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SPATIAL FOCUSING CHARACTERISTICS OF TIME REVERSAL UWB PULSE TRANSMISSION WITH DIFFERENT ANTENNA ARRAYS

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Abstract—Spatial focusing characteristics of time reversal (TR) electromagnetic waves are studied in this paper. Different antenna arrays are used as a TR mirror and their elements are arranged in one and two dimensions in the horizontal plane. The focused energy density around initial source location is investigated in non-line-of-sight (NLOS) and line-of-sight (LOS) cases, respectively. The results demonstrated that, roughly speaking, under the case of fixed space between two adjacent elements, the more the number of the array elements, the stronger the focused average energy density. However, in the case of fixed TR mirror array aperture, some abnormal phenomena are observed when additional elements are inset into the initial one.

1. INTRODUCTION

Ultra wideband (UWB) communication and its relative technologies have been studied extensively in the past decade [1–6]. Recently, time reversal (TR) UWB communication has received much attention because the propagation of TR UWB electromagnetic waves can obtain spatial focusing and time compression characteristics simultaneously [7, 8]. This unique property results in a big potential for improving the performances of Inter-Symbol Interference (ISI) and Co-Channel Interference (CCI) of the traditional UWB communication [7–10].

For studying ISI performance of TR UWB communications, the time compression characteristic has been studied by experiments. Some researchers have measured the time compression characteristic of TR electromagnetic wave and then extract the channel model between two fixed positions in given multi-path environment to evaluate the communication performance [11]. As an important performance, CCI of TR UWB communication needs also to be focused. In order to address on CCI topic, one needs to understand substantially the spatial focusing characteristic of TR electromagnetic wave. In 2004, Lerosey et al. have engaged in it [13], where a metal cavity was used to demonstrate the spatial focusing characteristic. The metal cavity is an ideal multi-path environment and has obvious difference from the practical one for UWB communication application. However, studying spatial focusing characteristic in practical environment is an inevitable work to push TR UWB communication into applications. To avoid time-consuming and expensive experiments, electromagnetic simulation is an alternative approach to carry out this investigation.

In this paper, we analyze the spatial focusing characteristics of TR UWB signals transmitted by arrays with different space arrangements and varying element numbers in a typical office platform. The finite-different time domain (FDTD) method is applied to simulate the propagation of TR UWB wireless signals [14]. The non-line-of-sight (NLOS) and line-of-sight (LOS) cases are considered in this study, some valuable conclusions are drawn and some interesting phenomena are observed.

2. CONFIGURATION OF OFFICE PLATFORM, ANTENNA LAYOUT AND SELECTED PULSE SOURCE

A simplified office is selected as the environment for electromagnetic wave propagation. Fig. 1(a) shows the top view of the office, which has a space of $H \times L \times W = 4.0\,\mathrm{m} \times 6.0\,\mathrm{m} \times 4.0\,\mathrm{m}$. The boundaries filled with diagonals are concrete wall with a dielectric constant of 8.0 and a thickness of 0.25 m. Seven rectangle book-cases are located in the office. Four of them are against the wall and the others are arranged in a line. They have a metal surface and an outer size of $h_b \times L_b \times W_b = 2.0\,\mathrm{m} \times 1.0\,\mathrm{m} \times 0.4\,\mathrm{m}$. The relative positions of metal book-cases to the office left-bottom corner are (0.0, 0.0, 0.0) m, (0.0, 0.0, 2.5) m, (0.0, 3.5, 3.1) m, (0.0, 2.75, 1.75) m, (0.0, 3.75, 1.75) m, (0.0, 4.75, 1.75) m, and (0.0, 2.5, 0.0) m, respectively. One window with area of $h_w \times L_w = 1.5\,\mathrm{m} \times 1.0\,\mathrm{m}$ is positioned at the center of each surrounding wall and above the ground 1.25 m. The desks, made of thin ligneous plates, are ignored because of a small average relative dielectric constant in its volume.

In this study, two antennas, Antenna 1 and Antenna 2 located at (1.0, 5.0, 3.0) m and (1.0, 1.25, 3) m, respectively, are used for User 1 and User 2. An array is used as the antenna of base station. The centre of the array for base station is (1.0, 1.5, 0.1) m. The element numbers of the array is variable and the array can be arranged in

