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# Optimizing Multiband Orthogonal Transmission of Low-Energy and Efficient Cognitive Ultra Wideband System

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Abstract. *Ultra wideband technology is a good low-energy wireless communication technology, but its spectrum flexibility is poor, this limits its application in wireless communication networks. This paper proposes an optimized multiband orthogonal parallel transmission cognitive ultra wideband system, it is flexible and efficient. Information data goes through the serial parallel conversion and is modulated to orthogonal pulses to replace the single subband pulse, interleaver in the modulation front could further improve the system reliability of information transmission. On this basis, the system simulation model is built, to analyze the signal power spectrum density and system BER performance on the Gauss white noise background and the interference of pulse correlation. The simulations reveal that pulse signal is a good approximation of the emission mask and orthogonal pulses pair can greatly improve the information transmission rate, meanwhile has smaller BER than serial system in low SNR.*

**Keywords:** Multiband, Orthogonal Pulse,Parallel Transmission, CUWB, Efficiency

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1. **Introduction.** The nodes in wireless communication networks are severely constrained in power supply and communication security, such as wireless sensor networks and vehicular ad-hoc network [1, 2]. Ultra wideband (UWB) technology has low-power consumption, high transmission rate and other advantages, has been used in the short distance wireless communication networks widely [3]. The traditional UWB system transmits pulse signal and occupies a wide spectrumbecause it lacks information of RF environment in the communication process, so the anti-jamming capability is weak and spectrum utilization is low, these are the topics we need to research. Cognitive radio (CR) technology is a kind of communication technology which has sensing and learning ability, it could sense the spectrum environment and provide environment information. Therefore, cognitive ultra wideband (CUWB) wireless communication system is designed which combines CR and UWB technology [4, 5]. System constructs the adaptive spectrum emission mask according to spectrum sensing information, and divides the available spectrum into multiple subbands, which can increase the system capacity dynamically and improve the spectrum utilization flexibility. It differs from the method in literature [6] which uses additional narrowband active noise control, when a small amount of narrowband interference occurs

in the available bandwidth, system only need to cancel the sub-band pulse in the interfering bands instead of changing the communication bands. So as to improve anti-jamming capability to adapt with the wireless environment.

In the field of broadband communication, related research of CUWB has received considerable attention, and many system structures and adaptive pulse design algorithms are developed. A idea of multiband pulse system was proposed [7] and the model was optimized from multiple users and interference suppression standpoint [8, 9]. But the above methods use band-pass filtering way to divide band, which makes complex of the filter design and realization. Literature [10]proposed a multiband adaptive pulse design, but still used serial transmission, did not improve the transmission rate. Literature [11]proposed multiband parallel transmission design, but did not fully consider the phase orthogonal properties between subband pulses.

At present, there are two mainly issues in the research of UWB system. First, when more MB-UWB systems design subband pulses using PSWF, they only use the first-order function with largest energy concentration, does not full use of the orthogonality between each order PSWFs. For example, in an approximate sequence generated by matrix method, the energy concentrations of first and second order PSWF are approximately equal, but the phase difference is $\pi/2$. The energy concentrations of third and fourth order are also approximately equal, only less than first two orders slightly, but they still can be used. Second, because of the UWB system power spectrum density is very low, information becomes prone to producing error code in transmission process, so the sender uses repetition encoder usually, but this will reduce the system information transmission rate. Therefore, this paper proceed from the two issues above, proposes a multiband parallel orthogonal transmission system, user serial data is converted into parallel data and be transmitted in different subbands. In each subband, uses multi-order PSWF to multichannel transmit in each subband, eliminates repetition encoder at the same time. Every subband uses a pair of orthogonal pulses, one pulse transmits the original information, and another pulse transmits the data after interleaving. It improves information transfer rate. Receiver uses the dual mask, demodulates two orthogonal signals in each subband, one path demodulation data is deinterleaved, then is accumulated with another path data, orthogonal pulses replace the repetition code of traditional system. In addition, since the introduction of interleaver, any bit data may be transmitted in different subband in parallel, obtains good signal diversity characteristics, and interleaver can improve the system capability of anti burst interference, make a plurality of successive bits damaged in the channel are dispersed in time, so they are regarded as random error, reduce the system bit error rate further.

