TELKOMNIKA Indonesian Journal of Electrical Engineering
Vol.12, No.2, February 2014, pp. 1385 ~ 1394
DOI: http://dx.doi.org/10.11591/telkomnika.v12i2.3971

Research of Adaptive Resolution Spectrum Sensing Method Based on Discrete Wavelet Packet Transform

Wei Naiqi*, Chen Zili, Zhu Anshi
UAV engineering department, Ordnance Engineering College, Shijiazhuang 050000, Hebei, China
*Corresponding author, e-mail: wnq_8510@163.com

Abstract

Spectrum sensing is the precondition of the realization of cognitive radio. In order to achieve efficient multi-resolution spectrum sensing, and find the available spectrum hole quickly, it proposes a variable resolution adaptive frequency spectrum energy sensing method based on discrete wavelet packet transform (DWPT). The method applied hierarchical decomposition and threshold denoising characteristic of wavelet packet transform, and solved the problem of subband sort disorder in wavelet packet decomposition process; it can eliminate the influence of uncertainty noise on detection performance, effectively. It also can reduce the computational complexity according to demand of selection resolution and perception band. The simulation results and its analysis show that the proposed method has advantages of high precision, simple arithmetic and fine flexibility, etc. The method is adapted to fast sensing in the cognitive radio environment.

Keywords: *cognitive radio, energy detection, wavelet-packet transform, non-stationary noise*

1. Introduction

Cognitive radio can effectively solve the spectrum scarcity problem in the development wireless communication; it is one of the main development directions in future wireless communications. Spectrum sensing is the premise and key technologies of cognitive radio. Now the spectrum sensing methods involve matched filtering method, energy method, cyclic steady characteristic test and cooperation method, etc. [1-3].

Matched filtering method is to realize match filtering of signal when the authorized user obtained prior knowledge of signal, and it can realize the maximization of signal-to-noise ratio of the receiving part, which can improve the performance of the cognitive system. If the prior information is not accurate, the matched filter detection performance will become very poor, while for each authorized user in cognitive radio receiver needs the independent single matched filter, its realization is too complex and its operability is very low. Circulation detection is using the characteristics of modulated signal e.g., periodicity and the characteristics of cycle stationary. It is due to cyclical statistical properties of the authorized user signal, while the noise has no characteristic as this, so cyclic steady state characteristics of the modulated signal can be detected. The specific characteristics of signal can be detected through cycle stationary detection method. This method is with high computational complexity and a long observed time.

Collaborative detection allows multiple cognitive users to exchange information between each other, and it also can improve the interception and testing the ability of spectrum. Its advantage is to improve the reliability of the test and reduce the detection time of each detector at the same time. In the actual environment, shadow fading and multipath fading will lead to the existence of the correlation. The information exchange process will produce additional spectrum expense. In the collaboration sensing method, the wrong report of malicious user will leads the wrong decision of the center.

Energy detecting method is one of the most common methods of spectrum sensing, is a kind of blind test, and it has a wide range of application, its implementation is also simple. But in the traditional energy detecting method based on FFT, the resolution method is not high and is vulnerable to affect by non-stationary noise, especially when the SNR is very low, the detection performance will be affected by the influence of uncertainty noise apparently [5-7]. Therefore, in papers [2-4], the energy detecting method based on wavelet transform is proposed through multi-scale wavelet decomposition and edge detection of frequency spectrum, it can effectively

Received July 22, 2013; Revised September 2, 2013; Accepted September 18, 2013

reduce the non-stationary noise effect on the performance of detection, and improve the detection speed, but its resolution is not high. In papers [5, 6] the energy detecting method based on wavelet packet transform is proposed, it eliminates noise uncertainty influence and improves the resolution at the same time, but the computation work is bigger, and the adaptive decomposition which can reduce the complexity of computation is not realized. In the paper [8-10], the energy detection method based on wavelet packet transformation is proposed, but it only applies wavelet packet transform on estimation of noise and threshold, it does not make full use of the excellent characteristics of the wavelet packet transform. In this paper, the energy detection method based on discrete wavelet packet transform (DWPT) of variable resolution adaptive frequency spectrum is proposed, detection principle and the model are presented, and the simulation results are also presented and analyzed [11-13].

