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Joint signal detection algorithm of cognitive radio in UWB

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Abstract With the progress of research on cognitive radio in ultra-wideband (UWB) open frequency-band, a joint detection algorithm integrating the energy and bi-spectrum detection is proposed in detail for non-Gaussian signal detection from Gaussian noise. The performance of the algorithm was evaluated by simulation, the result of which indicates that the joint detection not only solves the problem of the signal detection in low signal-to-noise ratio (SNR) but also improves the operational speed and the detection probability. Thus, the joint detection algorithm has definite prospect in practice.

Keywords ultra-wideband (UWB), cognitive radio, joint detection, bi-spectrum estimation

1 Introduction

Cognitive radio [1–3] is defined as a system that can sense and understand the change of electromagnetic environment as well as adjust itself to acclimate the statistical changes of the electromagnetic environment by altering its emission power, carrier frequency, modulation and encoding parameters of the radio-frequency according to the results of understanding.

In ultra-wideband (UWB) communication equipment in particular, the principle of coexistence [4,5] must be observed in its open frequency band. In other words, it must cognize the changes of electromagnetic environment and borrow “idle channel” to transmit information in a real-time manner without bringing about any interference to authorized users and other users around. It must release

the “borrowed” channels and switch to the next “idle channel” the moment the authorized users appear. Also, cognition must run through the whole process of communication.

Being at the initial stage and limited by many factors, the chief task of cognitive radio is to detect “spectrum-hole” from noise. Although there are many routine methods in traditional signal detection, such as the likelihood ratio detection [6,7], the cycle-spectrum detection [8] and the energy detection [9–12], the energy detection remains to be the most classical detection.

The algorithm and its performance has already been introduced [13–15] in detail, but the energy detection requires high signal-to-noise ratio (SNR). With low SNR or boundary detection, however, it has low probability of detection, just like in the case of the likelihood-ratio detection and the cycle-spectrum detection.

To ensure that the UWB communication equipment do not jam the authorized users and communicate in idle spectrum at the same time, a new joint signal detection algorithm is put forward in this paper through the study of key technology of cognitive radio to meet the real spectrum requirement of the UWB multi-band orthogonal frequency division modulation (MB-OFDM) device, which unites the fast Fourier transform (FFT)-energy detection and bi-spectrum detection [6]. Explanatorily, the background noise of detection algorithm should be Gaussian noise.

The European Computer Manufacturers Association (ECMA) standard proposes to adopt 528 MHz as a frequency-band unit. Each unit is divided into 128 sub-carrier channels, and the bandwidth of each sub-carrier is 4.125 MHz. The detection algorithm will perform the detecting, accessing and avoiding (DAA) processing to 128 sub-carriers of the 528 MHz frequency-band unit. After rapid detection, the UWB cognitive device may select the discontinuous and idle sub-carrier channels from the different frequency-band units to access and communicate according to the real-time detection result and the transmission rate. In order to avoid the collision, the device will quit the channel as soon as it detects the primary user signal.

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2 Joint detection algorithm

In order to carry out 110 Mbit/s data transmission via the double-band, the UWB equipment adopts OFDM to create 132 sub-carriers, and the bandwidth of each sub-carrier is 2.0625 MHz. According to this characteristic, 16 channel detection units in parallel are designed in the cognitive radio design scheme, and the algorithm processing of each channel detection unit is shown in Fig. 1.

The FFT operation of the sampled data is operated rapidly if the mean amplitude V of data exceeds the accumulated threshold V_T . If the FFT energy amplitude exceeds the mean energy in certain sub-carrier channel, it indicates that there exist authorized users or strong interference in that channel so that the channel will be ignored. The algorithm will perform bi-spectrum detection if the mean amplitude of the signal is equal to or below the threshold. After the detection of bi-spectrum, the sub-carrier channel will be ignored if the authorized signal is determined in the channel, or else the channel is regarded as the idle channel.

For the sake of universality, the signal is denoted as

$$s(t) = \text{Re}\{AU(t)\exp[j(2\pi f_0 t + \varphi)]\}, \quad (1)$$

where A is the signal amplitude, $U(t)$ is the normalized known complex envelope. So the received signal can be described as $x(t) = Is(t) + n(t)$, where I can be 0 or 1 corresponding to whether the signal is absent or present, $n(t)$ is zero mean Gaussian noise.