## 2. System Model of Multiband Orthogonal Parallel CUWB.

Multiband orthogonal parallel CUWB system is proposed on the basis of IR-UWB, according to the spectrum sensing results, the spectrum of FCC regulations is divided into multiple subbands flexibly, the original information and the interleaved information are modulated into orthogonal pulse on different subbands and parallel transmitted. It not only can improve the system transmission rate, use spectrum flexibly, obtain diversity characteristics, and can avoid the frequency band of narrowband interference, so as to improve the receiver performance. This paper uses orthogonal pulses pair to replace single pulse in each subband, and deletes the low efficiency repetitive code module. The principle diagram is shown in figure1.

According to results of sensing module, the subband division module has the flexibility to allocate each subband. The role of pulse generator is to produce a series of subband pulse, each subband has a pair of orthogonal pulse $p_x$ and $p_y$.Information data goes through the serial/parallel conversion module into multiple, if the information is an

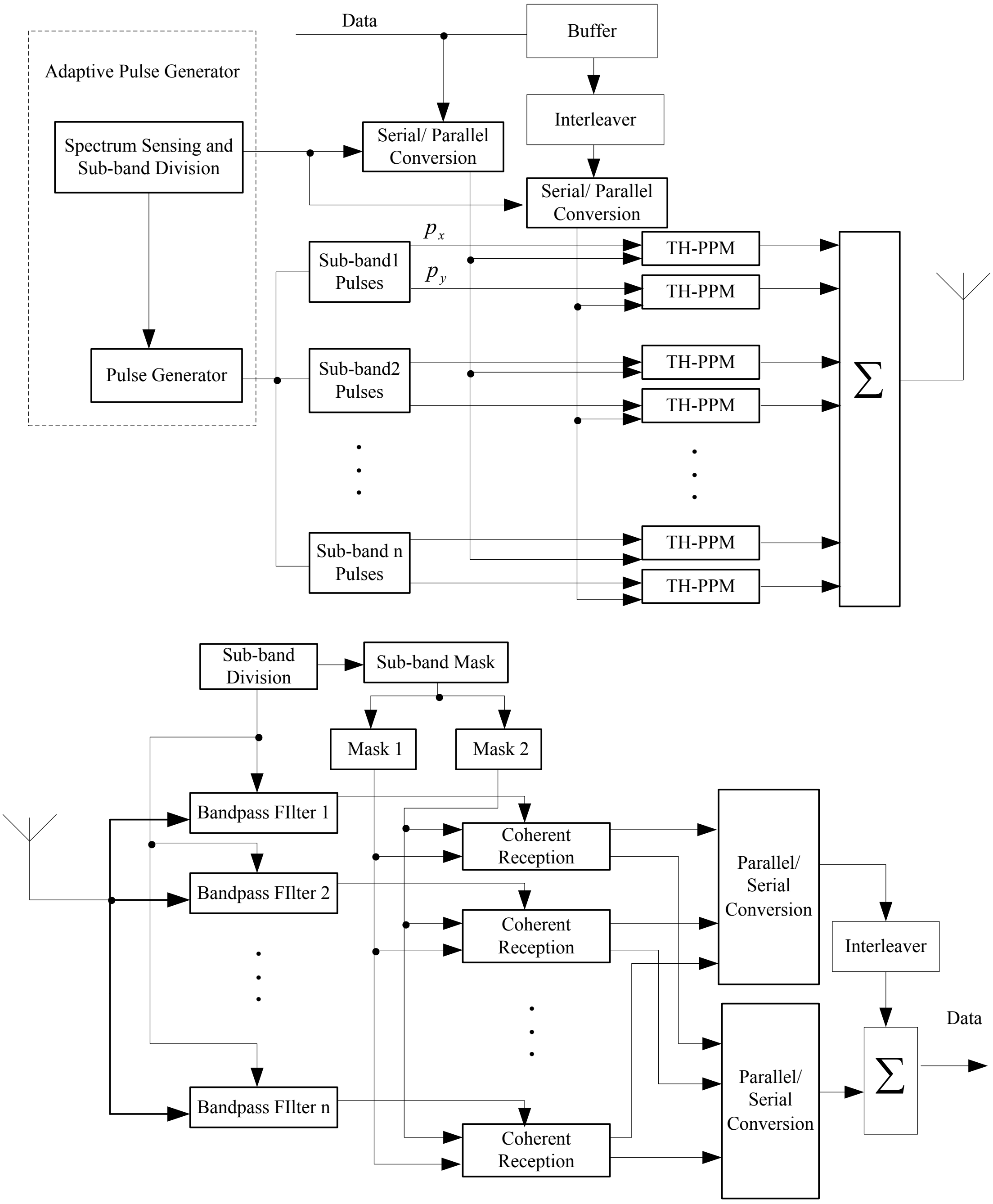


Figure 1. Principle Diagram of MB Parallel CUWB System

analog signal, it need to go through the ADC, converted into a digital sequence. Each way uses the pulse $p_x$ of different subband to parallel transmit respectively. At the same time, the information data after interleaving operation uses pulse $p_y$, two orthogonal UWB signals are superimposed in each subband. In transmitter, all subband pulses are weighted sum in the time domain and composed a line to send out through a single antenna. In receiver, signal through a set of band-pass filter is decomposed into subbands, then is coherent demodulated using a pair of orthogonal masks $mask_x$ and $mask_y$ in each subband respectively, finally, accumulate the two groups of demodulated data corresponding different masks in other subbands, get two path complete data, one path data corresponding $mask_y$ is deinterleaved and merged with another path.

3. **Interleaver operation.** The interleaving operation can disrupt the relationship between the information bits, the groups of burst errors in transmission channel are converted random errors, to improve the system reliability. This paper uses interweave encoder, the output information of channel coding module is divided into $n$ code blocks, each block is composed of $m$ data, form a matrix of $m \times n$, named interleaver matrix. Data interleaving operation is completed base on date input matrix in written-row and output in read-column, data can also be read from matrix according to other sequence, the ultimate aim is to disrupt the order of input data. If $j$ is the location of input data in the original sequence, $f(j)$ indicates the location of interleaver matrix output sequence, then the interleaver output can be represented by the following formula:

$$f(j) = [(j-1)modn]m + \lfloor (j-1)/n \rfloor + 1 \tag{1}$$

$\lfloor \cdot \rfloor$ represents a rounding function, mod represents remainder function.

The advantages of interleaving are increasing the ability of anti burst error, but system does not increase new supervision code, so the coding efficiency does not be reduced. In theory, the numbers of code group increase, the ability of anti burst error is stronger, but the requirement of decoder buffer is bigger, and the decoding delay is also corresponding increase.

4. **Design of Subband Pulse.** The late 1950s, bell labs D.Slepian and H.O.Pollack first proposed the prolate spheroidal wave function (PSWF), that is calculate the expression in time domain UWB pulse according to FCC emission mask. Multiband CUWB system requires a pulse signal both band-limited and time-limited to satisfy the high-speed transmission and low inter-symbol interference.PSWF is the complete orthogonal basis in band limited space $[-\Omega,\ \Omega]$ and time limited space $[-T/2, T/2]$ [12]. It satisfies the following integral formulas:

$$\int_{-T/2}^{T/2} \varphi(x) \frac{\sin \Omega(t-x)}{\pi(t-x)} dx = \lambda \varphi(t) \tag{2}$$

$$\int_{-T/2}^{T/2} \varphi_i(t)\varphi_j(t)dt = \begin{cases} \lambda & i = j \\ 0 & i \neq j \end{cases} \tag{3}$$

$\lambda$ is the corresponding eigenvalue, $1 > \lambda_0 > \lambda_1 > \cdots > \lambda_i > \cdots$, $\lambda_n$ is the energy concentration of output pulse. $\varphi_i(t)$ is PSWF corresponding eigenvalue $\lambda_i$.

$$\lambda_n = \frac{\int_{-T/2}^{T/2} |\varphi_n(t)|^2 dt}{\int_{-\infty}^{\infty} |\varphi(t)|^2 dt} \tag{4}$$

$\lambda_n$ is a value less than 1, it is decided by time bandwidth product $T_m\Omega/2$ and also represents the design freedom of subband pulse, $T_m$ is pulse duration.The value of time bandwidth product becomes bigger, the energy leakage is smaller. When $T_m\Omega/2 \geq 8$, we can deem that there is no energy leakage. However, this is not the case in practice, $T_m\Omega/2$ is taken less than 8, because the system bandwidth that can be used is limited, and as the requirements of transmission rate and power consumption, the value of $T_m$ can not take too much usually, so the range of general time bandwidth product is [1-4].