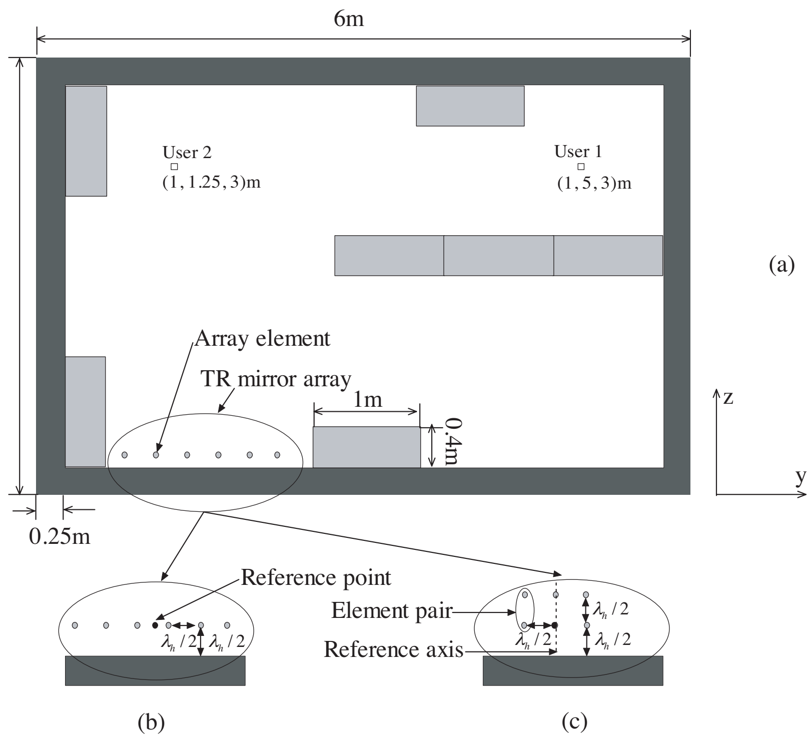


Figure 1. Configuration of communication platform and used antenna system, where λ_h is the wavelength in free space at frequency of 1.0 GHz, (a) platform for electromagnetic wave propagation, (b) linear array for base station antenna, (c) planar array for base station antenna.

one-dimension along y-axis and in two-dimension in yoz plane. The base station antenna can receive, record, time-reverse and retransmit wireless signals. Two links between base station array and User 1 and User 2 correspond to NLOS and LOS cases, respectively.

In TR UWB communication, wireless signal transmission includes two steps: (I) the transmitted field by user's antenna is initially recorded by the base station array; then (II) the recorded signal is time-reversed and retransmitted by the same array acting as a TR mirror. The resulting wave refocuses at the initial source position (spatial focusing) and is compressed into a pulse (time compression). The second derivative Gaussian pulse is used as a transmitted source by users' antennas. The FDTD method is used to simulate the electromagnetic wave propagation. The main frequency component is from 0.1 to 1.5 GHz. We select this frequency band to make sure that the whole communication environment can be simulated by the 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 $Nx \times Ny \times Nz = 160 \times 240 \times 160$ cells. Time step Δt is calculated by Courant stability condition. The omni-direction antenna model is used as transmitter or receiver antenna elements.

3. SPATIAL FOCUSING ANALYSIS OF TR UWB ELECTROMAGNETIC WAVES

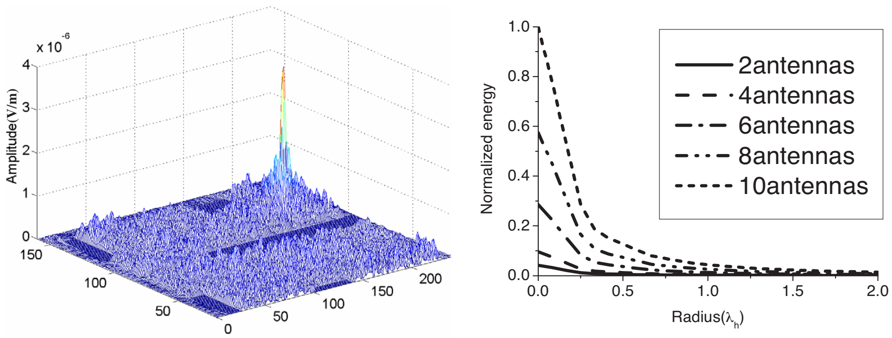
The propagation of UWB electromagnetic waves based on TR technique is studied in the communication platform mentioned above. The propagation process is simulated by the FDTD method. Two kinds of arrangement for base station antenna array, as shown in Figs. 1(b) and 1(c), are used.

3.1. Results for Linear Arrays

We analyze the case in which the base station array is arranged linearly (Fig. 1(b)). In this array, the distances between two adjacent elements and from array margin to wall are half wavelength at the frequency of 1.0 GHz. The element number in the array is even and the array is symmetrical with respect to the reference point when element number increases. Firstly, the case of NLOS (User 1) is simulated. Previous studies have indicated that the TR electromagnetic signal can be compressed into a pulse at a certain time [9]. Here, the focusing time is determined from the FDTD simulation. Then the spatial field distributions at the focusing time are studied. As examples, the field distribution in the horizontal plane containing User 1 is shown in Fig. 2(a) when a two-element array is used as the base station radiator (TR mirror). The result demonstrates that the spatial focusing of UWB electromagnetic wave is obtained due to introducing the TR operation.

