Progress In Electromagnetics Research C, Vol. 15, 103–115, 2010

A NOVEL SMART UWB ANTENNA ARRAY DESIGN BY PSO

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Abstract—In this paper, a new ultra wideband circular antenna array (UCAA) combining particle swarm optimizer (PSO) to minimize the bit error rate (BER) is proposed. The ultra wideband (UWB) impulse responses of the indoor channel for any transmitter-receiver location are computed by applying shooting and bouncing ray/image (SBR/Image) techniques, inverse fast Fourier transform and Hermitian processing. By using the impulse response of multipath channel, the BER performance of the binary pulse amplitude modulation (B-PAM) impulse radio (IR) UWB system can be calculated. Based on the topography of the circular antenna array, and the BER formula, the array pattern synthesis problem can be reformulated into an optimization problem and solved by the PSO. The novelties of our approach is not only choosing BER as the object function instead of sidelobe level of the antenna pattern, but also consider the antenna feed length effect of each array element. The strong point of the PSO is that it can find out the solution even if the performance index cannot be formulated by simple equations. Simulation results show that the synthesized antenna array pattern is effective to focus maximum gain to the LOS path which scales as the number of array elements. In other words, the receiver can increase the received signal energy to noise ratio. The synthesized array pattern also can mitigate severe multipath fading in complex propagation environment. As a result, the BER can be reduced substantially in indoor UWB communication system.

Received 11 May 2010, Accepted 2 July 2010, Scheduled 5 August 2010
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1. INTRODUCTION

Ultra wideband (UWB) technology is an ideal candidate for a low power, low cost, high data rate, and short rang wireless communication system. According to the Federal Communication Commission (FCC), UWB signal is defined as a signal having fractional bandwidth greater than 20% of the center frequency [1].

Smart antennas employ arrays of antenna elements and can integrate multiple antenna elements with a signal processing. These smart antennas combine the signals from multiple antennas in a way that mitigates multipath fading and maximize the output signal-to-noise ratio. It can dramatically increase the performance of a communication system.

In the past, most papers apply genetic algorithms for searching the minimum sidelobe level of the antenna [2–6]. In [7], desired phase weights determined by the scan angle and array geometry, the amplitude weights of elements are optimized by differential evolution algorithm to drive down the side-lobes. However, this pattern cannot guarantee to obtain the minimum BER performance. In this paper, we propose a smart ultra wideband circular antenna array at the transmitter to synthesize an array pattern for minimizing the BER performance in a UWB communication system. Unlike in a narrow band communication system, the UWB communication system spans a wide bandwidth in the frequency domain. In fact, adjusting the same excitation phase delay of the UWB antenna for different frequencies is difficulty. Thus we control the feed length of the array element. It provides the excitation phase delay which varies with different frequencies to synthesize the antenna array pattern.

When synthesizing the antenna array pattern to minimize the BER, the excitation problem is reformulated as an optimization problem and the constraint conditions are often highly nonlinear and non-differentiable. Thus, we use the PSO to regulate the antenna feed length of each array element to minimize the BER performance. As a result, the receiver can increase the received signal energy to noise ratio. Moreover, it can mitigate severe multipath fading and reduce the effective delay spread of the channel.

In this paper, the PSO is used to regulate the antenna feed length of each array element to minimize the BER performance of the communication system. The remaining sections of this paper are organized as follows: Section 2 briefly explains the formulation of the problem which includes antenna pattern, channel modeling and the BER calculation. Section 3 describes the particle swarm optimizer. The numerical results are then presented in Section 4 and conclusion is made in Section 5.