2. Wavelet Packet Transform
2.1. Principle of Wavelet Packet Transform

In the wavelet transform, the coefficients i.e., the high frequency part of the output of the filter is not in use in further decomposition, and only the low frequency part is decomposed, so its resolution in the high frequency part is poor. And wavelet packet transform not only decompose low frequency part and but also do the secondary decomposition in the high frequency part, so it can give out the details of signal characteristic. Wavelet packet transform keeps the advantages of wavelet transform at the same time, it makes up the deficiency of low frequency resolution. Wavelet packet transform is the development of wavelet transform; it can decompose the signal into different frequency band according to the arbitrary time-frequency resolution, and it can make projection of time domain component of the signal according to different frequency bands in orthogonal wavelet space.

The definition of the discrete wavelet packet transform can be expressed as below:

$$\psi_{j+1}^{2p}(t) = \sum_{n=-\infty}^{\infty} h[n]\psi_j^p(t - 2^j n) \tag{1}$$

$$\psi_{j+1}^{2p+1}(t) = \sum_{n=-\infty}^{\infty} g[n]\psi_j^p(t - 2^j n) \tag{2}$$

Where ψ_j^p represent the j layer, the number p branch wavelet packet $0 \le p \le 2^j - 1$, $h[n]$ denotes the coefficient of low pass wavelet packet filter.

$$h[n] = \left\langle \psi_{j+1}^{2p}(u), \psi_{j+1}^{2p}(u - 2^j n) \right\rangle \tag{3}$$

$\langle \cdot \rangle$ represents the inner product, $g[n]$ represents the coefficient of high pass wavelet packet filter.

$$g[n] = \left\langle \psi_{j+1}^{2p+1}(u), \psi_{j+1}^{2p+1}(u - 2^j n) \right\rangle \tag{4}$$

In the Figure 1, the wavelet packet decomposition structure diagram with three layers is presented, which presents the tree structure, it is also known as the binary tree structure. S0 is the original signal, S10 and S11 are low frequency part and high frequency part of first decomposition in S0 layer, respectively; S20 and S21 are the low frequency part and high frequency part of S10, S22 and S23 represent low frequency part and high frequency part of S11 and so on. So it can be found that the wavelet packet decomposes the low frequency and high frequency part of the signal at the same time. In the Wavelet packet transform, the frequency band is divided with multi-level, in the multi-resolution analysis, it makes further decomposition in the high frequency part, and it can choose the corresponding frequency band according to the adaptive characteristics of the signal, so it can improve the time-frequency resolution, increasing bandwidth utilization.

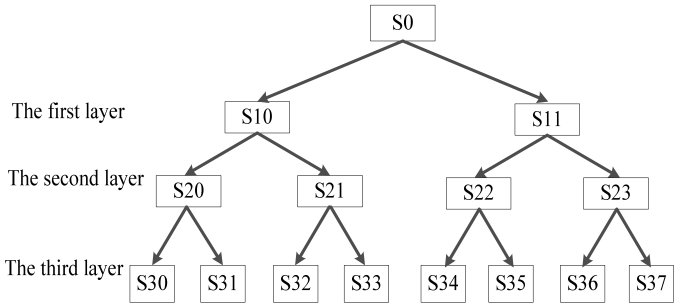

Figure 1. Diagram of Wavelet Decomposition Structure

The most important characteristic of wavelet packet transform is that in the spectrum analysis process, it divided spectrum into the high frequency and low frequency part, therefore, in the multilevel wavelet packet transform analysis, it is very convenient to divide the frequency band into several sub band. As shown in Figure 2, the layer of wavelet packet transform represents the different resolution; the higher transformation of layer represents the higher spectral resolution. $\downarrow 2$ denotes samples with two times.

