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Performance Research of Multiband Parallel Transmission Cognitive Ultra Wideband System

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Abstract. *Multiband parallel transmission cognitive ultra wideband system is an intelligent communication system with high speed and flexibility. It can coexist with the existing narrowband system, which can provide an effective method for relieving the spectrum resource tension. In this paper, a multiband division method with overlapping part is proposed. Based on the band-limited and orthogonal characteristics of prolate spheroidal wave function, information can be transmitted in multiple parallel bands, which can improve the system spectrum utilization and transmission rate. The system model is built and the BER formula is derived. Matlab simulation results indicate that the information transmission rate of multiband system is higher than that of single band system under the condition of same pulse duration, the BER performance is not affected by subband correlation in low SNR, the BER is similar to the Gaussian white noise channel theory value.*

Keywords: Cognitive ultra wideband, Multiband pulse, Spectrum overlap, Parallel transmission, PSWF

1. **Introduction.** Ultra wide-band (UWB) wireless communication and cognitive radio (CR) technology are effective methods to relieve spectrum resource tension. The traditional impulse radio UWB (IR-UWB) uses ultra short impulse as information carrier [1]. It has very wide frequency bandwidth and can implement ultra high data transmission speed. But as the signal occupies fixed wide spectrum, system has no interaction with the external environment, which leads to the weakness of UWB system both in the flexibility and spectrum utilization and restricts the further improvability in system transmission performance. Multiband cognitive ultra wide-band (CUWB) wireless communication scheme combine CR and UWB technology, and form a net intelligent wireless communication technology [2, 3]. While UWB technology builds a system platform for the CR and provides physical layer support. CR can provide the radio frequency environment information using the sensing and learning abilities. UWB wide spectrum range is divided into a plurality of subbands, data can be transmitted in multiple parallel bands, which

can dynamically expand system capacity and improve the flexibility of spectrum resource use. Although the system complexity is increased, but also improve spectrum utilization and anti interference effectively compared with single band systems.

In recent years, academic circles and industrial circles pay more attention to CUWB system. In 2004, Jaiganesh Balakrishnan [4] proposed an idea of multiband pulse system and proved that this method could improve the system transmission rate effectively. Martin Mittelbach [5] corrected the system model and proved that the transmission rate could be increased from single band Mbit/s to multiband Gbit/s. Aamish Hasan [6] and H.-U. Dehner [7] optimized the model from multiple users and interference suppression standpoint and improved the receiver BER performance. But the methods above use band-pass filtering way to divide band, the receiver uses non-coherent energy detection, which leads to the complex of the filter design and realization. Literature [8] proposed a multiband adaptive pulse design and improved the anti-interference performance, which used serial transmission,too, and did not improve the transmission rate. Literature [9] proposed multiband parallel transmission design, but did not fully consider the phase orthogonal properties between subband pulses, for this reason, the increase of data transmission rate was limited.

Above all, PSWF pulse is equivalent to ideal band-pass filter based on the band-limited and orthogonal properties, selects orthogonal pulse in different bands as subband pulse, disposes the spectrum overlap rate between adjacent band according to the phase, and finally achieve the purpose of improving transmission rate and spectrum utilization, the receiver uses coherent demodulation mode to realize the optimal receiver. Finally, the coexistence of multiband CUWB systems and existing narrowband communication systems are studied.

2. Subband Pulse Design.

The IR-UWB signal is mainly in the form of narrow pulses which can be used in many different waveforms, such as Gaussian waveform, raised cosine waveform, etc. The pulses are mostly based on the design from the time domain to the frequency domain. In the late 1950s, Bell Labs D. Slepian and H. O. Pollack first proposed the prolate spheroidal wave function (PSWF), and proposed the frequency domain to the time domain design ideas, which is calculate the expression in time domain UWB pulse according to Federal Communications Commission (FCC) emission mask. In multiband CUWB system, to satisfy the radiation mask requirements of signal power spectrum density (PSD) and reach to high-speed transmission and low inter-symbol interference, the system requires a pulse signal both band-limited and time-limited. PSWF is the complete orthogonal basis in band limited space $[-\Omega,\ \Omega]$ and time limited space $[-T/2, T/2]$. It satisfies the following integral equations:

$$\int_{-T/2}^{T/2} \varphi(x) \frac{\sin \Omega(t-x)}{\pi(t-x)} dx = \lambda \varphi(t) \tag{1}$$

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

$\varphi(x)$ is PSWF, λ is the corresponding eigenvalue, $1 > \lambda_0 > \lambda_1 > \cdots > \lambda_i > \cdots$, λ_n is the energy concentration of output pulse.

$$\lambda_n = \frac{\int_{-T/2}^{T/2} |\varphi_n(t)|^2 \, dt}{\int_{-\infty}^{\infty} |\varphi(t)|^2 \, dt} \tag{3}$$

Represents the equation (1) into discrete matrix form:

$$\mathbf{H}\boldsymbol{\varphi} = \lambda\boldsymbol{\varphi} \tag{4}$$

In the questions above, hermite matrix $\mathbf{H}$ is a symmetrical toeplitz structure, $\boldsymbol{\varphi}$ is different eigenvalue λ corresponding to eigenvector groups.