2. SYSTEM DESCRIPTION

2.1. Circular Array Pattern

We consider a circular array of eight UWB printed dipole antennas, as shown in Fig. 1. ℓ_n is feed length of the n-th each array element. Each element is apart along a circle of radius Γ. Each element is the UWB printed dipole antenna with circular arms, which has been designed in [8]. The radiation pattern between 3 GHz and 6 GHz is omnidirectional in the azimuth plane, which is interesting for communications between objects having undefined position in relation to each other. According to this advantage, we use this kind of antenna for circular array element. The array factor of this circular antenna array can be written as

$$AF(\theta,\phi,f)=\sum_{n=1}^{N_T-1} F_n \exp\left[-j\left(K\cdot X_n \sin\theta\cos\phi+K\cdot Y_n\sin\theta\sin\phi+\psi_n\right)\right] \tag{1}$$

where θ and ϕ are the spherical coordinate angles from the origin to the viewpoint in the elevation plane and azimuth plane. f is the frequency of a sinusoidal wave. N_T is the element number. $K = 2\pi/\lambda$ is the wavenumber, where λ is the wavelength of the sinusoidal wave. ψ_n is

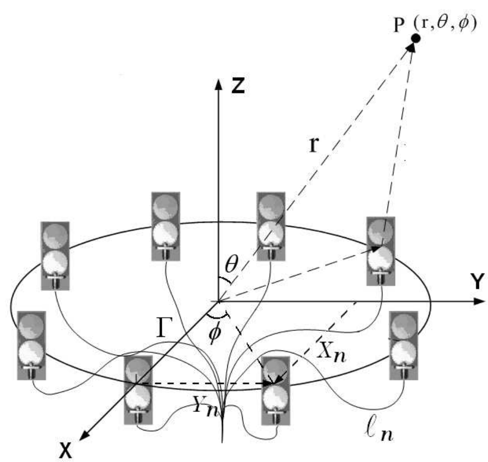

Figure 1. Geometry of a circular antenna of 8 UWB printed dipole antennas.

the phase delay of the excitation current for the n-th element and F_n is the amplitude of excitation current for the n-th element. In this paper, we regulate the F_n of each array element to get a optimal radiation pattern which can minimize the BER performance. X_n and Y_n are x-coordinate and y-coordinate positions of the n-th array element respectively. Thus the total radiation vector can be expressed as

$$\vec{N}(\theta, \phi, f) = AF(\theta, \phi, f) \cdot \vec{N}_e(\theta, \phi, f) \tag{2}$$

where $\vec{N}_e(\theta, \phi, f)$ is the radiation vector of individual element which can be obtained by the HFSS software based on the finite element method.

2.2. UWB Channel Modeling

The channel impulse response variations are significant for different types of antennas, since the UWB communication spans a wide bandwidth in the frequency domain. As a result, we describe the antenna radiation pattern which varies with different frequencies. We use the SBR/Image technique to calculate the channel impulse response which includes angular characteristics of radiation patterns and the variation between different frequencies of wave propagation.

SBR/Image techniques are good techniques to calculate channel frequency response for wireless communication. In this paper, we develop SBR/Image techniques including the antenna pattern to model our simulation channel. It can perform the major scattering objects causing reflection, diffraction and penetration in our simulation environment. The SBR/Image technique conceptually assumes that many triangular ray tubes (not rays) are shot from a transmitter. Here the triangular ray tubes whose vertexes are on a sphere are determined by the following method. First, we construct an icosahedron which is made of 20 identical equilateral triangles. Then, each triangle of the icosahedron is tessellated into a lot of smaller equilateral triangles. Finally, these small triangles are projected on to the sphere and each ray tube whose vertexes are determined by the small equilateral triangle is constructed. Then each ray tube will bounce and penetrate in the environments. If the receiver falls within the reflected ray tube, the contribution of the ray tube to the receiver can be attributed to an equivalent source (image). Using these images and received fields, the channel frequency response can be obtained as following

$$H(f) = \sum_{i=1}^{N_P} a_i(f) e^{j\theta_i(f)} \tag{3}$$

where f is the frequency of sinusoidal wave, i is the path index, θ_i is the i-th phase shift, a_i is the i-th receiving magnitude which depends on the radiation vector of the transmitting and receiving antenna in (2). Note that the receiving antenna in our simulation is a omnidirectional UWB dipole antenna. On the other hand, the transmitter is the UWB circular antenna array (UCAA) which has been described in above section. The channel frequency response of UWB can be calculated by Equation (3) in the frequency range of UWB.