The closed solution of $\varphi(t)$ is difficult to obtain, therefore, according to formula 2, using a simple discrete approach to obtain the discrete solution of prolate spheroidal wave function, generate subband pulse basefunctions. The subband pulse signal is equivalent to ideal bandpass filter with upper threshold $f_H$ and lower threshold $f_L$, the output is $\lambda\varphi(t)$. Taking $f_L$ = 4GHz, $f_H$ = 5GHz, $T_m$ = 2ns, time bandwidth product is 1. The pulse basefunctions time domain waveform are shown in figure2, power spectrum density and frequency domain phase of $\varphi_0(t)$, $\varphi_1(t)$, $\varphi_2(t)$ and $\varphi_3(t)$ are shown in figure3.

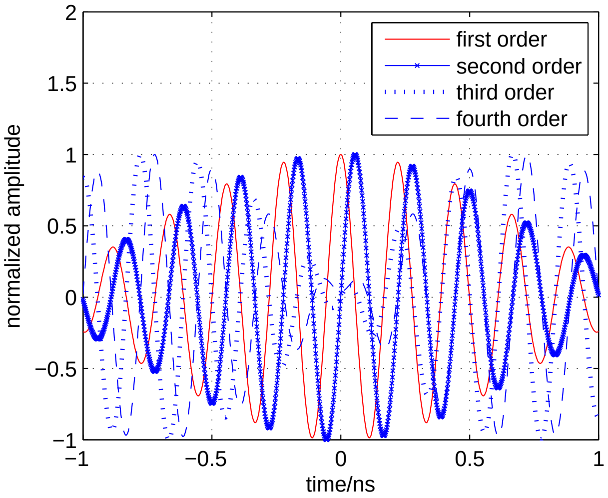
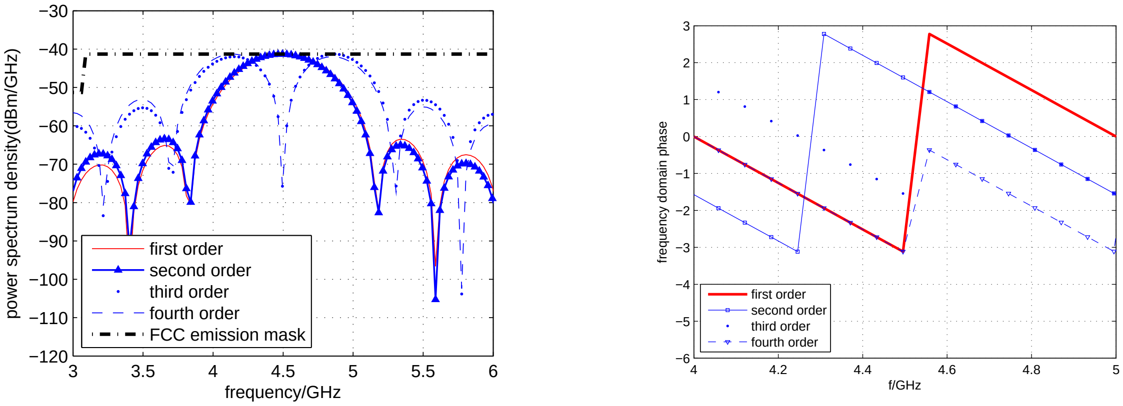


Figure 2. Principle Diagram of MB Parallel CUWB System



(A) power spectrum density (B) frequency domain phase

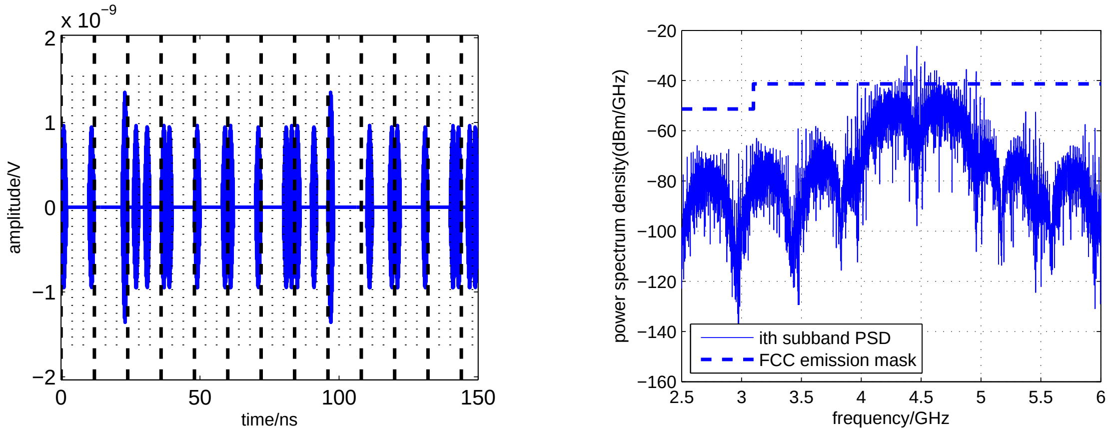
Figure 3. PSD and Phase of Pulse Functions