According to equation (1), subband pulse signal is equivalent to ideal bandpass filter with upper threshold f_H and lower threshold f_L,using discrete approximation solution method in which T_m is duration time and theoutput is $\lambda\varphi(t)$. Subband spectral mask is shown as:

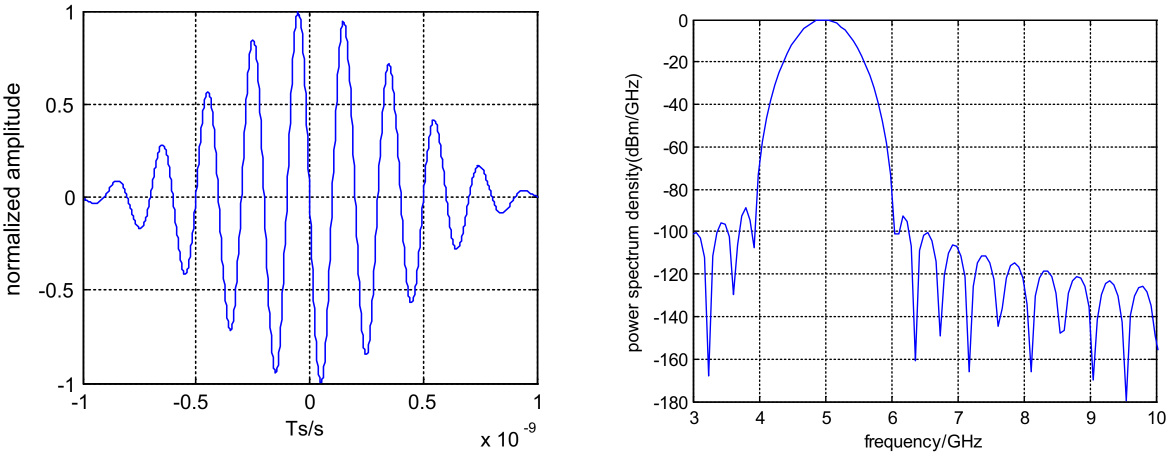
$$h_i(t) = 2f_{iL}\sin c(2f_{iL}t) - 2f_{iH}\sin c(2f_{iH}t) \tag{5}$$

$$H(f) = \begin{cases} 1 & f_{iL} < f < f_{iH} \\ 0 & others \end{cases} \tag{6}$$

Select $\varphi(x)$ corresponding maximum eigenvalue to be subband pulse. The closed solution of $\varphi(x)$ is difficult to obtain, therefore, an approach using of a simple discrete method to generate subband pulses, $h_i(t)$ is discretized, samples N values of pulse in the time interval to obtain the discrete solution of prolate spheroidal wave function.

$$\lambda\varphi(n) = \sum_{m=\frac{-N}{2}}^{\frac{N}{2}} \varphi(m) \times h(n-m) \tag{7}$$

Taking available frequency band $f \in [4\text{GHz}, 6\text{GHz}]$, pulse duration $T_m = 2ns$, the pulse time-domain waveform and PSD are shown in figure 1.



(A) Time domain waveform (B) Power spectrum density

Figure 1. Pulse time-domain waveform and power spectrum density

Subband pulse PSD consists of a main-lobe and some side-lobes. The diffuse to both sides and attenuate in a certain interval, which cause the energy leakage. Side-lobes height determines the degree of energy leakage. If side-lobe becomes smaller, more energy is concentrated in the main lobe, with less spectrum energy leakage. Energy concentration λ is decided by the time bandwidth product $C = T\Omega/2$, C also represents the design freedom of subband pulse. C is directly proportional to T_m, therefore in the condition of certain subband width, main-lobe width increases with the increase of C. The main-lobe energy increases, and the pulse time domain duration rises. Let $B(\omega)$ denotes the pulse leakage energy in band $|\omega| \leq \Omega$ and can prove that the upper limit of $B(\omega)$ is:

$$\sigma^2 T(1-\lambda_0) \approx 4\sigma^2 T\sqrt{\pi C}e^{-2C} \tag{8}$$

σ^2 is sample variance.

Table 1 is the corresponding relationship of C and upper limit of $B(\omega)$, when C increases, $(1-\lambda_0)$ decreases exponentially, when $C \geq 8$, all energy is concentrated in the frequency band $|\omega| \leq \Omega$.