The energy focusing extent versus the element numbers in array are studied in NLOS case. The average energy density (AED) around User 1 is calculated by the following expression,

$$AED(r_0) = \frac{\iint\limits_{S(r_0)} E^2(r,\varphi) r dr d\varphi}{S(r_0)} \tag{1}$$



(a) (b)

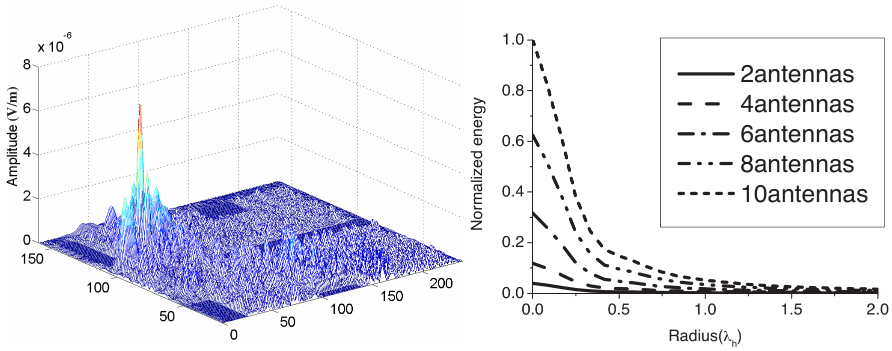
Figure 2. The spatial focus characteristic in NLOS case (User 1) when linear array is used as TR mirror, (a) the electric field distributions at the focusing time in the horizontal plane when two-element linear array is used, (b) the average energy density versus the element numbers in the linear array.

where, $E(r, \phi)$ denotes the electric field at the focusing time in the horizontal plane containing users, $S(r_0)$ is the circular area centered at the user with a radius of r_0 radius. The simulated results are shown in Fig. 2(b). All of the data are normalized to the AED at the user position in the case of ten-element array.

Similarly, the case of LOS (User 2) is analyzed. The studied results are shown in Figs. 3(a) and 3(b).

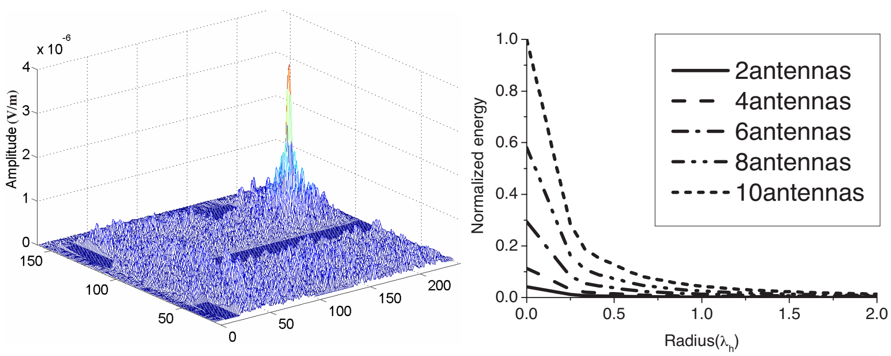
3.2. Results for Two-dimensional Arrays

The case in which the array of based station is arranged in two-dimension is studied in this subsection. The layout of the array is shown in Fig. 1(c). The spaces between two adjacent elements and from array margin to wall are the same as those of linear array case. A pair of elements is fixed on the reference axis, and then the element pairs are added on the left side and right side in turn when array elements increase from 4 to 10. NLOS and LOS links described above are considered. The spatial focusing characteristic is studied at the focusing time of TR electromagnetic wave. In NLOS case, the electric field distributions at the focusing time in the horizontal plane containing User 1 are shown in Fig. 4(a) when two-element array is used as the base station radiator. The AED around User 1 versus the element numbers in two-dimensional array is shown in Fig. 4(b). Similarly, in LOS case, the electric field distributions at the focusing time in horizontal plane containing User 2 are shown in Fig. 5(a) when



(a) (b)

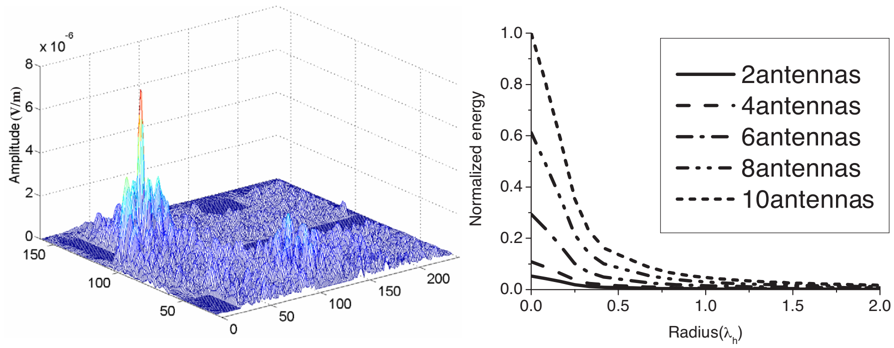
Figure 3. The spatial focus characteristic in LOS case (User 2) when linear array is used as TR mirror, (a) the electric field distributions at the focusing time in the horizontal plane when two-element linear array is used, (b) the average energy density versus the element numbers in the linear array.