The frequency response is transformed to the time domain by using the inverse fast Fourier transform with the Hermitian signal processing. Therefore the time domain impulse response of the equivalent baseband can be written as follows:

$$h_b(t) = \sum_{m=1}^{M_T} \alpha_m \delta(t - \tau_m) \tag{4}$$

where M_T is the number of paths. α_m and τ_m are the channel gain and time delay for the m-th path respectively.

2.3. Formulation of BER

The entire link can be described in terms of the block diagram in Fig. 2. It shows the B-PAM UWB modulator, equivalent baseband impulse response $h_b(t)$ which includes the effect of the circular antenna array, a correlation receiver (B-PAM demodulator) and feed length controller (regulated by the PSO to minimize BER).

As shown in Fig. 2, $\{b\}$ is the input binary data stream and $\{\hat{b}\}$ is the output binary data stream after demodulator and decision device.

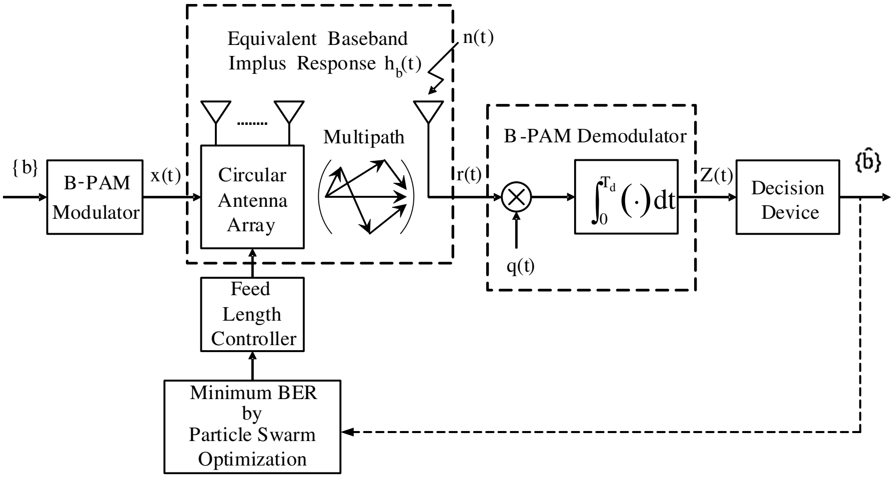

Figure 2. Block diagram of the simulated system.

When data stream $\{b\}$ passing through the B-PAM modulator, the transmitted UWB pulse stream is expressed as follows:

$$x(t) = \sum_{n=0}^{\infty} p(t - nT_d)d_n \tag{5}$$

where E_t is the average transmitted energy and $p(t)$ is the transmitted waveform. $d_n \in \{\pm 1\}$ is a B-PAM symbol and is assumed to be independent identically distributed (i.i.d.). T_d is the duration of the transmitting signal. The transmitted waveform $p(t)$ is the Gaussian waveform with ultra-short duration T_p at the nanosecond scale. Note that T_d is the duration of the transmitting signal and T_p is the pulse duration. The value of T_d is usually much larger than that of T_p. The Gaussian waveform $p(t)$ can be described by the following expression:

$$p(\mathrm{t}) = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{-t^2}{2\sigma^2}} \tag{6}$$

where t and σ are time and standard deviation of the Gaussian wave, respectively. The average transmit energy symbol E_t can be expressed as

$$E_t = \int_0^{T_d} p^2(t)dt \tag{7}$$

The received signal $r(t)$ can be expressed as follows:

$$r(t) = [x(t) \otimes h_b(t)] + n(t) \tag{8}$$

where $x(t)$ is the transmitted signal and $h_b(t)$ is the impulse response of the equivalent baseband, $n(t)$ is the white Gaussian noise with zero mean and variance $N_0/2$. The correlation receiver samples the received signal at the symbol rate and correlates them with suitably delayed references given by

$$q(t) = p[t - \tau_1 - (n-1)T_d] \tag{9}$$

where τ_1 is the delay time of the first wave. The output of the correlator at $t = nT_d$ is

$$\begin{aligned} Z(n) &= \int_{(n-1)T_d}^{nT_d} \left\{ \left[\sum_{i=0}^{\infty} p(t - iT_d)d_i \right] \otimes h_b(t) \right\} \cdot q(t)dt \\ &\quad + \int_{(n-1)T_d}^{nT_d} n(t)q(t)dt \end{aligned} \tag{10}$$