TABLE 1. Corresponding relationship of C and $1-\lambda_0$

C	0.5	1.0	2.0	4	8
$1-\lambda_0$	0.6903	0.4274	0.1194	0.0041	≈ 0

In figure 2, three different values of C are chosen to illustrate its influence on pulse waveforms.

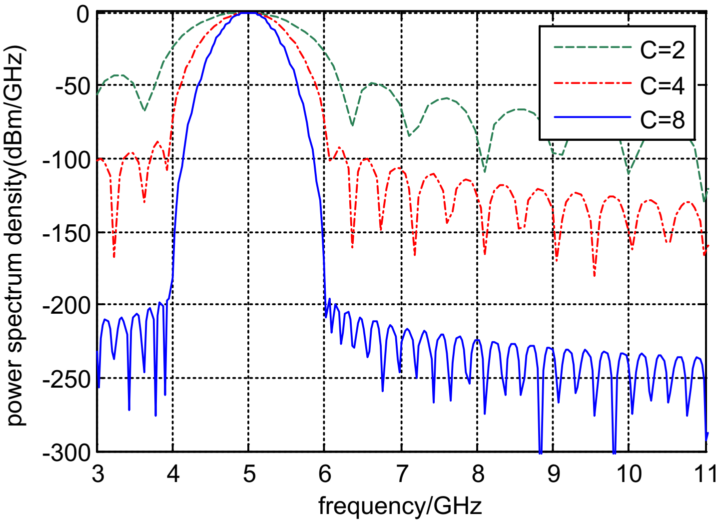


FIGURE 2. Pulse waveforms under the different time bandwidth product

3. Multiband parallel CUWB system model. Multiband parallel CUWB system design idea is a kind of scheme that available frequency band is divided into a plurality of subbands using PSWF to produce the corresponding subband pulse waveform, and user datum go through serial-to-parallel conversion into multiple line, every line uses respective subband pulse to transmit information, every subband is a UWB signal, and pulses between adjacent band are orthogonal. In transmitter, subband pulses are weighted in the time domain and composed a line to send out through a single antenna. In receiver, the received signal is decomposed by a set of bandpass filter firstly, then can be detected and judged in respective subband. Finally, orthogonal signal is used to coherent demodulate. It reduces the interference between adjacent subband. The principle diagram is shown in figure 3.

Multiband parallel CUWB system design is of flexibility and with a strong coexistence and rules of adaptability. When there is narrowband interference from licensed user or existing interruptions, in order to avoid mutual interference, it can make the subband pulse be added up to zero in the interference bands by prohibiting the use of some subbands or adjusting parameters, thus avoiding interference.