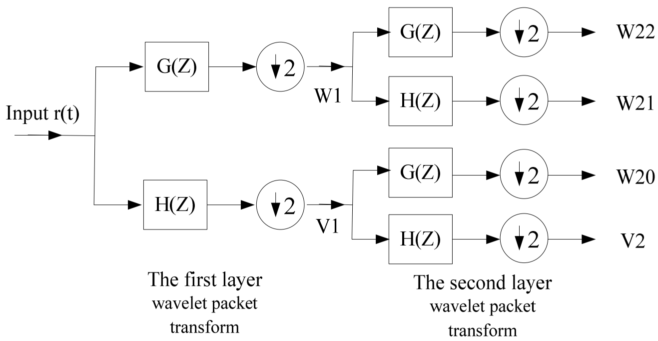

Figure 2. Diagram of Wavelet Packet Decomposition Structure

2.2. Band Scheduling Problems of Wavelet Packet Decomposition

Through related simulation, it can be found that the traditional Mallat algorithm based on wavelet packet fast algorithm of wavelet packet decomposition, the order of its subband is not in accordance with the frequency from low to high, and the order is chaos, e.g., the decomposition of the second layer, the arrangement of subband is according to the frequency from low to high as [S20 S21 S23 S22] (as shown in Figure 3), the third layer of the decomposed subband (as shown in Figure 4 and Figure 5) are arranged according to the frequency from low to high as [S30 S31 S33 S32 S36 S37 S35 S34], and in the further simulation, it can be found that the fourth layer of decomposed subband array presents messy, so it will bring a lot of problems to the analysis. According to this problem, in the paper [9], it puts forward the method that after the convolution of the wavelet filter, Fast Fourier Transform (FFT) will be performed, then set the value of extra frequency components in the spectrum as zeros, in order to get the results of the convolution results and the wavelet filter, then we continue making the wavelet packet decomposition and reconstruction, finally through look-up table, the problem of sequence confusion is solved. The improved algorithm increases calculation work, so it is not suitable for the rapid sensing of the spectrum environment.

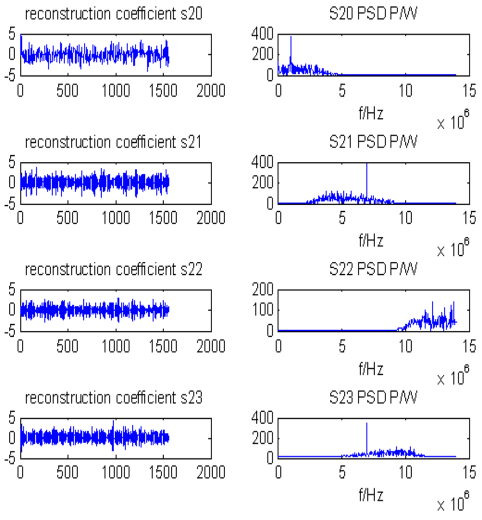

Figure 3. Reconstructed Coefficient and Its Power Spectrum after Two Layers Wavelet Packet Decomposition

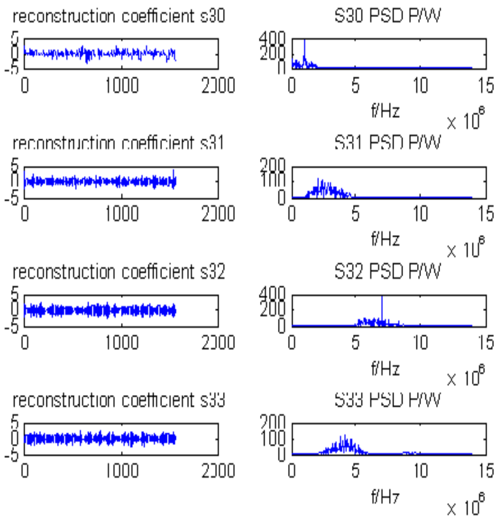

Figure 4. Reconstructed Coefficient and Its Power Spectrum after Three Layers Wavelet Packet Decomposition

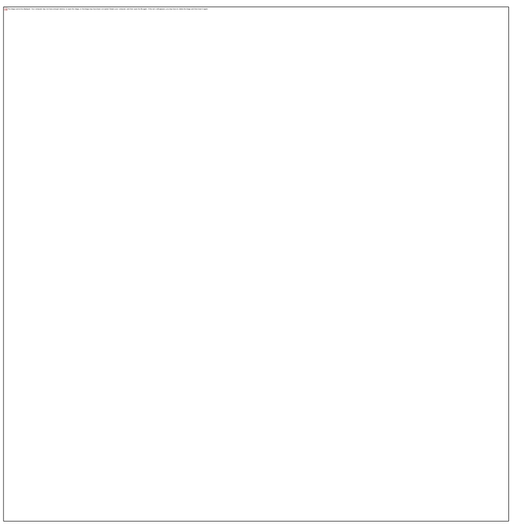

Figure 5. Reconstructed Coefficient and Its Power Spectrum after Three Layers Wavelet Packet Decomposition