It can be shown that the noise components $\eta(n)$ of (10) are uncorrelated Gaussian random variables with zero mean. The variance of the output noise η is

$$\sigma^2 = \frac{N_0}{2} E_t \tag{11}$$

The conditional error probability of the n-th bit is thus expressed by:

$$P_e\left[Z(n)|\vec{d}\right] = \frac{1}{2}erfc\left[\frac{V(n)}{\sqrt{2}\sigma}\cdot(d_n)\right] \tag{12}$$

where $erfc(x) = \frac{2}{\sqrt{\pi}}\int_x^\infty e^{-y^2}dy$ is the complementary error function and $\left\{\vec{d}\right\} = \{d_0, d_1, \ldots, d_n\}$ is the binary sequence. Note that the average BER for B-PAM impulse radio UWB system can be expressed as

$$BER = \sum_{i=1}^{2^n} P(\vec{d})\cdot\frac{1}{2}erfc\left[\frac{V(i)}{\sqrt{2}\sigma}\cdot(d_n)\right] \tag{13}$$

3. PARTICLE SWARM OPTIMIZER

Particle swarm optimizer algorithm (PSO) is a new technology in evolution computing. The method was originally proposed by Kenney and Eberhart as an optimization method in 1995 [9]. It is a population-based algorithm for searching global optimization problems. PSO has many advantages, such as fewer parameters needed to be adjusted and the rapid convergence speed. PSO ties to social life, like bird flocking or fish flocking, and has some common features of evolutionary computation such as fitness evaluation. PSO works with real number, rather than coding of parameters and it can process of the research on simulating the movement of the swarm in the optional n dimensional space. Each particle has its own position x, transfer vector V, x_{pbest} (the best position) and all the particles share x_{gbest} (the best position by all the particles). In the $n+1$-th transfer, the d-th coordinate component of transfer vector of the i-th particle is manipulated according to the following equation (constriction coefficient):

$$v_{id}^{n+1} = \zeta\cdot\left(v_{id}^n + c_1\cdot\varphi_1\cdot\left(x_{pbest_{id}} - x_{id}^n\right) + c_2\cdot\varphi_2\cdot\left(x_{gbest_d} - x_{id}^n\right)\right) \tag{14}$$

where $i = 1, \ldots, m$ and m is the size of the swarm; $d = 1, \ldots, Nr$ and Nr is the size of space of a given problem; $\zeta = \frac{2}{\left|2-\varphi-\sqrt{\varphi^2-4\varphi}\right|}$ is constriction factor, $\varphi = c_1 + c_2, \varphi \geq 4$, c_1 and c_2 are positive constants; φ_1 and φ_2 are both the random numbers between 0 and 1; Nr determines the iteration number. Each agent moves according to the following equation:

$$X_{id}^{n+1} = X_{id}^n + V_{id}^{n+1} \tag{15}$$

When analyzing the circular antenna array, the feed length of each array element provides the phase delay of excitation current which varies with different frequencies. The relationship between the n-th antenna feed length ℓ_n and the excitation current phase delay ψ_n can be expressed as follows:

$$\psi_n = \frac{2\pi}{\lambda}\ell_n \tag{16}$$

where λ is the wavelength. Thus, we regulate the antenna feed length of each array element to get a optimal radiation pattern which can minimize the BER performance. The feed length of each array element can be decoded by the following equationG

$$\ell_n = Q_{\min} + \frac{Q_{\max} - Q_{\min}}{2^M - 1} \sum_{i=0}^{M-1} b_i^{\ell_n} 2^i \tag{17}$$

where $b_0^{\ell_n}, b_1^{\ell_n}, \cdots, b_{M-1}^{\ell_n}$ (genes) are M-bit strings of the binary representation of ℓ_n. The $Q_{\min}$ and $Q_{\max}$ are the minimum and the maximum values admissible for ℓ_n, respectively. In practical cases, $Q_{\min}$ and $Q_{\max}$ can be determined by the prior knowledge of the objects.