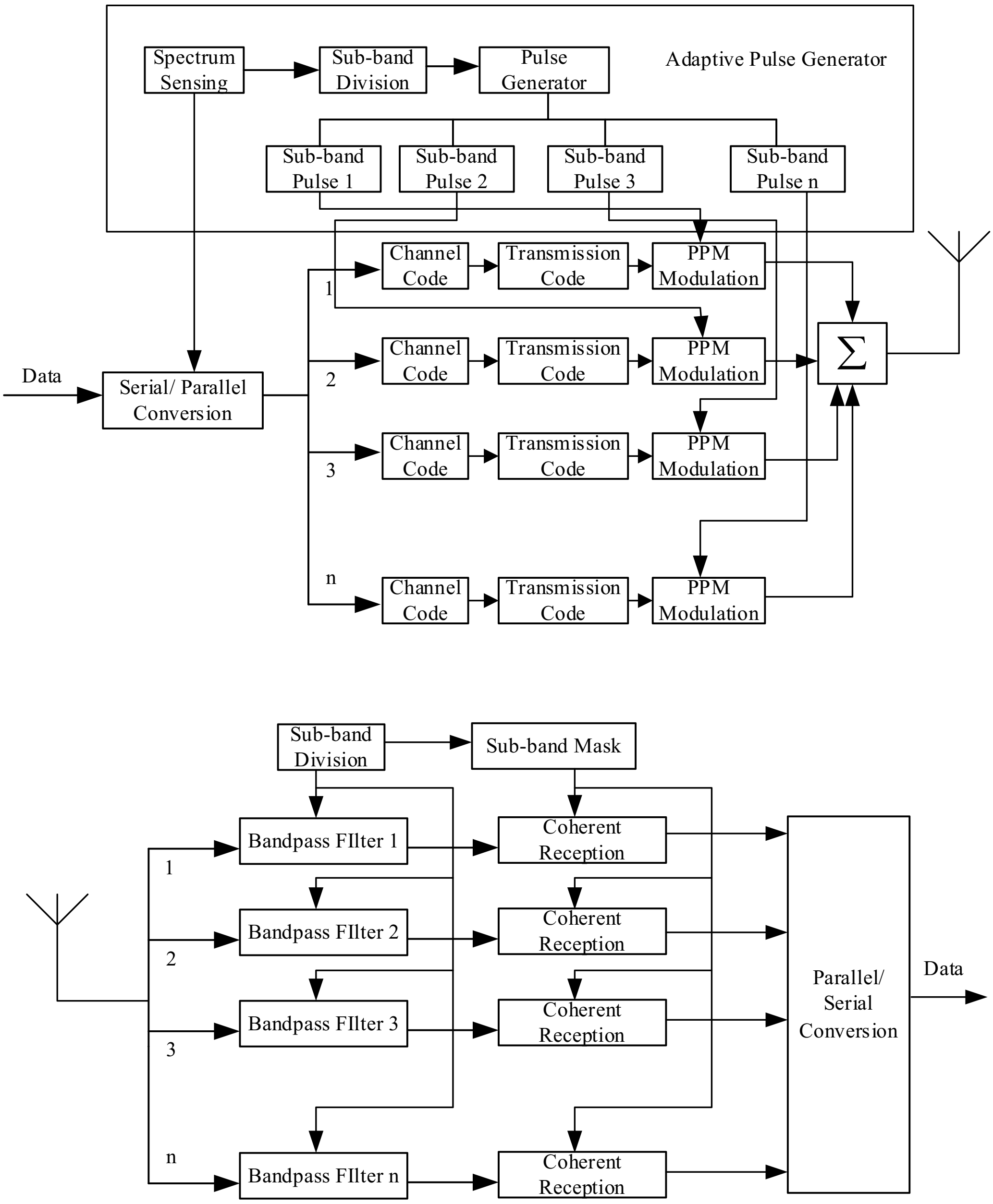


Figure 3. Principle diagram of Multiband parallel CUWB system

Before the designing, CUWB system first senses radio spectrum environment and selects the band which satisfies communication requirements, the adaptive spectrum mask $S_{CUWB}(f)$ is constructed dynamically, which has better flexibility than fixed spectrum mask.

CR user determines the position of the divided subband $[f_{iL}, f_{iH}]$ and the number of sub bands M which is based on the spectrum bandwidth of the pulse B, the subband pulse duration T_m and width B_0. In order to make better use of spectrum resources and improve the spectrum utilization, when dividing each subband, the band between subbands is overlapping, namely $f_{iH} \geq f_{(i+1)L}$, this paper presents the concept of overlap rate υ:

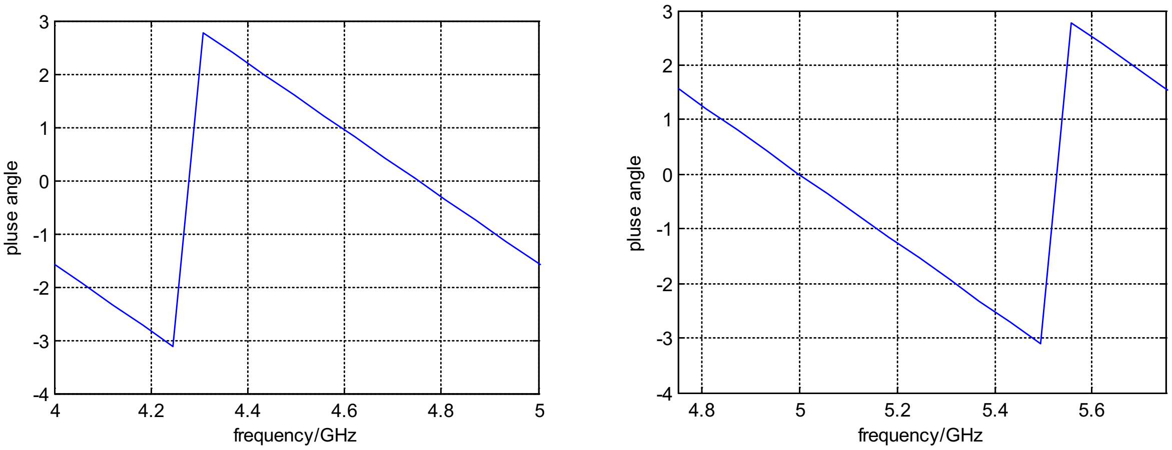
$$\upsilon = \frac{(f_{(i-1)H} + f_{iH}) - (f_{iL} + f_{(i+1)L})}{2 \times (f_{iH} - f_{iL})} \times 100\% \tag{9}$$

Assuming each subband has the same width B_0, and $B_0 = C/T_m$, then we can calculate the width of the subband and determine the number of subband M by the following equation:

$$B = B_0[M - v(M-1)] \tag{10}$$

Subband pulses are selected from the top m PSWF with larger concentration energy, you can design m^M multi-band pulse in theory. Let the i-th subband spectrum range be $[f_{iL}, f_{iH}]$, in all the waveforms that satisfy the conditions, selecting the PSWF φ_k with energy concentration λ_k as a subband pulse $p_i(t)$.