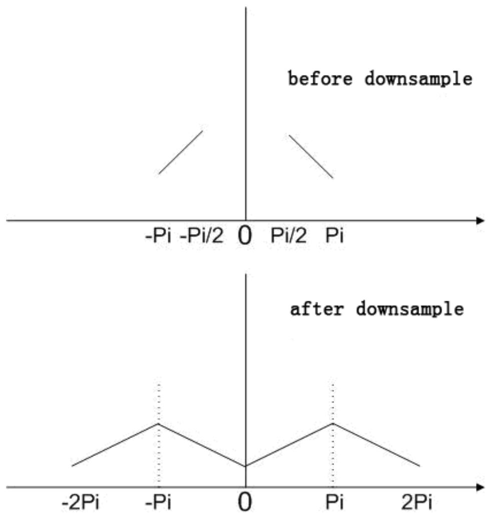

Figure 6. Schematic Diagram of the Twice Sampling

Through related analysis it can be found that the problem in the process of wavelet packet decomposition algorithm is the two times sampling. As shown in Figure 6, after high-pass filtering, if we make the assumptions as sampling signal spectrum is limited between (pi/2, pi). Two-times sampling of the high frequency signals can be performed in two steps: the first step is to enhance spectrum with double and reduce the amplitude to half; the second step is to prolongate the spectrum with 2 Pi in the cycle. So after the sampling signal spectrum shape in the (0, Pi) will flip around, that is the original high frequency Pi will change into 0, and original subband of low frequency Pi/2 into the high-frequency Pi. Therefore, after wavelet packet decomposition, all the high frequency order will flip once.

According to this law, after the further research and analysis, it can be found that, the order of spectrum corresponds to gray code of communication, namely that 0-N subband obtained from the wavelet packet decomposition needs to be converted to binary gray code, and then it converts the binary value directly to decimal value, and then the arranged the order from high to low is obtained, e.g., three layers decomposed sub-band [0 1 2 3 4 5 6 7], when it is converted to binary gray code ,the code [000 001 011 010 010 111 110 011] will be obtained, and then it is converted to a decimal the code [0, 1 2 3 4 5 6 7] will be obtained, then the frequency band sequence obtained is the needs. So after the simple code conversion, scheduling problem of the wavelet packet decomposition subband will be solved.

3. Spectrum Energy Detection Model

The block diagram of DWPT based on energy detection principle is shown as Figure 7. Radio frequency signal received when it is conversed to baseband or intermediate frequency band after modulus conversion, after discrete binary wavelet packet transformation, the band at all levels of wavelet coefficients and scale coefficient are obtained, and then through the wavelet threshold denoising according to the wavelet coefficients, scale coefficient and the relationship between the power, the signal power of each frequency band can be estimated, finally if we combine the threshold, the available free spectrum can be checked out.

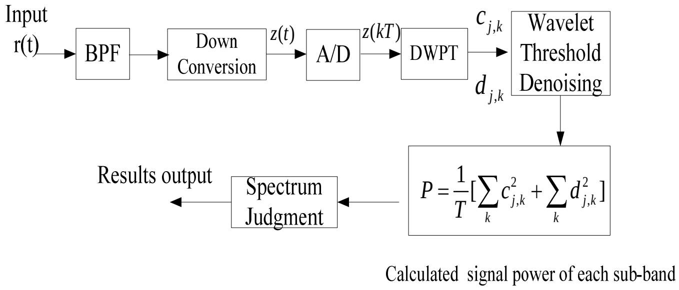

Figure 7. Diagram of the DWPT 's Energy Detector

If we set the input signal as $r(t)$, the transfer functions of low-pass filter and high-pass filters of the wavelet filters, are $H(z)$ and $G(z)$, respectively. The corresponding wavelet functions and scale function are $\psi(t)$ and $\Phi(t)$ respectively, after the j layer of wavelet packet decomposition is to get the number k wavelet coefficient $c_{j,k}$ and scale coefficient $d_{j,k}$ for:

$$\begin{cases} c_{j,k}=\langle r,\phi_{j,k}\rangle=\sum_l h_l^* c_{j-1,l} \\ d_{j,k}=\langle r,\psi_{j,k}\rangle=\sum_l g_l^* c_{j-1,l} \end{cases} \tag{5}$$