Finally, we adjust the antenna pattern in order to minimize the BER. In the synthesis procedure, the PSO algorithm is used to minimize the following cost function (CF):

$$\mathrm{CF} = \sum_{i=1}^{2^n} P(\vec{d}) \cdot \frac{1}{2} erfc\left[\frac{V(i)}{\sqrt{2}\sigma} \cdot (d_n)\right] \tag{18}$$

where CF is the average BER for B-PAM impulse radio UWB system. PSO is used to search the excitation voltage and feed Length to minimize the BER of the communication system. Reproduction is a process in which individual strings are copied according to their cost function as some measure of cost, utility or goodness that we want to minimize. Copying strings according to their cost values means that strings with lower value have a higher probability of contributing one or more offspring in the next generation. The exciting sources are randomly produced by the PSO algorithm and their corresponding antenna pattern can be determined by solving integral equation. Then, the SBR/Image method is used to calculate the BER in the environment. The PSO algorithm iteratively generates a new population that offspring from the previous population through the application of the reproduction by mutation and replacement operators. In our simulation, when the object function is less than the threshold value or PSO do not find a better individual within 300 successive generations, the PSO will be terminated and a solution is then obtained.

4. NUMERICAL RESULTS

A realistic environment is investigated for line of site (LOS) and non-line of site (NLOS) scenarios at the microwave Lab. Fig. 3 is the Microwave laboratory in Tamkang University and laboratory has dimensions of 9.2 m (Length) × 10 m (Width) × 3 m (Height). The building walls are made of concrete block. The partitions are wood structured. The doors are made of wood. The Lab environments are equipped with many electronic and measurement devices which are located on tables. Most of these devices are made of metallic materials. The plan view of the simulated environment is shown in Fig. 3. The transmitting antenna Tx and receiver Rx1, Rx2 were all mounted 1.7 meter above the floor. The transmitting and receiving antennas are UWB antennas. The transmitting antenna Tx (7.43 m, 3.75 m, 1.7 m) m is located in the center of the right area in the Microwave laboratory. Two scenarios with different Rx positions are simulated. Scenario I has a line-of-sight path with Rx1 (7.43 m, 1.45 m, 1.7 m). Tx and Rx1 are at a distance of approximately 2.3 meter. Scenario II has non line-of-sight path with Rx2 (2.03 m, 3.75 m, 1.7 m), since there is a structure wood partition between the Tx and Rx2. The Tx–Rx2 distance on the horizontal plane is about 5.4 meter in Scenarios II. A three-dimensional SBR/Image technique combined antenna radiation

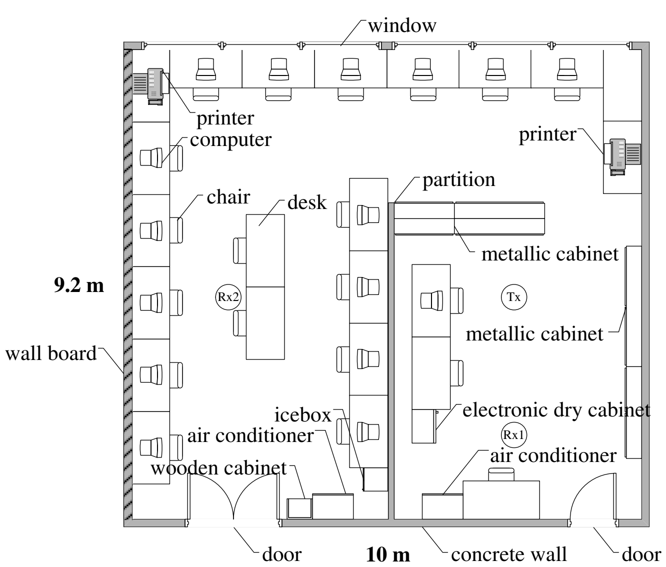

Figure 3. A plan view of the simulated environment.

