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A NUMERICAL STUDY ON TIME-REVERSAL ELECTROMAGNETIC WAVE FOR INDOOR ULTRA-WIDEBAND SIGNAL TRANSMISSION

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Abstract—In this paper, the propagation of ultra-wideband (UWB) pulse based on time reversal (TR) technique is studied by finite-different time-domain method in indoor environment. Time compression and spatial focusing of TR waveform are simulated and the propagation of multi-waveform string is analyzed. Then UWB wireless signal transmission based on TR concept is studied numerically. The studied results indicate that the UWB communication based on TR technique can obtain better Inter-Symbol Interference (ISI) and Co-Channel Interference (CCI) performance than traditional one because of its unique property.

1. INTRODUCTION

From the view of electromagnetics, ultra-wideband (UWB) wireless communication uses short pulse to transmit data, at the same time, occupies wide spectrum. Because of its high data rate, big capability and ability to anti-interference, UWB communication becomes a hot spot of research and is considered as one of the important candidates for next generation wireless communication [1–6]. Generally, UWB commutation is utilized to transmit data in short distance, such as in offices or other indoor environments. Rich multi-path scattering is generated by complex application surrounding, which results in a serious problem: Inter-Symbol Interference (ISI). ISI together with Co-Channel Interference (CCI) are two important factors to influence the performance of UWB wireless communication [7–9].

Recently, a novel technique, i.e., Time Reversal (TR) mirror, is introduced into UWB communication system to further improve performance [10–13]. In TR UWB communication, wireless signal transmission includes two steps: (I) the field radiation by source is initially recorded at a transducer antenna; then (II) it is time-reversed and retransmitted by the same antenna acting as a TR mirror. The resulting wave refocuses at the initial source position (spatial focusing) and is compressed into a pulse (time compression). Actually, TR mirror is a time-spacing matching filter technique. Time compression and spatial focusing of transmitted electromagnetic pulses are resulted from the TR process [14]. This unique property reduces not only ISI but also CCI in UWB communication [15].

In traditional UWB communication, the space information is only differentiated by the distance between transmitter and receiver, which has been revealed by IEEE UWB channel modeling suitable for the frequencies within 3.1 GHz–10.6 GHz [16]. However, it is very difficult to analyze TR UWB communication roundly and deeply using those previous technologies because one of the most important potentials of TR UWB communication is to utilized space information to realize perfectly the concept of Space Division Multiple Access (SDMA). Many challenges are encountered in the study of TR communication. TR mirror is presented based on reciprocity theorem and applied into underwater acoustic communication firstly [17]. Some efforts have been carried out to investigate TR electromagnetic wave [18]. Based on existing studies, we can draw a conclusion that one has only an abecedarian understanding on TR UWB communication and a deeper understanding in TR electromagnetism is needed to exploit the application potential in wireless communication. To avoid time-consuming and expensive experiments, numerical simulation based on computational electromagnetics methods is an alternative approach to study TR electromagnetic wave for UWB wireless signal transmission.

In this paper, the finite-different time domain (FDTD) method is applied to simulate the propagation characteristic of TR UWB electromagnetic wave in indoor environment [19–21]. The characteristics of time compression and spacing focusing of TR UWB signals are analyzed, and UWB signal transmissions for TR UWB communication are studied numerically to demonstrate its potential applications.

2. GEOMETRY OF COMMUNICATION ENVIRONMENT

The selected communication environment for simulation is a simplified office. Figure 1 shows the top view of the office, which have a space of $W \times L \times H = 4.0\,\text{m} \times 6.0\,\text{m} \times 4.0\,\text{m}$. The boundaries filled with diagonal are concrete wall with dielectric constant of 8.0 and thickness of 0.25 m.