According to the relationship between the power spectrum and wavelet coefficients, we can get average signal power of the number K sub-band as:

$$P=\frac{1}{T}[\sum_k c_{j,k}^2+\sum_k d_{j,k}^2] \tag{6}$$

Wavelet packet transform based on threshold can eliminate the background noise and its basic principle is that the wavelet transform has the strong ability to eliminate correlation of data. Therefore, after the wavelet decomposition, the wavelet coefficient of signal is bigger than the wavelet coefficient of noise; after wavelet decomposition, when the wavelet coefficients with large amplitude can be looked as signal and the amplitude coefficient with relatively small amplitude can be looked ad noise. Then, by applying the threshold value method can keep signal coefficients, we make the most noise coefficient reduced to zero.

Here, we can use hard threshold wavelet for denoising, and choose a threshold value λ, when it is greater than the threshold value of the wavelet coefficient $w_{j,k}$, it is keep, when it is below the threshold value λ of the wavelet coefficient $w_{j,k}$, it is set to zero, that is:

$$\tilde{w}_{j,k} = \begin{cases} w_{j,k}, if \ |w_{j,k}| > \lambda \\ 0 \quad , if \ |w_{j,k}| < \lambda \end{cases} \tag{7}$$

In order to reduce the computational complexity, in the paper, we present a method of adaptive variable resolution spectrum sensing based on DWPT. As shown in Figure 8, the basic idea is in each layer of wavelet packet transform, according to the wavelet coefficients of each sub-band average signal power, and comparing with the corresponding layer of threshold, if the signal power is lower than the threshold, it means the sub-band spectrum is empty; the next level of wavelet packet transform is stopped. If the signal power is higher than the threshold, then according to the empty spectrum of has been found or resolution meets the demand of the sub-band to decide whether or not to the next level wavelet packet transform. If it needs more spectrum holes of the sub-band to the next level wavelet packet transform, until we find the spectrum holes, or layers of wavelet packet transform to limit the layers, so that we can control the layer of wavelet packet transform and scope according to the demands, compared with the traditional wavelet packet transform, it can reduce the times of transformation and the complexity of computation.

The flexible applications of wavelet packet transform spectrum perception and judgment method not only can avoid the existence of decomposition low frequency component the traditional wavelet transform and ignore the decomposition of the high frequency component. It can also control of the layers and scope of the wavelet packet transform according to the specific needs of cognitive radio, and reduce the complexity of the transform, and the application of wavelet packet threshold denoising can greatly restrain noise effect on the performance of perception, so as to improve the detection precision in low SNR situation. This method is simple and intuitive and easy to realize.

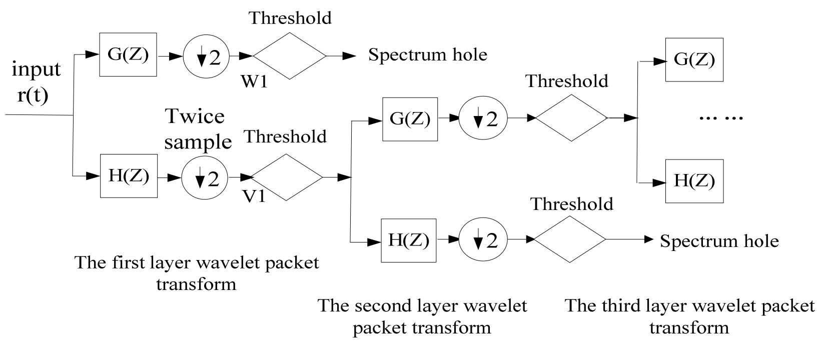

Figure 8. Spectral Energy Detection Diagram Adaptive Wavelet Packet Transform

4. Detection Algorithm Performance Simulation

The main detecting process is:

1) Make the initialization of wavelet packet transform layer K = 1, set up appropriate wavelet filter transfer function.

2) On the frequency without any logo, we make the DWPT of the K layer, then obtain wavelet coefficients of different frequency, then we apply wavelet threshold for denoising processing; the value of the Wavelet denoising threshold is the half of the decomposed mean wavelet coefficients.