Focus that pulse phase is cyclical phase. The principle of selecting subband pulse is: under the condition of the energy with the greatest possible, try to make adjacent subband pulses have $\pi/2$ phase difference in overlapped spectrum. Figure 4 shows the two pulses phase corresponding eigenvalue λ_0 with $T_m = 2$ns in $f_1 \in$ [4GHz, 5 GHz] and $f_2 \in$ [4.75GHz, 5.75 GHz], the phase difference is $\pi/2$.



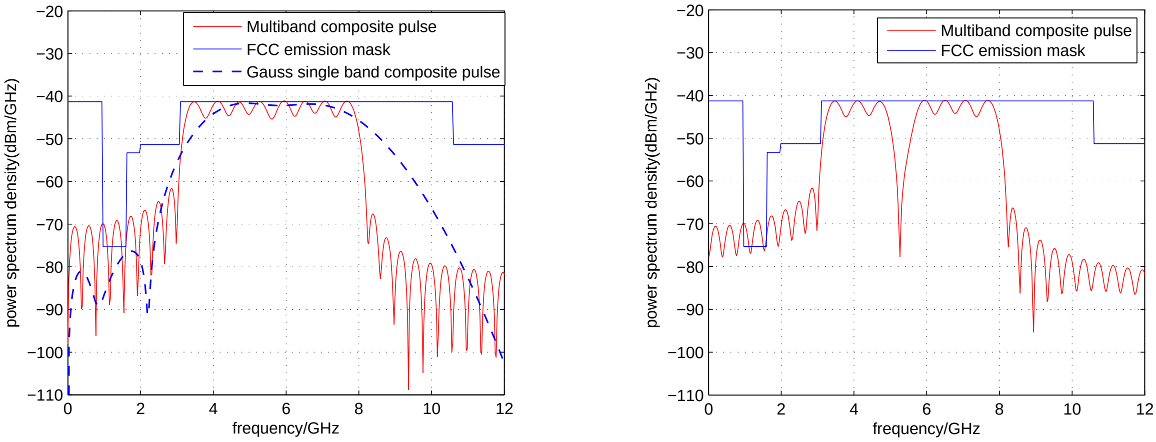
(A) φ_0 phase of firse subband (B) φ_0 phase of second subband

FIGURE 4. Subband pulse phase

Figure 5(a) is the PSD of multiband composite pulse and Gauss single band composite pulse, assuming the available frequency band is $f \in$ [3.1GHz, 8GHz], the Gauss composite pulse is a combination of 15 order derivative functions, these derivative functions occupy the same band. The other signal is multiband composite pulse PSD with pulse duration $T_m = 2ns$, the number of subband is 8, width of subband is 800MHz, pulse frequency band overlapping is 25%. Gauss composite pulse does not make full use of band, and the band as a whole for pulse designing, this is not conducive to coexisting with narrowband system. Figure5(b) is the PSD while narrow-band interference occurs, when the pulse in the frequency band [4.8GHz, 5.6GHz] gets a groove within a depth of 40dB, these grooves can make CUWB wireless communication system avoid interfering the narrowband systems on this band, so as to be coexistence.

In practical applications, due to the energy concentration of subband pulse $\lambda_0 < 1$. There is a small part of the energy leakage, and therefore the leaked subband pulse power will still cause interference to other subband, resulting in the weighted sum pulse power declined in portion band, and can not fully satisfy the requirements of FCC radiation mask. Calculate the pulse spectrum utilization is one way to measure the pulse of the merits of CUWB, spectrum utilization is defined as [10]:

$$\eta = \frac{\int_B S_p(f)df}{\int_B S_{\text{CUWB}}(f)df} \times 100\% = \frac{\int_B \frac{1}{T_s}\left|P(f)\right|^2 df}{\int_B S_{\text{CUWB}}(f)df} \times 100\% \tag{11}$$



(A) PSD of composite signal

(B) PSD of signal coexistence with narrowband interference

Figure 5. PSD of composite signal

Here, T_s is the pulse repetition period.

Table 2. Spectrum utilization of pulses

pulse	spectrum utilization
15 order Gauss composite pulse	50%
33 order Gauss composite pulse	92%
8 subbands multiband composite pulse	72%
10 subbands multiband composite pulse	86%

Table 2 shows the spectrum utilization of different subband number and order, it can be seen from the table, with the subband number and order increasing, spectrum utilization is improved gradually. Spectrum utilization of multiband composite pulse is less than 33 order derivative functions Gauss composite pulse, but higher than 15 order derivative functions Gauss composite pulse. When the subband number increases to 10 or more subbands, the spectrum utilization of parallel CUWB system can reach 80% in normal condition, this value is higher than traditional UWB system. But as the bandwidth is wide, CUWB system may cause interference with narrowband wireless systems. When a small amount of narrowband interference occurs, we only need to cancel the subband pulse in the interfering bands instead of changing the communication bands. So as to realize revising seamless transmitted waveform to adapt with the wireless environment. Multiband composite signal can still ensure over 80% spectrum utilization while escaping from interference successfully. However, Gauss composite pulse can not coexist with narrowband systems, it need to abandon the entire band, causing waste of spectrum. Multiband composite pulse has flexible design, strong anti-interference, high spectrum utilization, it applies to emission mask in different countries, and has smaller performance loss when spectrum handoff.