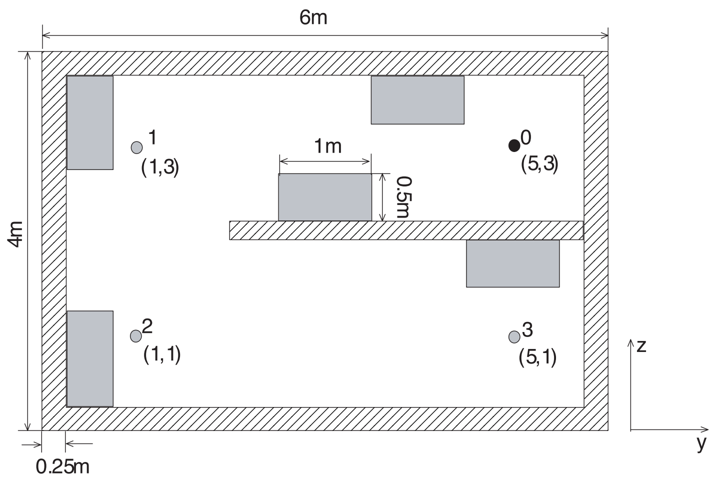

Figure 1. Top view of the office.

Five rectangle book cases are located in the office and against the wall. They are made of metal plates and have an outer size of $L_b \times W_b \times h_b = 1.0\,\text{m} \times 0.5\,\text{m} \times 2.0\,\text{m}$. The relative positions of the left-bottom corner of metal book cases to office left-bottom corner are (0.0, 0.0, 0.0)m, (0.0, 0.0, 2.75) m, (0.0, 2.5, 2.5) m, (0.0, 3.5, 3.25) m and (0.0, 4.5, 1.5) m, respectively. One window with area of $L_w \times h_w = 2.0\,\text{m} \times 1.0\,\text{m}$ is positioned at the center of each surrounding wall and away from the ground 2.0 m. The desks, made of thin ligneous plates, are ignored because of a small average relative dielectric constant in its volume.

Four antennas, Antenna 0, Antenna 1, Antenna 2 and Antenna 3, are used in this communication platform to transmit or receive signals. Four antennas are located at (1.0, 5.0, 3.0) m, (1.0, 1.0, 3.0) m, (1.0, 1.0, 1.0) m, and (1.0, 5.0, 1.0) m, respectively. Antenna 0 is used as a base station antenna in which the recorded signals can be time-reversed and retransmitted. Antenna 1, Antenna 2 and Antenna 3 are the antennas for User 1, User 2 and User 3, respectively. Three links between base station and users correspond to one line-of-sight (LOS) case and two non-line-of-sight (NLOS) cases.

3. SIMULATIONS AND DISCUSSIONS

3.1. UWB Electromagnetic Pulse Source in Simulation

FDTD method is used to simulate UWB wireless signal propagation in present communication environment. In order to explore the pulse response between base station antenna and user's antenna, the user's antenna emits a short pulse, and the response is recorded by base station antenna. The short pulse source transmitted by users' antennas is a Gaussian pulse:

$$E_x(t) = exp(-\frac{(t-t_0)^2}{\tau^2}) \tag{1}$$

where $t_0 = 1.\,\mathrm{ns}$ and $\tau = 0.\,\mathrm{ns}$ are chosen in this simulation. The frequency with $-10\,\mathrm{dB}$ attenuation in Gaussian pulse spectrum is about 1.0 GHz. We select this frequency band to make sure that the whole communication environment can be simulated by FDTD method. During the course of simulation, the space steps along x-, y- and z- axis are $\Delta x = \Delta y = \Delta z = 0.025\,\mathrm{m}$. The computational domain is divided into $N_x \times N_y \times N_z = 160 \times 240 \times 160$ cells. Time step of $\Delta t = 48.1458\,\mathrm{ps}$ is selected to satisfy stability condition. The time width of Gaussian pulse is about $60\Delta t$. The ideal dipoles occupied one grid in the x-direction are used as transmitter or receiver antennas. we must mention that the low frequency components of Gaussian pulse can be filtered in FDTD simulation automatically.

3.2. Point-to-point UWB Signal Transmission Simulation

Firstly, we simulate a point-to-point communication case. As a example, the link between Antenna 0 and Antenna 2 is analyzed numerically. User 2 emits a short pulse, the pulse response is recorded by base station antenna. Then the recorded waveform is time-reversed and transmitted by Antenna 0. The resulting wave travels back and the corresponding response is received by User 2 finally. The normalized response is plotted in Fig. 2(a). The field distribution on the horizontal plane above ground 1.0 m at the peak time of the recovered response is showed in Fig. 3. For comparison, the normalized channel response of Gaussian pulse itself in the selected communication link is shown in Fig. 2(b). The FDTD simulation indicates that the Gaussian pulse response converges well enough at $t = 10000\Delta t$. Based on Figs. 2 and 3, it can be noticed that at User 2, the channel response of TR signal gets its peak and decline very quickly in time and spacing. This phenomenon is called as time-compression and spatial focusing of TR electromagnetic wave.