(a) (b)

Figure 4. The spatial focus characteristic in NLOS case (User 1) when two-dimensional array is used as TR mirror, (a) the electric field distributions at the focusing time in the horizontal plane when two-element array is used, (b) the average energy density versus the element numbers in the two-dimensional array.

two-element array is used as the base station radiator. The *AED* around User 2 versus the element numbers in two-dimensional array is shown in Fig. 5(b).



(a) (b)

Figure 5. The spatial focus characteristic in LOS case (User 2) when two-dimensional array is used as TR mirror, (a) the electric field distributions at the focusing time in the horizontal plane when two-element array is used, (b) the average energy density versus the element numbers in the two-dimensional array.

3.3. Results for Linear Array with Fixed Array Aperture

A linear array with fixed aperture is used as a base station antenna to study the influence of element distributions on spatial focusing characteristic of TR UWB electromagnetic wave. The total size is the same as that of 10-elements linear array shown in Subsection 3.1. The antenna elements are numbered from 1 to 10 in turn. Five kinds of array arrangements are chosen to study the spatial focusing performance of TR electromagnetic wave. These arrays are formed by removing some elements from 10-element linear array. The kept elements in five selected arrays are (1, 10), (1, 5, 10), (1, 4, 7, 10), (1, 3, 6, 8, 10) and all elements, respectively. The spatial energy focusing extents of the five arrays in NLOS (User 1) and LOS (User 2) cases are shown in Figs. 6(a) and (b), respectively.

3.4. Result Analysis and Discussion

Based on the results shown in Figs. 2(a), 3(a), 4(a) and 5(a), a remarkable spatial focusing characteristic is observed. In Figs. 2(b), 3(b), 4(b) and 5(b), we can find that, generally speaking, the more the number of the array elements, the better the spatial focusing performance. From these results, it is easy to determine the required element number of array based on the required energy density distribution.

However, some abnormal results are observed in Fig. 6. In case

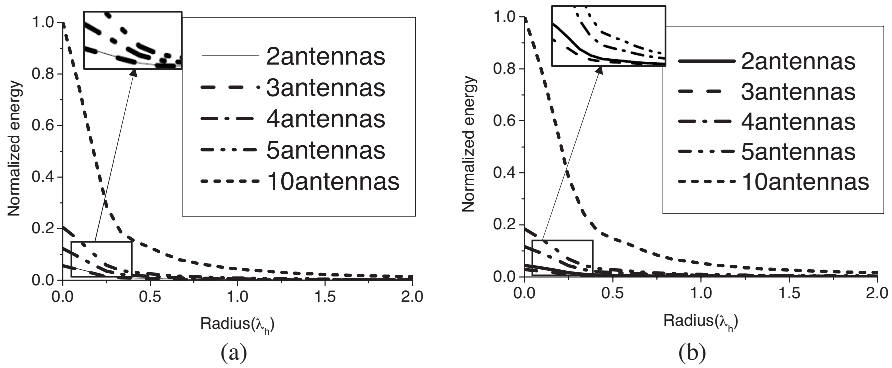


Figure 6. The energy focusing extents of five selected arrays, (a) NLOS case, (b) LOS case.

of NLOS, when the element number in the array with fixed aperture size is changed from 2 to 3, the focused energy density has not been enhanced. Especially, in case of LOS, the focused energy density has been decreased when the element number in the array with fixed aperture size is changed from 2 to 3. This phenomenon is adverse to designing the TR mirror in UWB wireless communication system. Therefore, one must understand it clearly and deeply. This topic will be further analyzed in future.

4. CONCLUSION

In this paper, the spatial focusing ability of TR electromagnetic wave transmitted by different antenna arrays has been studied. The linear and two-dimension TR mirror arrays are used, respectively. The spatial focusing characteristics are simulated by the FDTD method. The focused average energy density versus the element numbers in TR mirror arrays with variable and fixed aperture size are analyzed in NLOS and LOS cases, respectively. The analysis indicates that, in generally speaking, the more the number of the array elements, the stronger the focused energy density at user's location. However, some abnormal results indicate that the spatial focusing characteristic depends on the TR mirror array arrangement. This interesting phenomenon will be focused in future.

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