In the frequency domain, the odd order and even order PSWF have similar power spectrum density, but the phase difference is $\pi/2$, they are a pair of orthogonal pulses. Select odd order pulse basefunctions combination and even order pulse basefunctions combination to be $i$th subband pulses $p_{x,i}(t)$ and $p_{y,i}(t)$.

$$p_{x,i}(t) = \sum_{j=2k}^{N} \varphi_j(t) \qquad k = 0, 1, 2, \cdots \tag{5}$$

$$p_{y,i}(t) = \sum_{j=2k+1}^{N} \varphi_j(t) \qquad k = 0, 1, 2, \cdots \tag{6}$$

Figure4 is time domain waveform and PSD of ith subband. System uses binary orthogonal TH-PPM modulation, transmission code module uses a pseudo random sequence $C$ to introduce TH displacement for signal, the elements are integers, and the maximum upper bound of $C$ element is $N_h$, assuming $N_h$ is 3, period of $C$ is $N_p$, transmission code can be used for multiple access code.



(A) time domain waveform (B) power spectrum density

Figure 4. Time Domain Waveform and PSD of $i$th Subband

As shown in figure 4(a), although using different transmission code, two signals within the same subband still overlap in the time domain, but because two pulses phase are orthogonal, so the receiver can correctly receive data using orthogonal mask. In frequency domain, the envelope of PSD depends on the Fourier transform of pulse wave function unit impulse response, if the basefunctions could approximate to emission mask, the pulse through modulation and coding may be a good approximation of the emission mask, as shown in figure 4(b).

## 5. Performance Analysis.

### 5.1. Pulse Correlation Property.

Theoretically, different orders PSWF within each subband are mutually orthogonal, so cross-correlation value of any two pulses is zero, and because the PSWF energy is concentrated in subband, the pulses in different subbands are independent, there is no interference. However, in practice, PSWF are not strictly orthogonal, table 1 shows the auto-correlation and cross-correlation of basefunctons in same subband, simulation result is computed with PC. Because of the good correlation property, the interference between pulses pair is very small.

Table 1. Correlation between orthogonal pulses in same subband

| Correlation calculation | $\varphi_0(t)$ | $\varphi_1(t)$ | $\varphi_2(t)$ | $\varphi_3(t)$ |
|---|---|---|---|---|
| $\varphi_0(t)$ | 1 | $-3.55 \times 10^{-12}$ | $-1.1 \times 10^{-16}$ | $-1 \times 10^{-16}$ |
| $\varphi_1(t)$ | $-3.55 \times 10^{-12}$ | 1 | $3.7 \times 10^{-16}$ | $1.03 \times 10^{-16}$ |
| $\varphi_2(t)$ | $-1.1 \times 10^{-16}$ | $3.7 \times 10^{-16}$ | 1 | $3.5 \times 10^{-12}$ |
| $\varphi_3(t)$ | $-1 \times 10^{-16}$ | $1.03 \times 10^{-16}$ | $3.5 \times 10^{-12}$ | 1 |

In addition to the interference between orthogonal pulses in same subband, there is mutual interference between adjacent subbands. Subband pulse PSD consists of a main-lobe and some side-lobes, side-lobes diffuse to both sides and attenuate in a certain interval, thus cause the energy leakage. Meanwhile, for this reason, there is interference between adjacent subbands, controlling the time bandwidth product parameter can reduce energy leakage, in the condition of certain subband width, with the increase of time bandwidth product, the main-lobe energy increases, but the pulse time domain duration rises.