Propagations of TR waveform strings between Antenna 0 and Antenna 2 are also simulated. The TR waveform string formed by the isolated time-reversed pulse response waveforms (with periodicity of $10000\Delta t$) is transmitted by Antenna 0 and the normalized response recorded by User 2 is shown in Fig. 4(a). Then, the time-reversed

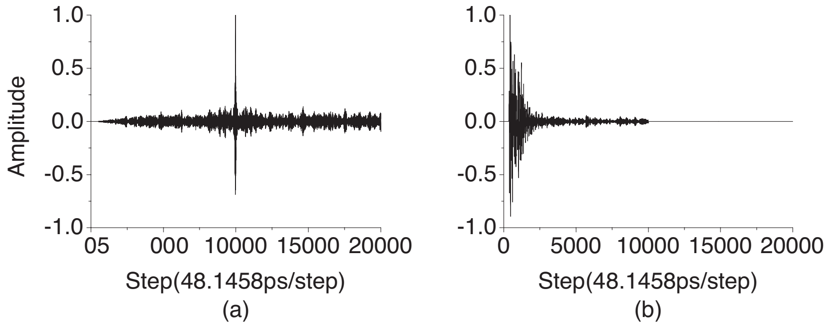

Figure 2. The normalized single pulse response between Antenna 0 and Antenna 1; (a) channel response of time reversal waveform and (b) channel response of Gaussian pulse.

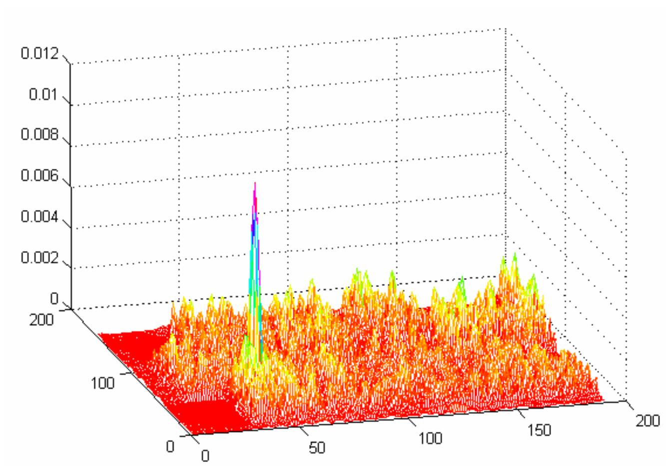

Figure 3. Field distribution on the horizontal plane above ground 1.0 m at peak time.

waveform strings with periodicity of $600\Delta t$ and 60 Δt are transmitted, respectively. In these cases, the time-reversed response waveforms are overlapped each other partly. Their normalized responses are shown in Fig. 5(a) and Fig. 6(a). For the purpose of comparison, the normalized channel responses of Gaussian pulse strings with same time periods are shown in Figs. 4(b), 5(b) and 6(b), respectively.

From Figs. 4–6, it can be seen that, by using time-reversed waveform as a transmitting template an excellent anti-ISI performance can be observed though the waveform periodicity is very small.

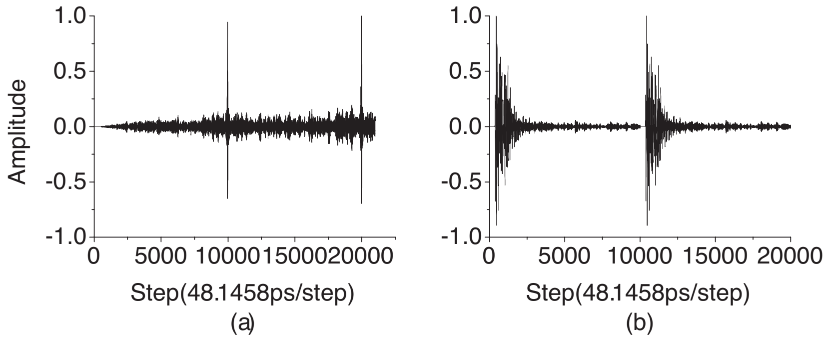

Figure 4. The normalized response of waveform strings with periodicity of 10000 time steps; (a) for TR waveform, and (b) for Gaussian pulse.