4. **Performance analysis.**

4.1. **System Complexity and Power Consumption.** CUWB system complexity and power consumption are composed mainly of two parts, the baseband module and RF circuit. The baseband part is coded module, multiband parallel transmission CUWB in this paper proposes orthogonal pulses to replace the repetition coding module in traditional UWB system, reduces the complexity and power consumption of baseband part. RF circuit includes clock circuit, pulse generator, pulse modulator, power amplifier and filter besides antenna. The complexity and power consumption focus on two parts, adaptive pulse generator and pulse modulator, where the complexity of generator is associated with pulse wave design, and its power consumption is associated with pulse repetition frequency. Discrete solution of equation (7) is used as a subband pulse, after M times $N \times N$ matrix operations, each subband has r major eigenvalues, and other $N - r$ eigenvalues converge to zero rapidly, corresponding r eigenvectors have greater energy concentration and orthogonal to each other, this provides r orthogonal subband pulses for parallel transmission.

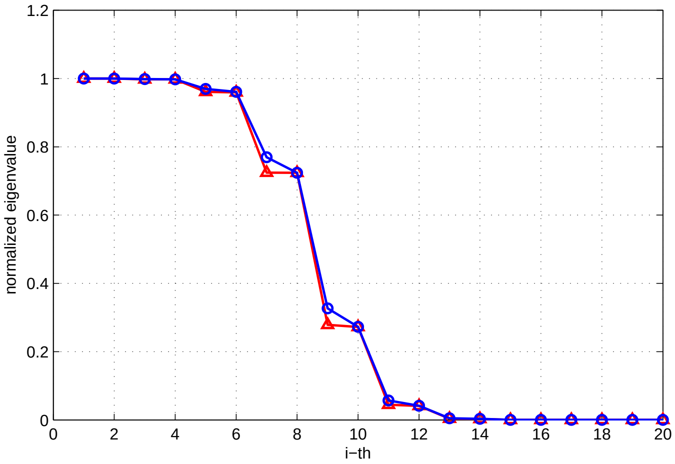


Figure 6. Major 20 Eigenvalues

Figure 6 shows the major 20 eigenvalues with $N = 1024$ and $N = 64$, it can be seen that the appropriate range of r is 1-8 and the value of N has little effect on convergence rate, therefore, in order to reduce calculation, the value of sampling points N can be reduced.

When a licensed user appears, the traditional UWB system needs to redesign pulse wave, but the design method proposed in this paper does not have to redesign pulse for returning band, reduces the transmitter complexity. Furthermore, table 1 shows that in order to reduce energy leakage, C is required to a large value, so the pulse duration will be longer on same subband width, that is the pulse repetition frequency is lower, thus the power consumption of system is reduced.

In the pulse modulating module, each sub-band is equivalent to a conventional single band system, subbands are composed a line by $M-1$ times complex accumulate operation. The complexity increases with M, but the subbands are processed in parallel, therefore the modulation module computation time does not increase. Compared with the single band system, the CUWB systems is more complex, but it can bring higher transmission rate. At present, due to the demand of transmission rate is growing daily, so the multiband parallel CUWB communication technology has important advantages.

4.2. **Information transmission rate.** Multiband pulse generator produces a series of pulses for parallel transmitting data information. In sender, channel code module uses the packet coder of repetition code $(N_s, 1)$, and introduce redundancy, transmission code module adopts integer values sequence C and the elements are integers, $0 \leq C_j \leq N_h - 1$, period of C is N_p, set $N_p = N_s$. Transmission code can be used for multiple access code. Consider single user, using binary orthogonal TH-PPM modulation, in case of conventional single band pulse has the same duration T_m with multiband composite signal. Assuming single band system transmission rate is R_1, transmission rate for the multiband system is R_2, then:

$$R_1 = \frac{1}{N_s N_h T_m} \tag{12}$$

$$R_2 = \frac{M}{N_s N_h T_m} \tag{13}$$

Equation (12)-(13) show that in the same conditions, the multiband parallel transmission rate is M times of single band system. FCC allow to allocate 7500 MHz of spectrum for unlicensed use of UWB devices for communication applications in the [3.1GHz,10.6GHz] frequency band. The instantaneous bandwidth minimum allowed by the FCC ruling is 500MHz, so maximum value of M is 15 without subband overlap. Based on method presented in this paper, the maximum value can reach 19 with 25% overlap rate. In practical application, the narrower band width, the longer pulse duration is, the more serious energy leakage is, which will lead to cross correlation coefficient between adjacent subband be larger and more interference.