5.2. **System energy.** System complexity and power spectrum density embody the low-energy, mainly in the following three aspects. First, this system can coexistence with existing wireless systems, does not need to redesign the physical layer, reduces the complexity of pulse generation module, to avoid the double counting and reduce power consumption. Second, TH-PPM modulation signal power spectrum density is constructed of a continuous spectrum and a discrete spectrum, the energy is concentrated in some spectrum lines. It will produce unwanted lines, because these lines will exceed the requirement of FCC mask, as shown in figure 4(b). This paper eliminates repetition encoder, reduces the periodicity, through TH modulated, the whitening effect of information code is more obvious, energy is distributed in a larger spectrum range and spectrum lines peak become smaller. Third, system in this paper makes full use of licensed bandwidth, in the absence of the licensed user, system can access licensed spectrum at random, the average bandwidth reaches a maximum, which makes the amplitude of each spectrum component is reduced, in other words, the power spectrum density of the signal is reduced.

5.3. **Information Transmission Rate.** Traditional single band UWB system and most MB UWB system use the packet coder of repetition code ($N_s$,1)in sender, in order to introduce redundancy, but it may reduce the information transmission rate. In this paper, packet coder is replaced by a pair of orthogonal pulses. In the condition of certain pulse duration $T_m$, assuming single band system transmission rate is $R_1$, ordinary multiband parallel system transmission rate is $R_2$, transmission rate of multiband parallel system using orthogonal pulses is $R_3$, then:

$$R_3 = N_s R_3 = M N_s R_3 = \frac{M}{N_h T_m} \tag{7}$$

$M$ is the number of subbands.

Formula (7) shows that in the same conditions, $R_3$ is $N_s$ times of $R_2$, $M \times N_s$ times of $R_1$, information transmission rate is improved greatly. FCC agreed to allocate 7500 MHz of spectrum for unlicensed use of UWB devices for communication applications in the 3.1-10.6GHz frequency band, the instantaneous bandwidth minimum allowed by the FCC ruling is 500MHz, so maximum value of $M$ is 15. In practical application, the narrower band width, the longer pulse duration, energy leakage is more serious, this will lead to interference between adjacent subband be larger.

5.4. **System Bit Error Rate.** In this paper, the channel is Gaussian white noise channel, the received useful signal is $r_0(t)$ in receiver, it is disturbed by plus noise $n(t)$ , the received signal can be expressed as:

$$r(t) = r_0(t) + n(t) \tag{8}$$

$n(t)$ is achieved by a random Gaussian process, its PSD is $N_0/2$, $r_0(t)$ is the system emission signal after loss and time - delay.

$$r_0(t) = \alpha^2 s(t - \tau) \tag{9}$$

Wherein the channel gain $\alpha$ and channel time-delay $\tau$ depend on the distance $D$ between the transmitter and receiver.

$$\alpha^2 = \frac{c_0}{\sqrt{D^\gamma}} \tag{10}$$

$c_0$ is the reference gain constant when $D = 1$m, $\gamma$ is the power loss index.

$$\tau = D/c \tag{11}$$

$c$ is the velocity of light.

According to figure 1, system emission signal is the sum of a series of orthogonal pulses pairs, it can be expressed as follows:

$$s(t) = \sum_{i=1}^{M} s_i(t) = \sum_{i=1}^{M} \sum_{j=-\infty}^{\infty} \sqrt{E_p^{(i)}} p_{x,i}(t - jT_s - \theta_{x,j}^{(i)}) + \sqrt{E_p^{(i)}} p_{y,i}(t - jT_s - \theta_{y,j}^{(i)}) \tag{12}$$

$s_i(t)$ is the emission signal of $i$th subband; $E_p$ is pulse carrying energy; $p_i(t)$ is pulse waveform; $\theta_j$ is time random displacement.

$$\theta_j = C_j T_c + a_j \varepsilon = \eta_j + a_j \varepsilon \tag{13}$$

$\eta_j$ is random TH jitter; $a_j\varepsilon$ is PPM modulation displacement.

In Gauss white noise channel, the receiver can receive $M$ subbands signals and noise, the sum $r(t)$ can be expressed as:

$$r(t) = \sum_{i=1}^{M} \sum_{j=-\infty}^{\infty} \sqrt{\alpha^{(i)} E_p^{(i)}} p_{x,i}(t - jT_s - \theta_{x,j}^{(i)} - \tau_x^{(i)}) + \sqrt{\alpha^{(i)} E_p^{(i)}} p_{y,i}(t - jT_s - \theta_{y,j}^{(i)} - \tau_y^{(i)}) + n(t) \tag{14}$$

$\alpha E_p$ is the energy that receiver obtains from a single pulse, the communication distance $D$ of CUWB system is far less than the velocity of light $c$, so assuming $\tau = 0$, namely it is logical that receiver and sender are synchronous, and $p_i$ is the energy normalized pulse signal.