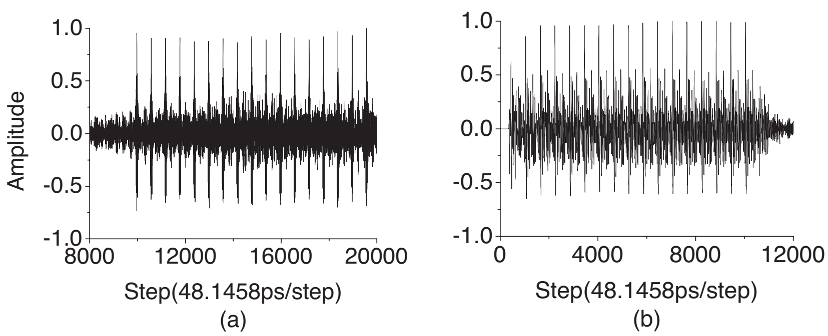

Figure 5. The normalized response of waveform stings with periodicity of 600 time steps; (a) for TR waveform, and (b) for Gaussian pulse.

However, bad ISI performance can be found when Gaussian pulse waveform is used as a template and transmitted with a small periodicity. Fig. 5 indicates that when the periodicity is ten times time width of Gaussian pulse the amplitude of response peak has about 50% increasing (from 0.65 to 1) by ISI in traditional UWB communication, but only 3% fluctuation is observed in TR case. Especially, Fig. 6 shows that an acceptable anti-ISI performance can be obtained still even if the repeat periodicity of TR waveforms is the same as the time width of Gaussian pulse, but it is unacceptable to use such short periodicity in traditional scheme. These studies imply that higher data rate can be obtained more conveniently in TR UWB communication,

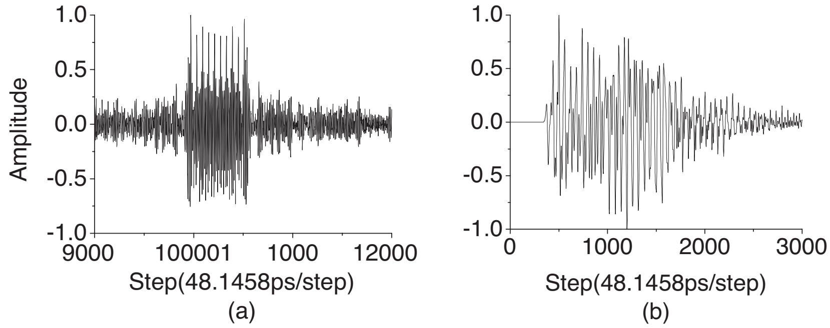

Figure 6. The normalized response of waveform stings with periodicity of 60 time steps; (a) for TR waveform, and (b) for Gaussian pulse.

and compared with traditional UWB receiver, the receiver structure of TR UWB communication system can be simplified because the complex rake selection receiving is not needed.

3.3. Multi-user UWB Signal Transmission Simulation

Multi-user TR communication issue is simulated in this subsection. Three users with long distance, i.e., User 1, User 2, and User 3, are selected to demonstrate the electromagnetic interferences among them in present communication environment. In the first step, Gaussian pulse responses between base station antenna and users' antennas are calculated and recorded, respectively. These responses are time-reversed and used as respective signal element template for different users. In order to identify the interferences directly, the Time-Hopping Pulse Position Modulation (TH-PPM) scheme is used to modulate the time-reversed waveform strings. Fig. 7(a), Fig. 8(a) and Fig. 9(a) show three sequences modulated by TH-PPM codes for three users in one TH code periodicity, respectively. The modulated time reversed waveform strings are added together and transmitted by base station antenna simultaneously. The received signals by User 1, User 2, and User 3 are shown in Figs. 7(b), 8(b) and 9(b), respectively. The simulated interference peak values resulted from other users are extracted and listed in Table 1.

