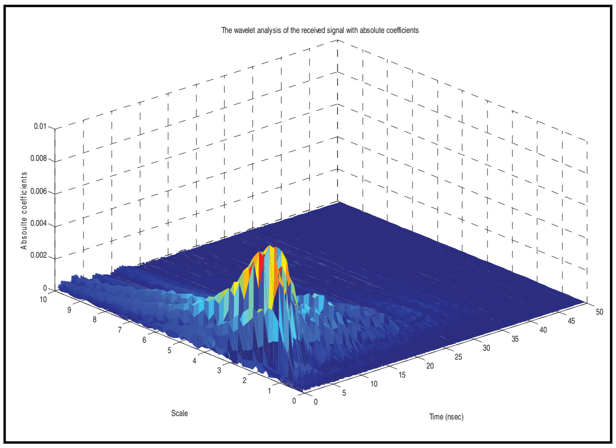

Figure 7. The wavelet analysis of received signal showing the different frequency components (scales) arriving at different delays

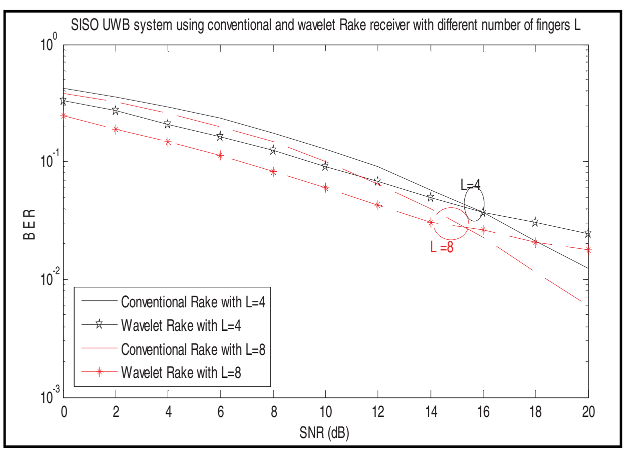

Figure 8. The BER performance of SISO UWB system using conventional Rake and WR

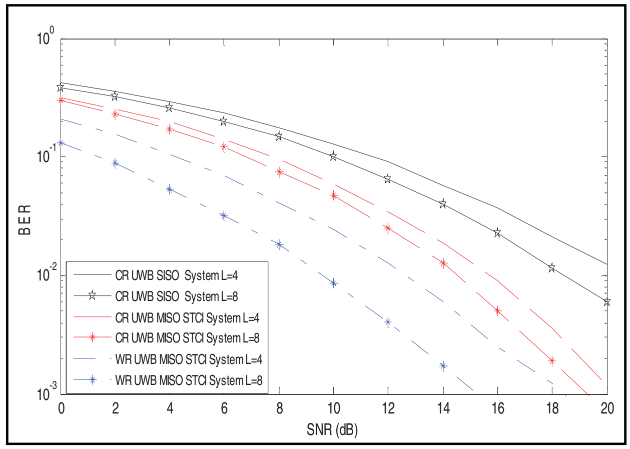

Figure 9. Comparison of the BER performance of MISO STCI using CR and WR receivers for CM1

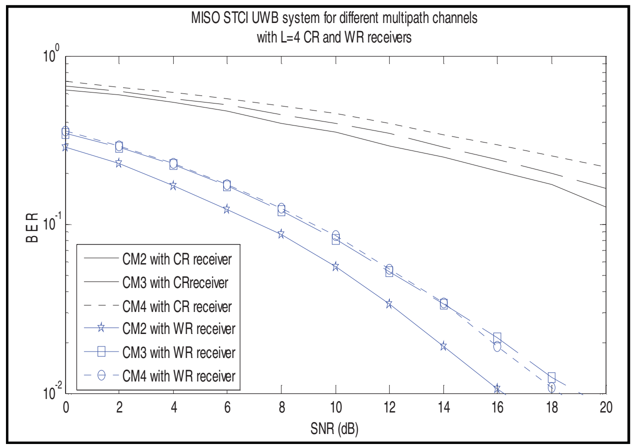

Figure 10. Comparison of the BER performance of MISO STCI using CR and WR receivers for different multipath channels and *L*=4