The noise bandwidth is pre-filtered by a pass-band filter with a perfect amplitude-frequency characteristic to limit the average power of noise:

$$H(f) = \begin{cases} 0, & |f - f_0| > \frac{\Delta f}{2}, \\ \frac{2}{\sqrt{N_0}}, & |f - f_0| \leq \frac{\Delta f}{2}. \end{cases} \quad (2)$$

The following is the narrow-band signal from the filter output:

$$y(t) = \text{Re}\{Y(t)\exp(j2\pi f_0 t)\}, \quad (3)$$

where

$$Y(t) = I \frac{2A}{\sqrt{N_0}} U(t)\exp(j\varphi) + N(t)$$

is the complex envelope of the signal, and $N(t)$ is the complex envelope of Gaussian noise.

2.1 Calculation of V_T

After startup of the UWB equipment, they must first detect the frequency-band from 3 GHz to 6 GHz at a 2.0625 MHz interval. As for a single detection unit, it accomplishes A/D sampling and quantification of $y(t)$, i.e., to sample N points to the down-conversion signal and obtain the discrete-time digital data. Then the detection unit will calculate the average of N points data and carry out preparatory

operation of digital signal to obtain $V = \frac{1}{N} \sum_{i=0}^N Y(i)$.

In Fig. 1, V_T is a variable at different environment or at the same environment but at different time, which can be estimated from the testing results of the background noise in the real electromagnetic environment. In terms of the channel scanning scheme of global system for mobile communications (GSM) mobile station and carrier-sense multiple access (CSMA) standard [16], the cognitive UWB communication equipment samples N points respectively at K channels which need to be detected before sorting them in terms of the data average V repeatedly. For the last J channels ($J \leq K$, J also is a variable, which is associated with the communication number of authorized users, interference or strong noise), the average is nearly equal because of no authorized user signals or the weak signal of the authorized users hidden in noise in the channel. So V_T is temporarily approximated to the average. Owing to restricting the UWB transceiver to indoor quasi-settled equipment in present China, a statistical value of V_T can only be accumulated by certain tests in a relatively steady indoor electromagnetic environment.

2.2 Energy detection algorithm

Before setting up communication, V should be measured repeatedly by the UWB communication equipment and compared with V_T to collect the whole idle channels. If V is larger than V_T , it indicates that there exists authorized users, interference or strong variable background noise in that channel. Then, the discrete-time data is sent to the energy detection for further detection. The energy detection algorithm performs FFT conversion of the data to get

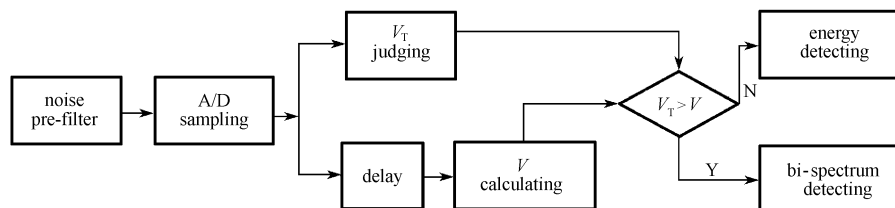


Fig. 1 Joint detection algorithm

the FFT result Y_{FFT} first. On the basis of the result, the algorithm completes power-spectrum calculation and approximates to get

$$P = \frac{2}{N} |Y_{\text{FFT}}|^2,$$

where P is the required detection energy.

The UWB equipment will communicate according to the practicality of the energy detection if the channel is taken up by burst interference or strong noise.

The algorithm will perform bi-spectrum detection if the average of the data is equal to or smaller than the threshold V_T , which means that there may be no authorized user signal or the authorized user's weak signal is hidden in noise in the channel.

2.3 Bi-spectrum detection algorithm [17]

The essence of bi-spectrum estimation is to detect weak signal from strong noise by making use of high-order cumulant. This kind of estimation is available for both deterministic signal and non-Gaussian signal with additive Gaussian noise.

For $y(t)$, its three-order cumulant $C(\tau_1, \tau_2)$ is zero and its bi-spectrum amplitude $B_{yy}(\omega_1, \omega_2)$ is also zero for all the τ_1, τ_2 . Whereas for non-Gaussian process, its bi-spectrum amplitude $B_{yy}(\omega_1, \omega_2)$ should be bigger than zero. $B_{yy}(\omega_1, \omega_2)$ indicates the entire offset extent of the random process from Gaussian noise. Thus, it provides an efficient way to eliminate Gaussian noise from signal. The process of bi-spectrum estimation is described as follows.