Sequentially, the electromagnetic interferences among close users are studied in TR UWB system. In LOS case, the electromagnetic interference to User 1 is observed. Three additional users are set near Antenna 1 with distances of $d = 30\,\text{cm}$, 15 cm and 7.5 cm, respectively,

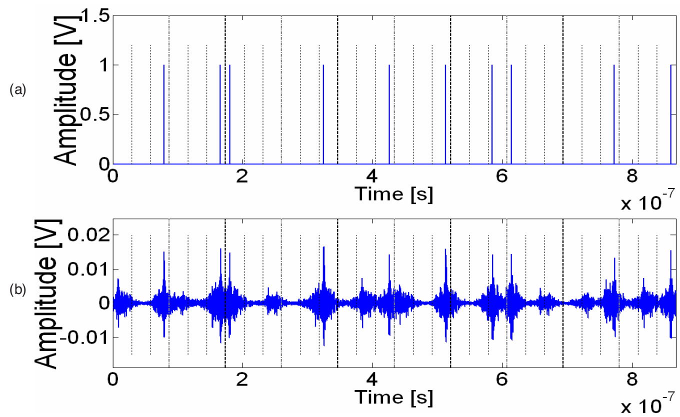

Figure 7. (a) TH-PPM signals for User 1 in TR communication case and (b) the recorded response by User 1 with interferences from User 2 and User 3.

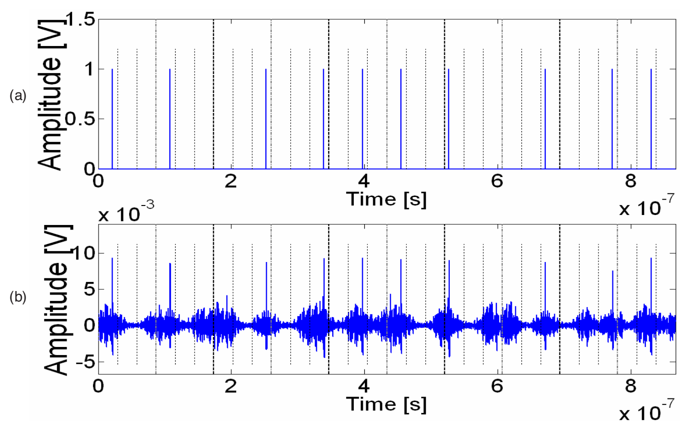

Figure 8. (a) TH-PPM signals for User 2 in TR communication case and (b) the recorded response by User 2 with interferences from User 1 and User 3.

they correspond to one wavelength, half of wavelength and quarter wavelength at the upper limit frequency of Gaussian pulse. Fig. 10 shows the interference to User 1 from near users in one TH code periodicity. User 2 and User 3 are used as samples for NLOS case. Three additional users are set around User 2 and User 3, respectively, and the additional users are set like in LOS case. Similarly, the electromagnetic interferences to User 2 and User 3 are simulated

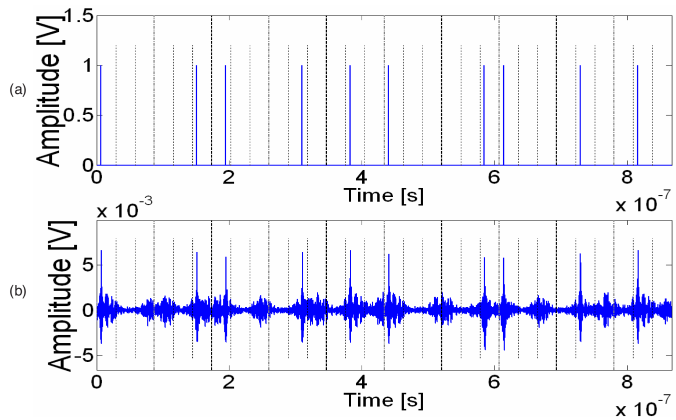

Figure 9. (a) TH-PPM signals for User 3 in TR communication case and (b) the recorded response by User 3 with interferences from User 1 and User 2.