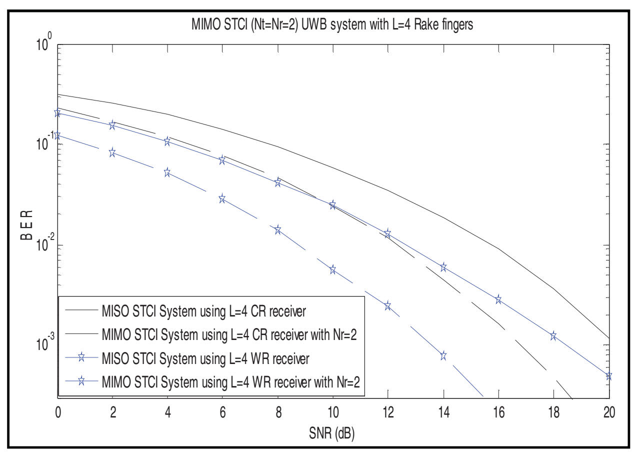

Figure 11. Comparison of the BER performance of MISO and MIMO STCI Systems using CR and WR receivers

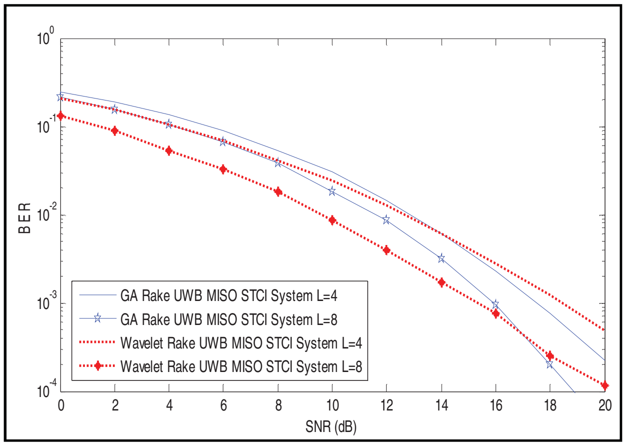

Figure 12. Comparison of the BER performance of MISO STCI UWB system using GA Rake and WR receivers for different number of fingers

VII. CONCLUSION

In this paper a Wavelet Rake receiver is introduced with a SISO, MISO STCI, and MIMO STCI UWB systems. The Wavelet Rake is compare to the conventional Rake receiver and the adaptive Rake using Genetic Algorithm for the previously mentioned systems. Simulations showed that the Wavelet Rake receiver outperforms the conventional Rake receiver for different channel models. The enhancement is greatly increased when using the STCI scheme (increasing the diversity gain) with MISO and MIMO systems especially with L=8. This is in addition to the ability of the Wavelet Rake receiver to decrease the complexity of the receiver. Where, the Wavelet Rake can obtain the same performance of the conventional Rake with lower number of fingers.

The Wavelet Rake performance is also compared to the GA Rake receiver which uses GA to adjust the Rake fingers delays to select the optimum paths. Simulation also showed that the Wavelet Rake introduces better performance than a GA Rake receiver. This is in addition to the simplicity of construction of the Wavelet Rake receiver and decreasing the processing time due to the GA process in the adaptive GA Rake receiver.

REFERENCES

[1] Said E. El-Khamy, Ehab F. Badran, Amira I. Zaki “UWB Analog Space Time Coding Systems Using A Genetic Algorithm Based Adaptive Rake Receiver,” Proceedings of the 4th International Conference on Signal Processing and Communication Systems, Australia, December 2010.

[2] John D. Choi, and Wayne E. Stark “Performance of Ultra-Wideband Communications with Suboptimal Receivers in Multipath Channels,” IEEE Journal on Selected Areas in Communications, vol. 20, No. 9, December 2002.

[3] I. Oppermann, M. Ha¨ma¨ la¨ inen and J. Iinatti “UWB Theory and Applications,” England, John Wiley & Sons, Ltd, 2004.

[4] M. Ghavami, L. B. Michael, R. Kohno “Ultra Wideband Signals and Systems in Communication Engineering,” England, John Wiley & Sons, Ltd, 2004.