4.3. **Interference between adjacent subband.** According to figure 3, emission signal of multiband parallel CUWB system can be expressed as follows:

$$s(t) = \sum_{i=1}^{M} s_i(t) = \sum_{i=1}^{M} \sum_{j=-\infty}^{\infty} \sqrt{E_p^{(i)}} p_i(t - jT_s - \theta_j) \tag{14}$$

Where $s_i(t)$ is the emission signal of ith subband; E_p is pulse carrying energy; $p_i(t)$ is pulse waveform; θ_j is time random displacement.

$$\theta_j = C_j T_c + a_j \varepsilon = \eta_j + a_j \varepsilon \tag{15}$$

Where η_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:

$$r(t) = \sum_{i=1}^{M} \sum_{j=-\infty}^{\infty} \sqrt{\alpha^{(i)} E_p^{(i)}} p_i(t - jT_s - \theta_j^{(i)} - \tau^{(i)}) + n(t) \tag{16}$$

Assuming receiver and sender are synchronous, namely $\tau = 0$, and first subband signal is $r_u(t)$, $r_{mui}(t)$ is sum of other subbands.

$$r_u(t) = \sum_{j=1}^{N_s} \sqrt{\alpha^{(1)} E_p^{(1)}} p_1(t - jT_s - \theta_j^{(1)}) \tag{17}$$

$$r_{mui}(t) = \sum_{i=2}^{M} \sum_{j=1}^{N_s} \sqrt{\alpha^{(i} E_p^{(i)}} p_i(t - jT_s - \theta_j^{(i)}) \tag{18}$$

The relative mask for judgment $m(t)$ is:

$$m(t) = \sum_{j=1}^{N_s} p_1(t - jT_s - C_j^{(1)} T_c) - \sum_{j=1}^{N_s} p_1(t - jT_s - C_j^{(1)} T_c - a_j^{(1)} \varepsilon) \tag{19}$$

The output of decision is $Z = Z_u + Z_{mui} + Z_n$, for N_s pulses in a bit, a bit energy E_u is got out in first subband.

$$E_u = (Z_u)^2 = \alpha^{(1)} E_p^{(1)} N_s^2 \left(\int_0^{T_m} p_1(t) p_1(t) dt \right)^2 \tag{20}$$

$p_i(t)$ is the energy normalized pulse signal, then E_u is expressed as:

$$E_u = \alpha^{(1)} E_p^{(1)} N_s^2 \tag{21}$$

For receiver, other signals except the first subband signal are interference, interference generating by nth subband is:

$$\sigma_{mui^{(i)}}^2 = N_s^2 \alpha^{(i)} E_p^{(i)} \left(\int_0^{T_m} p_1(t) p_i(t) dt \right)^2 \tag{22}$$

All the pulses are independent for each other, so the total interference energy is signal energy of other $N_u - 1$ subbands, in receiver, multiple bands interference for a bit information is:

$$\sigma_{mui}^2 = \sum_{i=2}^{M} \sigma_{mui^{(i)}}^2 = N_s^2 \sum_{i=2}^{M} \alpha^{(i)} E_p^{(i)} R_{p_1 p_i}^2(0) \tag{23}$$

$R_{p_1 p_i}^2(t)$ is cross correlation function of pulse $p(t)$.

In generally, all band transmission power is same, the statistical average of bit received energy $E_b^{(i)} = N_s E_p^{(i)}$ is same through common channel, too. The received energy is considered to be equal approximately in different subbands, so BER of multiband parallel transmission UWB system is:

$$P_{r_b} = \frac{1}{2} erfc \left(\sqrt{ \frac{1}{2} \left(\left(\frac{2E_b^{(1)}}{N_0} \right)^{-1} + \left(\frac{1}{\sum_{i=2}^{M} R_{p_1 p_i}^2(0)} \right)^{-1} \right)^{-1} } \right) \tag{24}$$

Multiband system improves the information transmission rate and spectrum efficiency by dividing a plurality of subbands, but the cost is BER increasing. According to equation (24), the error rate of CUWB system is higher than traditional single band UWB system, because system BER is determined by two parties, thermal noise and interference between subbands, wherein the second part is particular to multiband system and it is influenced by subband number M and pulse cross correlation function $R_{p_1 p_i}^2(t)$, these parameters become smaller, influence between bands become less. In low SNR, thermal noise is the most limiting factor for system, with SNR increasing, the influence of interference between subbands is become obvious.