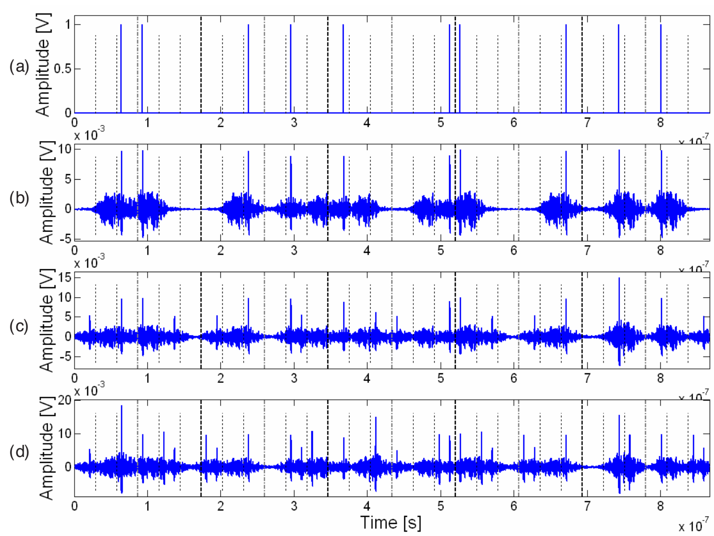

Figure 10. The interference to User 1 by close users, (a) TH-PPM signals, (b) the response with the interference from one user with distance of 30 cm, (c) the response with the interferences from two users with distances of 30 cm and 15 cm, and (d) the response with the interference from three users with distances of 30 cm, 15 cm and 7.5 cm.

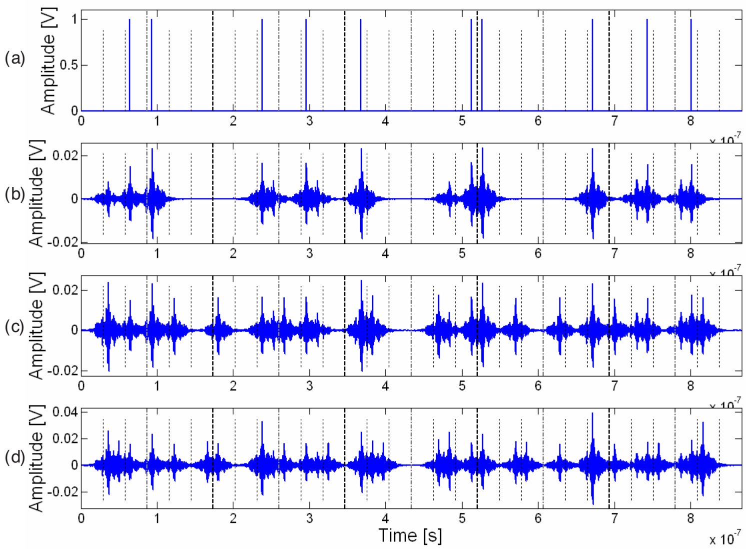

Figure 11. The interference to User 2 by close users, (a) TH-PPM signals1, (b) the response with the interference from one user with distance of 30 cm, (c) the response with the interferences from two users with distances of 30 cm and 15 cm, and (d) the response with the interference from three users with distances of 30 cm, 15 cm and 7.5 cm.

numerically. The results are indicated in Figs. 11 and 12. The related interference peak values between two close users (essentially, interference peak value denotes the correlation of two channel impulse response) are extracted and shown in Table 1.

Table 1. The interference peak values from other users.

User	Related interferences from other users with different distance			
	Two users	One user	One user	One user
	long distances	d=30cm	d=15cm	d=7.5cm
LOS: User 1	0.28	0.48	0.98	1.1
NLOS: User 2	0.31	0.28	0.6	0.98
NLOS: User 3	0.15	0.39	0.49	0.8