First, the data is segmented into K segments with M samples in each segment, i.e., $N=KM$, and subtract the average value of each segment:

$$\bar{y} = \frac{1}{M} \sum_{i=0}^{M-1} y(i), \quad (4)$$

where $y(i) = Y(i) - \bar{y}$.

Then, zeros are added at the end of each segment to obtain a convenient length M for the FFT. In order to increase the number of segments while not decreasing the number of samples of each segment, 50% samples may be overlapped in each segment. However, the overall length of data is still $N=KM$.

Assuming that $\{y^k(0), y^k(1), \dots, y^k(M-1)\}$ are the data of segment $\{k\}$, the discrete Fourier transform (DFT) coefficients are obtained:

$$y^k(\lambda) = \frac{1}{M} \sum_{n=0}^{M-1} y^k(n) \exp\left(-\frac{j2\pi n\lambda}{M}\right), \quad (5)$$

where $k = 1, 2, \dots, K$, $\lambda = 0, 1, \dots, M/2$.

The bi-spectrum estimation based on the DFT coefficients is as follows:

$$\hat{b}_k(\lambda_1, \lambda_2) = \frac{1}{\Delta_0^2} y^k(\lambda_1) y^k(\lambda_2) y^k(\lambda_1 + \lambda_2), \quad (6)$$

where $k = 1, 2, \dots, K$, $0 \leq \lambda_2 \leq \lambda_1$, $\lambda_1 + \lambda_2 \leq f_s/2$, and $\Delta_0 = f_s/N_0$.

The bi-spectrum estimation of the given data is the average over the K segments:

$$\hat{B}_D(\omega_1, \omega_2) = \frac{1}{K} \sum_{i=1}^K \hat{b}_k(\omega_1, \omega_2), \quad (7)$$

where

$$\omega_1 = \frac{2\pi f_s}{N_0} \lambda_1,$$

$$\omega_2 = \frac{2\pi f_s}{N_0} \lambda_2.$$

3 Performance evaluation of joint detection algorithm

Currently, the conception of the joint detection algorithms has been set forth in detail. During real performance evaluation, however, the signal with quadrature phase shift keying (QPSK) modulation is transmitted by the standard signal source. The test result of V_T is -105.39 dBm with no signal being transmitted.

After the signal is transmitted from signal source with SNR from -10 dB to 10 dB, the A/D module of the detection circuit will first accomplish 4096 points to the down-frequency-conversion signal. Then, according to the result V_T compared with the average of samples, the detection circuit completes the operation of the detection. For the sake of length, this paper only presents the typical detection figures. Figures 2 and 3 are the energy spectrum

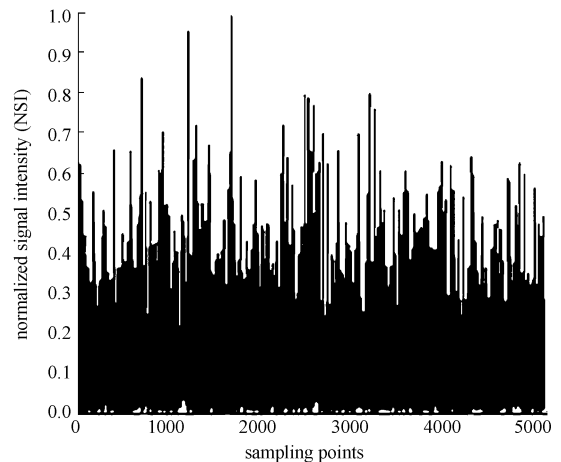


Fig. 2 Energy spectrum of signal with SNR = -9 dB

of signal with SNR = -9 dB and SNR = 0 dB, and Figs. 4 and 5 are the corresponding bi-spectrum.