Figure 7 illustrates the BER of multiband parallel transmission UWB system, simulation condition is 10 subbands, overlap rate 25% and TH-PPM modulation. When the SNR is below 0dB, multiband system and single band system have almost same BER, the impact on the BER of the pulse waveform is not obvious. For example, when the SNR is -5dB, the error bits caused by first party is 2×10^8 times of second party, when SNR exceeds 5dB, the difference in BER curves is primarily due to pulse cross correlation function, system is influenced by multiband. When SNR reaches 17dB, the error bits of two parties are approximately equal. That is when the SNR is lower than 0dB, two systems have same error rate characteristic, but the information transmission rate of multiband system is raised M times, and multiband system can adjust spectrum quickly, has more flexible.

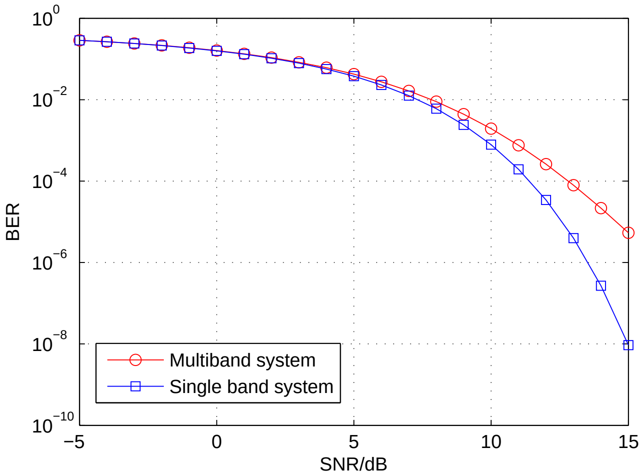


Figure 7. System bit error rate

5. **Conclusion.** Multiband CUWB system bandwidth can be adjusted according to spectrum environment, the division is more effective. At the same time, because the spectrum of sunband signal is composed by a series of discrete band. Therefore, each band can be used independently to improve the transmission rate and flexibility of UWB system. Subbands are independent of each other, therefore, CUWB system can coexist with existing wireless systems by remising partial subbands. Different countries and regions have different distribution methods of spectrum, so the single band UWB system is difficult to adapt to all the circumstances, but multiband UWB can increase the applicability greatly on a global scale. Of course, it also makes the complexity, cost and power consumption of the system increased.

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REFERENCES

[1] L. Yang and G. B. giannakis, Ultra-wideband communications: an idea whose time has come, *IEEE Signal Processing Magazine*, vol.21, no.6, pp. 26–54, 2004.

[2] X. B. Chen, H. Chen and Y. Chen, Spectrum sensing for cognitive ultra-wideband based on fractal dimensions, *in Fourth International Workshop on Chaos-Fractals Theories and Applications*, Hangzhou, pp.363–367, 2011.

[3] J. Yang, X. J. Jian and Z.F. Hou, Interference Suppression by Adaptive Pulses for Cognitive UWB, *Processing on 9th International Conference on Signal*, Beijing, pp. 1780–1783, 2008.

[4] A. Batra, J. Balakrishnan, G. R. Aiello, J. R. Foerster and A. Dabak, Design of a multiband OFDM system for realistic UWB channel environments, *IEEE Trans. on Microwave Theory and Techniques*, vol. 52, no.9, pp. 2123–2138, 2004.

[5] M. Mittelbach, R. Moorfeld and A. Finger, Performance of a multiband impulse radio UWB architecture, in 3rd *International Conference on Mobile Technology, Applications & Systems*, Bangkok, Thailand, pp.17, 2006.

[6] A. Hasan, A. Anwar, H. Mahmood, On the performance of multiuser multiband DS-UWB system for IEEE 802.15. 3 a channel with hybrid PIC rake receiver, *Proc. on 2011 International Conference on Computer Networks and Information Technology*, Abbottabad, pp. 65–69, 2011.

[7] H. U. Dehner, R. Moorfeld, H. Jakel, D. Burgkhardt, A. Finger, F. K. Jondral, Multi-band impulse radio–an alternative physical layer for high data rate UWB communication, *Frequenz*, vol.63, no.9, pp. 200–204, 2009.

[8] B. Li, Z. Zhou, W. X. Zou, A Novel Spectrum Adaptive UWB Pulse: *Application in Cognitive Radio, in 2009 IEEE 70th Vehicular Technology Conference Fall*, Anchorage, pp. 1–5, 2009.

[9] L. L. Chen, X. Yu, Z. Dou, Research on the performance of multiband impulse radio UWB communication system based on PSWF, *Journal of Harbin Engineering University*, vol. 35, no. 4, pp. 499–503, 2014.

[10] X. R. Wu, Z. Tian, T. N. Davidson, Optimal waveform design for UWB radio, *IEEE Trans. on Signal Processing*, vol.54, no.6, pp. 2009–2012, 2006.