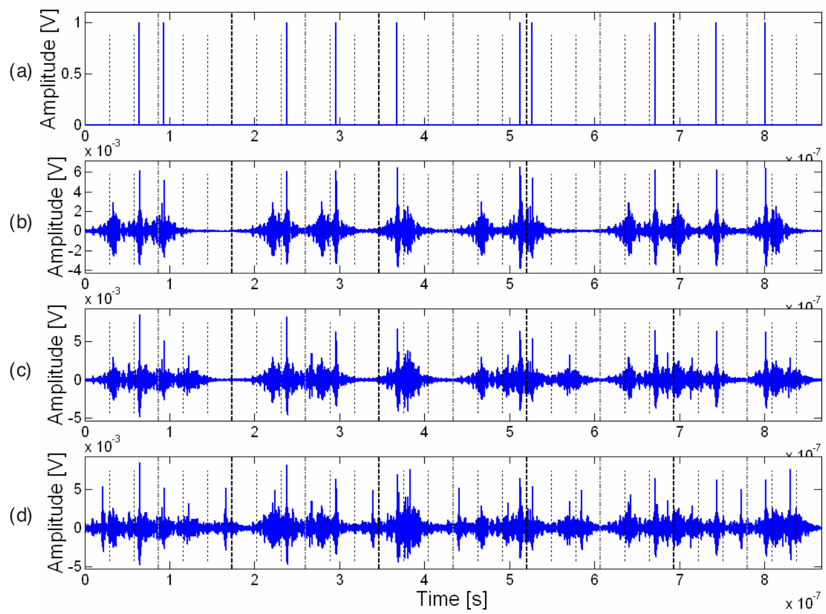

Figure 12. The interference to User 3 by close users, (a) TH-PPM signals1, (b) the response with the interference from one user with distance of 30 cm, (c) the response with the interferences from two users with distances of 30 cm and 15 cm, and (d) the response with the interference from three users with distances of 30 cm, 15 cm and 7.5 cm.

From Figs. 7–12 and Table 1, it can be found directly that the channels' correlation is weak when the distance between users is large enough, typically, one wavelength at the upper limit frequency of Gaussian pulse. The electromagnetic interference between users is still acceptable even if the distance between users equals to half of wavelength at the upper limit frequency of Gaussian pulse. The interferences among User 1, User 2 and User 3 are simulated in traditional UWB communication. The results show that the electromagnetic interfaces are very serious even if the distance between users is long. As a typical example, Fig. 13 shows the recorded signal response by User 3 when Gaussian pulse template is adopted. Based on these results, on can see that a better anti-CCI performance can be obtained and the communication capability can be increased dramatically due to combining TR mirror concept into traditional UWB communication.

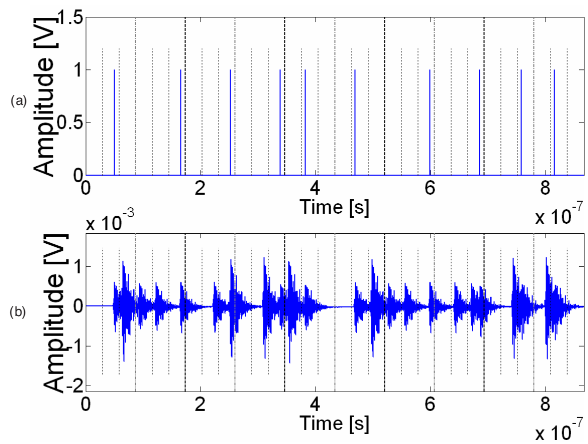

Figure 13. (a) The transmitted TH-PPM signals for User 3 and (b) the recorded response by User 3 under the case of traditional UWB multi-user communication.

4. CONCLUSIONS

TR UWB signal has a propagation property of time compression and spatial focusing. In this paper, this unique property is simulated firstly by the FDTD method in indoor environment. Then the FDTD method is used to simulate UWB signal transmission based on TR technique in point-to-point communication case. The studies indicate higher data rate can be obtained in TR UWB communication system compared with the traditional one. Finally, the case of TR multi-user communication is analyzed by electromagnetic simulation. In our examples, one can observe that when the distance between different users is larger than one wavelength at the maximum frequency of Gaussian pulse the communication links for them are almost independent each other due to combining TR technique into traditional UWB communication system. The studies indicate that there is a huge potential to improve the communication capability in TR UWB communication.