3) The wavelet coefficients after noise cancellation can be calculated according to the formula (6), average signal power of sub-band can be obtained;

4) Each sub-band of average signal power is compared with magnitude of the threshold, and each level of the threshold can be set to the minimum signal average power; If the average signal power is smaller than the magnitude of threshold, then the sub-band can be taken as empty. If average signal power is greater than the magnitude of threshold, and then judge whether the bandwidth has been reached according to the current number of spectrum holes found, if demand has been reached, the next layer of wavelet packet transform is cancelled, then change to 6). If it does not meet requirements, and the level of wavelet packet transforms K layer is lower than the maximum permissible transform levels, the step is changed to 5). If the level of wavelet packet transform K reached maximum allowable transform, the step is transferred to 6);

5) K is added with 1. Continue the step 2) - 4);

6) In the spectrum holes found before according to the requirements within the band, choose the smallest frequency signal power as secondary working frequency of the system. Figure 9 is the test flow chart according to the analysis put forward above is based on DWPT adaptive frequency spectrum energy assay.

Now we make the simulation of the sine monophonic signal the frequency of which respectively at 7 MHZ and 1 MHZ the noise ratio (SNR) is -15dB, the signal sampling rate of simulation is set at 28 MHZ. Figure 10 is the each sub-band of the calculated power after three layer of wavelet packet decomposition, and then FFT method based on the energy cannot identify interference, it can be judged from existing interference signal in the sub-band of the graph 1, 4, 5, and the 2, 3, 6, 7, 8 sub-band can be used in the work. Figure 11 is the each sub-band energy after four layers wavelet packet decomposition and calculation, it can be seen from the graph2, 8 and 9, sub band jamming signal, the rest of the 12 sub band can be used in the work.

It can be seen from the Figure 9 and 10, the four layers wavelet packet transform can restrain the influence of noise, and improve the frequency resolution, through the method we can find more holes of the spectrum, to achieve better effect of spectrum sensing. When layers of decomposition is 12, the spectrum sensing results is shown as in Figure 11, It can seen the more accurate test results are obtained, from the results we can find that the spectral resolution is far higher than the energy detecting method based on FFT. Through the comparing with Figure 10 and Figure 11, 12 layers of wavelet packet transform can restrain the influence of noise, improve the frequency resolution, and achieve better effect of spectrum sensing. With the need of perception accuracy, we can improve the layer of wavelet packet decomposition to meet demand of perception accuracy

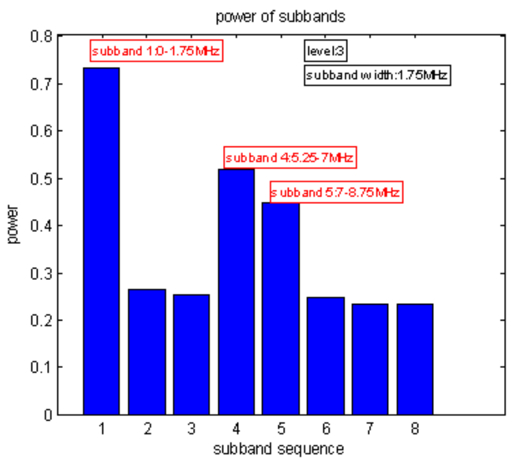

Figure 9. Three Wavelet Packet Decomposition of each Sub-band Power with Low Signal-to-noise Ratio

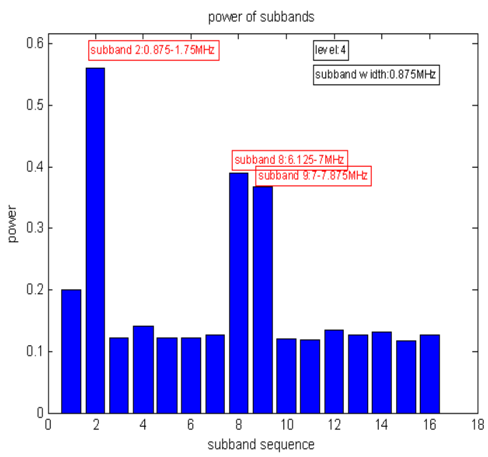

Figure 10. Four Wavelet Packet Decomposition of each Sub-band Power with Low Signal-to-noise Ratio