pattern has been presented in this paper. This technique is used to calculate the UWB channel impulse response for each location of the receiver. Based on the channel impulse response, the number of multipath components, the root mean square (RMS) delay spread τ_{RMS} and the mean excess delay τ_{MED} are computed. Furthermore, we use the impulse response to calculate the BER. The frequency range for the UWB channel is simulated from 3 GHz to 6 GHz, since the array element has the omnidirectional characteristic in this frequency range [8]. The specifications of the antenna and PSO are set as below: The searching ranges of excitation voltage and feed Length are $0 \sim 1$ volt and $0 \sim 10$ cm, respectively. We set the $Q_{\min} = 0.0$ cm and $Q_{\max} = 10.0$ cm which is according to the minimum frequency 3 GHz. Then the unknown coefficients in (17) are described by a 10 bit string (chromosome). The relative coefficient of the PSO are set as below: The learning coefficients, c_1 and c_2, are set to 2.8 and 1.3 respectively. The mutation probability is 0.15 and the population size set to 30. The operation frequency is $3 \sim 7$ GHz. LOS and NLOS cases are considered in the followings:

4.1. LOS Case

In this case, the receiving antenna Rx1 is chosen at (7.43 m, 1.45 m, 1.7 m). Scenario I using three kinds of transmitting antennas: (a) Only one UWB printed dipole antenna (OUA) (b) A circular array of eight UWB printed dipole antennas, each element antenna has the same feed length (UCAA) (c) A circular array of eight UWB printed dipole antenna, each element antenna feed length was regulated by PSO (UCAA-PSO).

Figure 4 shows the corresponding radiation patterns for UWB circular antenna array (UCAA-PSO). It is seen the pattern is more directional to the receiver by the PSO algorithm.

In order to determine the multipath effect, the τ_{RMS} and τ_{MED} were calculated. A summary of these values are given in Table 1 for Scenarios I. For the LOS case in Scenario I, the τ_{RMS} in OUA and in UCAA-PSO is 11.57 ns and 4.62 ns respectively. It is clear that τ_{RMS} for the UCAA-PSO case is the smallest, since the directive antenna can mitigate multipath effect. Fig. 5 shows the BER V.S. SNR for Scenario I using three different kinds of transmitters. Here SNR is defined as the ratio of the average transmitting power to the noise power. The results show that the BER curve decreases greatly when the UCAA-PSO is used as transmitter. It is due to the fact that the UCAA-PSO can minimize the fading and reduce the mulitpath effects. It also can focus the synthesized antenna array pattern to optimize the available processing gain to the receiver.

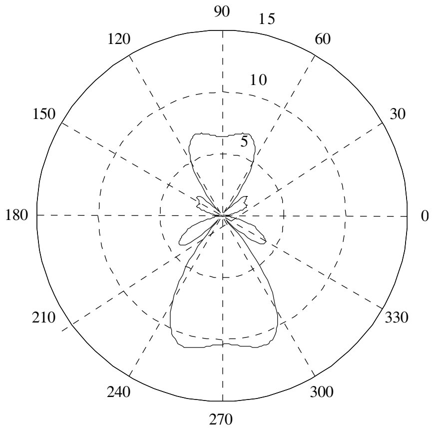

Figure 4. Radiation pattern of UCAA-PSO in the LOS case (Rx1).

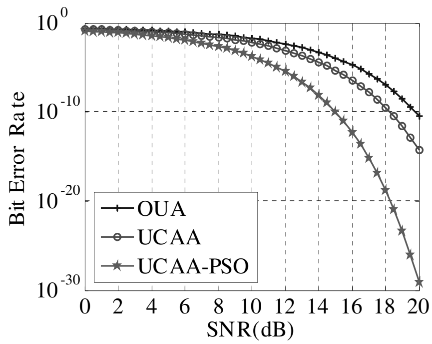

Figure 5. BER V.S. SNR over Scenario I for three kinds of transmitters.