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REFERENCES

1. Qiu, R. C., H. P. Liu, and X. Shen, "Ultra-wideband for multiple access," *IEEE Commun. Mag.*, Vol. 43, No. 2, 80–87, Feb. 2005.
2. Choi, J. D. and W. E. Stark, "Performance of ultra-wideband communications with suboptimal receivers in multipath channels," *IEEE J. Select. Areas Commun.*, Vol. 20, No. 9, 1754–1766, Dec. 2002.
3. Chen, Z.-N., X. H. Wu, H. F. Li, N. Yang, and M. Y. W. Chia, "Considerations for source pulses and antennas in UWB radio systems," *IEEE Trans. Antennas Propagat.*, Vol. 52, No. 7, 1739–1748, July 2005.
4. Fan, Z., L. X. Ran, and J. A. Kong, "Source pulse optimizations for UWB radio systems," *Journal of Electromagnetic Waves and Applications*, Vol. 20, 1535–1550, 2006.
5. Yang, D., C. Liao, and W. Chen, "Numerical solution on coupling of UWB pulse into a rectangular cavity through slots," *Journal of Electromagnetic Waves and Applications*, Vol. 19, 1629–1638, 2005.
6. Klemm, M. and G. Troester, "EM energy absorption in the human body tissues due to UWB antennas," *Progress In Electromagnetics Research*, Vol. 62, 261–280, 2006.
7. Shen, X., M. Guizani, R. Qiu, and T. Le-Ngoc, *UWB Wireless Communications and Network*, John Wiley, New York, 2006.
8. Chong, C.-C. and S. K. Yong, "A generic statistical based UWB channel model for high-rise apartments," *IEEE Trans. Antennas Propagat.*, Vol. 53, No. 8, 2389–2399, Aug. 2005.
9. Arslan, H., Z. N. Chen, and M.-G. Di Benedetto, *UWB Wireless Communications*, John Wiley, New York, 2006.
10. Kyritsi, P., G. Papanicolaou, P. Eggers, and A. Oprea, "Time reversal techniques for wireless communications," *Proc. 60th IEEE Vehicular Technology Conference*, 26–29, 2004.
11. Thomas, S., E. Majid, H. Jan, P. George, and A. J. Paulraj, "Application of time-reversal with MMSE equalizer to UWB communications," *Proc. 2004 IEEE Global Telecommunications Conference*, 3123–3127, 2004.
12. Li, K., X. Wang, G. Yue, and L. Ping, "A low-rate code-spread and chip-interleaved time-hopping UWB system," *IEEE Journal on Selected Areas in Communications*, Vol. 24, No. 4, 864–870, Apr. 2006.
13. Yue, L. and S. Lambotharan, "A new tap constrained constant

modulus algorithm for blind equalization of time reversal space time block codes," *Proc. 2004 IEEE 5th Workshop on Signal Processing Advances in Wireless Communication*, 273–277, 2004.

14. Qiu, R. C., C. Zhou, N. Guo, and J. Q. Zhang, "Time reversal with MISO for ultrawideband communication: experiment results," *IEEE Antenna and Wireless Propagation Letters*, Vol. 5, 269–273, 2006.
15. Nguyen, H. T., J. B. Andersen, and G. F. Pedersen, "The potential use of time reversal techniques in multiple element antenna systems," *IEEE Communications Letters*, Vol. 9, No. 1, 40–42, 2005.
16. Di Benedetto, M.-G. and G. Giancola, *Understanding Ultra Wide Band Radio Fundamentals*, Pearson Education Inc., 2004.
17. Wu, F., J.-L. Thomas, and M. Fink, "Time reversal of ultrasonic fields-Part II: Experimental results," *IEEE Trans. on Ultrasonic, Ferroelectrics, and Frequency Control*, Vol. 39, No. 5, 567–578, May 1992.
18. Lerosey, G., J. D. Rosny, A. Tourin, A. Derode, and M. Fink, "Time reversal of wideband microwaves," *Applied Physics Letters*, Vol. 88, 154101-3, 2006.
19. Gong, Z. and G.-Q. Zhu, "FDTD analysis of an anisotropically coated missile," *Progress In Electromagnetics Research*, Vol. 64, 69–80, 2006.
20. Gao, S., L.-W. Li, and A. Sambell "FDTD analysis of a dual-frequency microstrip patch antenna," *Progress In Electromagnetics Research*, Vol. 54, 155–178, 2005.
21. Uduwawala, D., "Modeling and investigattion of planar parabolic dipoles for gpr applications: a comparison with bow-tie using FDTD," *Journal of Electromagnetic Waves and Applications*, Vol. 20, 227–236, 2006.