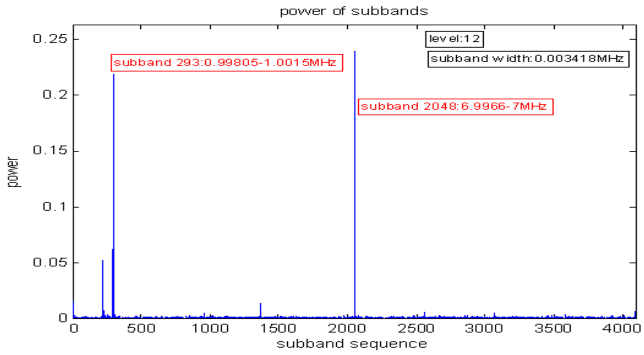

Figure 11. The Sub-band Power after 12 Layers Wavelet Packet Decomposition with Low Signal-to-noise Ratio

The detection performance comparison of the detection performance under uncertainty noise based on the energy of the FFT method and energy method based on DWPT are analyzed through simulation. First we introduce the concept of uncertainty of noise. In the previous discussion, we make the assuming that all receive noise is Gaussian white noise, and its energy in all frequency band are the same, but in fact, the noise is not only come from the receiver part and the system thermal noise, it also comes from some unknown external environment. So the actual noise in the circumstance is just close to Gaussian white noise, the noise energy in some frequency bands are also not sure. In order to study the effect of uncertainty of noise on the performance of the spectrum detection, we assume that receiving noise presents the Gaussian distribution, the noise energy is the unknown variable within the given value scope. We make the assumption that N_0 is the noise value, and the estimation value of the noise is $\hat{N}_0$ the error range of estimation is as follows:

$$(1-\varepsilon_1)N_0 \le \hat{N}_0 \le (1+\varepsilon_2)N_0 \tag{8}$$

Where $0 \le \varepsilon_1 \le 1$, $\varepsilon_2 \ge 0$, the uncertainty of the noise is defined as (9):

$$U = 10\lg[\frac{1+\varepsilon_2}{1-\varepsilon_1}] \tag{9}$$

Figure 12, 13, are the detection performance simulations under non-stationary noise conditions based on the energy of the FFT method and energy method based on DWPT in noise uncertainty condition U=0Db, U=1dB, U=2 dB and U=5 dB, respectively. It can be seen from Figure 12, when noise uncertainty U=0 dB, namely that the background noise is certain, detection performance of the FFT based energy is superior to detection performance of noise uncertainty situation such as U =1dB, 2dB and 5dB, and with the increase of uncertainty of noise, the system detection performance is getting worse gradually, energy detection reliability is also reduced, especially in the low noise ratio, the detection probability is almost zero, i.e. energy detection function has been lost. It also can be seen from the Figure 13, compared with FFT based energy method. The influence of different noise uncertainty on DWPT energy detection has been greatly reduced, performance of the spectrum environment detection system in non-stationary noise environment has been greatly improved.

As can be seen from the simulation results, adaptive frequency spectrum perception and estimation based on the discrete wavelet packet transform has more accurate detection performance, especially in the case of low SNR and non-stationary noise conditions, and combined with wavelet threshold method, the ability of suppress noise will be strengthen. compared to traditional energy detection algorithm ,the wavelet packet transform has better performance. In addition, based on the flexible characteristics of the wavelet packet transform, in the paper, detection algorithm we proposed can realized flexible adaptive control of wavelet packet transform according to the demand of spectrum perception, thus reduced the complexity of the processing, thus provide spectrum perception for resolution in the frequency domain, the realize the efficient multi-resolution spectrum perception.

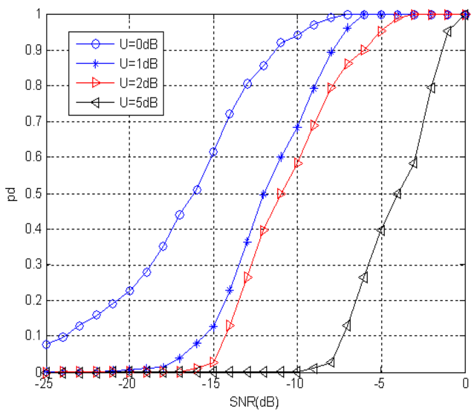

Figure 12. Energy detection performance Based FFT Method under Non-stationary Noise Conditions