Every branch has two orthogonal relative mask for judgmentthey have the same form $m(t)$:

$$m(t) = p_i(t - jT_s - C_j T_c) - p_i(t - jT_s - C_j T_c - a_j \varepsilon) \tag{15}$$

The BER of one orthogonal branch is:

$$P_{r_b} = \frac{1}{2} erfc \left( \sqrt{ \frac{1}{2} \left( \left( \frac{2E_b}{N_0} \right)^{-1} + \left( \frac{1}{2 \sum\limits_{i=1}^{M} \sum\limits_{j=1, i \neq j}^{M}} R_{p_i p_j}^2(0) \right)^{-1} + \left( \frac{1}{\sum\limits_{i=1}^{M} R_{p_{x,i} p_{y,i}}^2(0)} \right)^{-1} \right)^{-1} } \right) \tag{16}$$

$R_{p_{x,i} p_{y,i}}^2(t)$ is cross correlation function of pulse $p(t)$.

$$R_{p_{x,i} p_{y,i}}^2(t) = \int_0^{T_m} p_i(t) p_j(t) dt \tag{17}$$

Formula(16) shows that system BER is determined by thermal noise, interference between subbands and interference between orthogonal pulses, the second part and third part of BER are influenced by subband number $M$ and pulse cross correlation function $R_{pp}(t)$, these parameters smaller, influence between bands less. Making a reasonable assumption that when the two branches of the same information bit occur error, the information bit error. The BER of serial CUWB system and orthogonal parallel CUWB system are shown in figure 5.

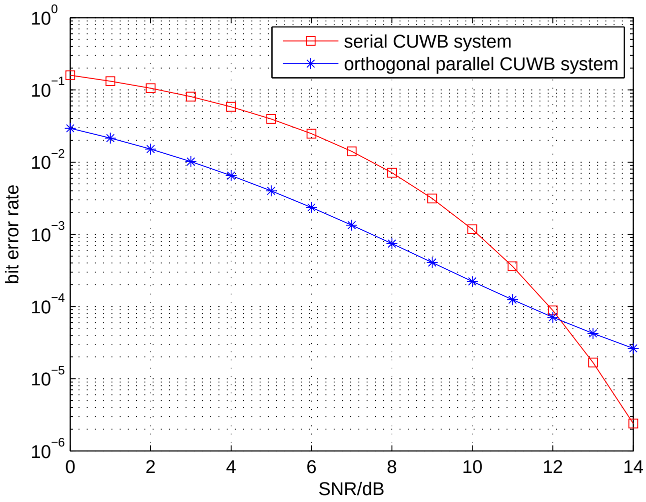


Figure 5. System bit error rate

The simulation condition is 7 subbands, TH-PPM modulation. Figure 5 illustrates that multiband orthogonal parallel CUWB system BER is smaller than serial CUWB system, the main reason is that every information bit has 3dB gain. In low SNR, thermal noise is the most limiting factor for system, when SNR exceeds 12dB, the difference in BER curves is primarily due to cross correlation function of orthogonal pulses pair, system is influenced by correlation property between two branches in same subband.

## 6. Conclusion.

In this paper, the poor performance of traditional UWB system is revealed by simple analysis. An optimized multiband orthogonal parallel CUWB system is proposed to effectively improve the system efficiency. First, subband width of multiband modulation can be adjusted according to the results of spectrum sensing module, this can improve the flexibility of spectrum utilization. Because the RF signal spectrum is composed of a series of discrete subbands, therefore, the mutual interference between different subbands is very small. Second, there is a pair of orthogonal pulses in same subband, it provides diversity characteristic, instead of the repetition code in traditional UWB system, enhance the system transmission rate greatly. Meanwhile, every information bit has 3dB gain, so the system BER is reduced. Third, the interleaver can enhance the ability of anti burst interference, improve the system reliability. At last, due to the various subbands are independent of each other, when narrowband system or narrowband interference occurs within the working frequency band, system can remise subbands according to the actual situation, achieve coexistence with existing wireless systems.

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