[5] B. Mielczarek, M. Wessman, A. Svensson “Performance of Coherent UWB Rake Receivers with Channel Estimators,” IEEE 58th, Vehicular Technology Conference, vol. 3, October 2003.

[6] M. Z. Win ,G. Chrisikos, N. R. Sollenberger “Performance of Rake Reception in Dense Multipath Channels: Implications of Spreading Bandwidth and Selection Diversity Order,” IEEE Journal on Selected Areas in Communications, vol. 18, no. 8, August 2000.

[7] L. Yang, G. B. Giannakis “Analog Space–Time Coding for Multi-antenna Ultra-Wideband Transmissions,” IEEE Transactions on Communications, vol. 52, no. 3, March 2004.

[8] T. Kaiser, F. Zheng, E. Dimitrov “An Overview of Ultra-Wide-Band Systems with MIMO,” IEEE Proceedings, vol. 97, no. 2, February 2009.

[9] Said E. El-Khamy, Ehab F. Badran, Amira I. Zaki “Interference Rejection in UWB Systems Using Smart STC Based on GA Rake Receivers and TR Technique,” Proceedings of the 28th National Radio Science Conference, NRSC 2011, Cairo, Egypt, March 2011.

[10] M. K. Lakshmanan, H. Nikookar “A Review of Wavelets for Digital Wireless Communication,” Wireless Personal Communications, vol. 37, no. 3, May 2006.

[11] H. M. Oliveira, H. A. Silva, E. A. Bouton “Wavelet Shift-Keying: A New DigitalModulation,” XX Simpósio Bras. de Telecomunicações, Rio de Janeiro, October, 2003.

[12] Fadel S. Hassen “The Performance of Orthogonal Wavelet Division Multiplexing (OWDM) in Flat Rayleigh Fading Channel,” Journal of Engineering and Development, vol. 12, no. 1, March 2008.

[13] Abbas Hasan Kattoush, Waleed A. Mahmoud, S. Nihad “The Performance of Multiwavelets Based OFDM System Under Different Channel Conditions,” Digital Signal Processing, vol. 20, no. 2, March 2010.

[14] L. F. Chernogo, O. V. Lasorenko “Application of The Wavelet Analysis for Detecting Ultra-Wideband Signals in Noise,” VIIIth International Conference on Mathematical Methods in Electromagnetic Theory, 2000.

[15] Limin Yu, Langford B. White “Design of Complex Wavelet Pulses Enabling PSK Modulation for UWB Impulse Radio Communications,” Auswireless Conference, 2006.

[16] Y. Kim, B. Jang, C. Shin, B. F. Womack “Orthonormal Pulses for High Data Rate Communications in Indoor UWB Systems,” IEEE Communications Letters, vol. 9, no. 5, May 2005.

[17] Bikramaditya Das, Susmita Das “Interference Cancellation Schemes in UWB Systems Used in Wireless Personal Area Network based on Wavelet based Pulse Spectral shaping and Transmitted Reference UWB using AWGN Channel Model,” International Journal of Computer Applications, vol. 2, no. 2, May 2010

[18] Lloyd Emmanuel, Xavier N. Fernando “Wavelet-Based Spectral Shaping of UWB Radio Signal for Multisystem Coexistence,” Computers and Electrical Engineering Journal, vol. 36, no. 2, March 2010.

[19] J. Foerster, M. Pendergrass, A. F. Molisch “A channel model for ultra-wideband indoor communications,” Proceedings of the 6th International Symposium on Wireless Personal Multimedia Communications, Yokosuka, Japan, pp. 116–120, 2003.

[20] J Blauert, p. Laws “Group Delay Distortion in Electroacoustical Systems,” Acoustical society of America, vol. 63, no. 5, May 1978.

[21] Ali N. Akansu, Wouter A. Serdijn, Ivan W. Selesnick “Emerging Applications of Wavelets: A Review,” Physical Communication, vol. 3, no. 1, 2010

[22] S. E. El-Khamy, M. Al-Ghoniemy “The Wavelet Transform a Review and Application to Enhanced Data Storage Reduction in Mismatched Filter Receivers,” Proceedings of the National Radio Science Conference, NRSC, Cairo, Egypt, March 1996