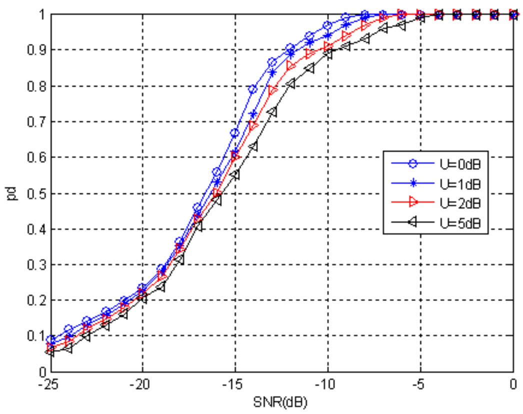

Figure 13. Energy Detection Performance Based DWPT Method under Non-stationary Noise Conditions

5. Conclusion

Spectrum perception technology is one of the premise and key technologies of cognitive radio. Energy method is not only one of the most commonly method, but also it is the fastest of all single node assay method, but the traditional FFT based energy were easily affected by noise uncertainty. In order to solve the problem, and realize the quick and accurate spectrum perception of the environment, in the paper, we proposes the adaptive frequency spectrum energy perception method with variable resolution based on the discrete wavelet packet transform, detection model and the flow charts are also given, in the paper we solve the chaos problem of subband sorting in the wavelet packet decomposition process effectively, we adopt the wavelet packet threshold denoising and multi-level decomposition reduce the influence of noise uncertainty on detection performance and computational complexity, effectively, and the multi-resolution spectrum perception is realized. Simulation results and analysis show that the presented method has high precision, simple algorithm, the flexible agiligy, etc, it can be used for rapid spectrum perception in cognitive radio system.

References

[1] Pan Jianguo, Dixu Ping the Energy Detection Based Spectrum Sensing Method. *Shanghai University of Science and Technology (Natural Science).* 2009; 15(1): 54-59. [in Chinese]

[2] Soamsiri Chantaraskul, Klaus Moessner. *Implementation of Wavelet Analysis for Spectrum Opportunity Detection.* IEEE 20th International Symposium on Personal. Indoor and Mobile Radio Communications. 2009: 2310-2314.

[3] Soamsiri Chantaraskul, Klaus Moessner. *Experimental Study of Multi-Resolution Spectrum Opportunity Detection Using Wavelet Analysis.* IEEE Symposium on New Frontiers in Dynamic Spectrum. 2010: 1-6.

[4] A Chandran, R Anantha Karthik, etc. *Discrete Wavelet Transform Based Spectrum Sensing in Futuristic Cognitive Radios.* International Conference on Devices and Communications. 2011: 1-4.

[5] Youngwoo Youn, Hyoungsuk Jeon, Hoiyoon Jung, Hyuckjae Lee. *Discrete Wavelet Packet Transform Based Energy Detector for Cognitive Radios.* IEEE 65th Vehicular Technology Conference. 2007: 2641-2645.

[6] Sunghyun Kim, Youngwoo Yoon, Hyungsuk Jeon, Minjae Kim, Hyuckjae Lee. *Selective Discrete Wavelet Packet Trnasform-based Energy Detector for Cognitive Radios.* MILCOM 2008-2008 IEEE Military Communications Conference. 2008:1-6.

[7] Shi-bing Zhang, Jin-jing Qin. *Energy Detection Algorithm Based on Wavelet Packet Transform under Uncertain Noise for Spectrum Sensing*. International Conference on Computational Intelligence and Software Engineering. 2010; 1-4.
[8] Tephane Mallat, etc. SignalProcessing Wavelet Guide. Beijing: *China Machine Press*, third edition. 2012.
[9] Yang Jianguo. Wavelet Analysis and Its Engineering Application. *Beijing: Mechanical Industry Press.* 2005.
[10] Sonnenschein A, Fishman PM. Radiometric Detection of Spread-spectrum Signals in Noise of Uncertain Power. *IEEE Trans on AES.*1992; 28(3): 654-660.
[11] Wei Feng, Wenxing Bao. An Improved Technology of Remote Sensing Image Fusion Based Waveled Packet and Pulse Coupled Neural Net. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2012; 10(3).
[12] Huiling Liu, Hongxia Pan, Aiyu Wang. Rough Sets Algorithm and Its Application in Fault Diagnosis. *TELKOMNIKA Indonesian Journal of Electrical Engineering.* 2013; 11(9).
[13] Dong Zhang, Ming Xu, Jiang-Ping Gu, Yue-Jin Huang, Xi Shen. Analysis of Impact Fatigue Life for Valve Leaves in Small Hermetic Reciprocating Compressors. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2013; 11(12).