Table 1. Mean excess delay and RMS delay spread for the two scenarios.

Transmitting Antennas / Scenarios	OUA		UCAA		UCAA-PSO	
	$\tau_{\rm MED}$ (ns)	$\tau_{\rm RMS}$ (ns)	$\tau_{\rm MED}$ (ns)	$\tau_{\rm RMS}$ (ns)	$\tau_{\rm MED}$ (ns)	$\tau_{\rm RMS}$ (ns)
Scenario I LOS (Rx1)	**3.20**	**11.57**	**3.09**	**10.94**	**0.12**	**4.62**
Scenario II NLOS (Rx2)	**11.28**	**16.71**	**10.44**	**16.19**	**10.01**	**9.55**

4.2. NLOS Case

In this case, we choose the receiving antenna Rx2 at (2.03 m, 3.75 m, 1.7 m). There are some obstructions between the transmitter and receiver. Scenario II using three kinds of transmitters. In this scenario, there are non LOS paths for the three channels.

The radiation patterns are shown in Fig. 6. In the NLOS case, the transmitting signal can reach the receiver directly.

Table 1 also shows the RMS delay spread τ_{RMS} decreases when using the UCAA-PSO as the transmitting antenna in the Scenario II. A summary of these values are given in Table 1 for Scenarios I and II, respectively, which clearly shows the τ_{MED} increase for the NLOS case (Scenario II). Fig. 7 shows the BER V.S. SNR for Scenario II using three different kinds of transmitters. The results show that the BER curve decreases a little when using the UCAA-PSO as the transmitter.

All of the above results demonstrate the UCAA-PSO which is presented in this paper is powerful for LOS and NLOS propagation environment. It can increase the ratio of combined receiving signal energy to noise. It also can mitigate severe multipath fading in complex propagation environment. As a result, the BER can be reduced substantially in indoor UWB communication system.

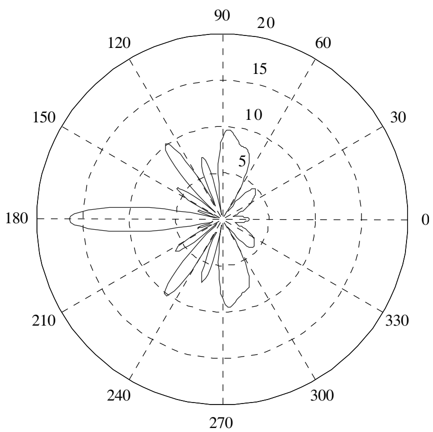

Figure 6. Radiation pattern of UCAA-PSO in the NLOS case (Rx2).

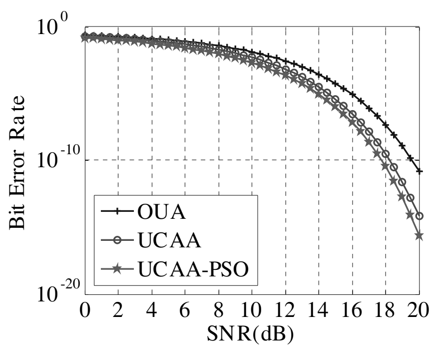

Figure 7. BER V.S. SNR over Scenario II for three kinds of transmitters.

5. CONCLUSIONS

Using the smart UWB circular antenna array to minimize the BER performance in LAB environment is presented. The impulse response of the channel is computed by SBR/Image techniques, inverse fast Fourier transform and Hermitian processing. By using the impulse response of the multipath channel and the PSO synthesizing optimal antenna radiation pattern, the BER performance of a B-PAM impulse radio UWB communication system is investigated. Based on the BER formulation, the synthesis problem can be reformulated into an optimization problem. In this paper, the cost function is defined as the reciprocal of BER of the system. The PSO minimizes the cost function by adjust the feed length of each antenna. Numerical results show that the BER can be reduced substantially in indoor UWB communication system.

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