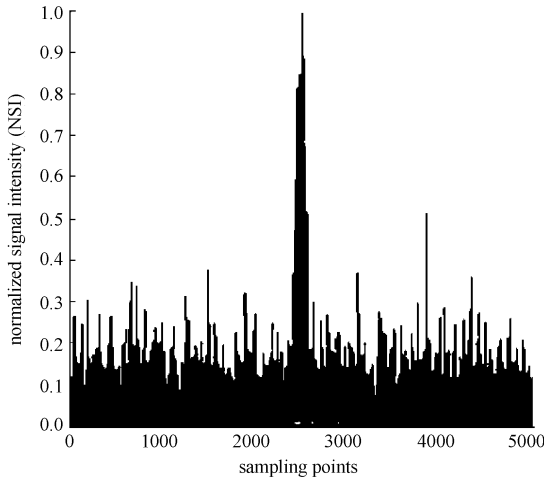


Fig. 3 Energy spectrum of signal with SNR = 0 dB

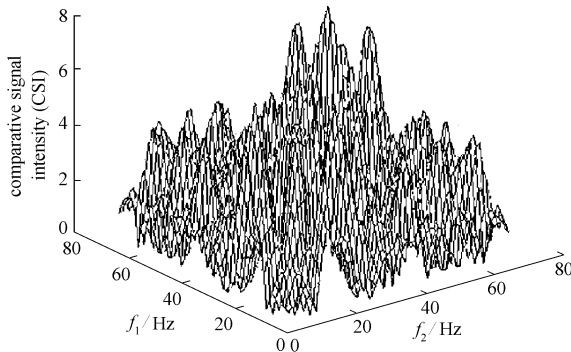


Fig. 4 Bi-spectrum of signal with SNR = -9 dB

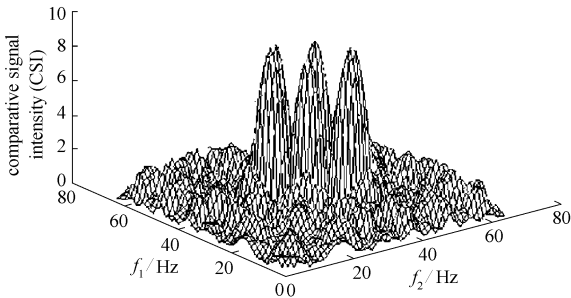


Fig. 5 Bi-spectrum of signal with SNR = 0 dB

In the above figures, it is obvious that the spectrum peak of the signal can be detected by the bi-spectrum algorithm in low SNR, but the weak signal is difficult to be detected by the FFT-energy detection. While in high SNR, the FFT-energy algorithm can complete the task of detection. Although the bi-spectrum algorithm has better performance in high SNR, the FFT-energy algorithm is adopted

because of its less calculation amount as against the bi-spectrum algorithm.

Figure 6 is the receiver operating characteristics (ROCs) of input signal, of which the detection probability is derived from Monte Carlo simulation.

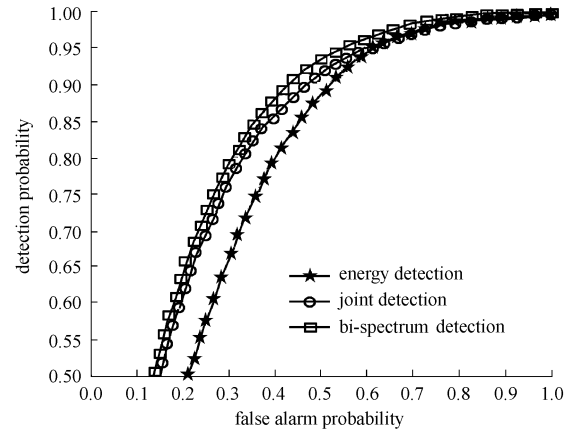


Fig. 6 Probability of detection

As is known to all, the FFT-energy detection requires high SNR and the operation time of the bi-spectrum detection is longer because of the amount of calculation. Therefore, a compromise is adopted in joint detection algorithm, which overcomes the shortcoming of the FFT-energy detection and the bi-spectrum detection. The energy detection is performed first, the result of detection is given immediately for signal with high SNR; otherwise, the bi-spectrum detection will be calculated to detect the authorized users. From the figures above, we can see that the whole time of detection is reduced to approximately 50% in contrast to the bi-spectrum when SNR is varied from -10 dB to 10 dB.

4 Conclusion

In this paper, the joint detection algorithm is introduced for non-Gaussian signal detection from Gaussian noise. Through experiment, it is obvious that the joint detection not only solves the problem of the signal detection in low SNR but also has the comparative detection probability. Although the single signal is generated to verify the performance of the joint detection algorithm, the result illustrates that it has definite prospects and can meet the actual requirement.

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