Wideband Spectrum Sensing by Multistep Frequency Domain Energy Detection in GNU Radio

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Abstract: - Wideband spectrum sensing capability can be enabled in GNU Radio, which is an open source software radio platform. In order to improve the detection performance of GNU Radio in practice, we studied its approach of wideband spectrum sensing, i.e., multistep frequency-domain energy detection. We first gave a detailed analysis of the functions and implementation details in its wideband spectrum sensing procedure. Then, we simulated the whole procedure of the wideband spectrum sensing by using MATLAB. With the simulation results, we discussed the factors influencing the decision threshold of energy detection and proposed a method to determine the decision threshold for each step in the multistep detection. The results presented in this paper can be used for setting parameters of GNU Radio to achieve more precise spectrum sensing.

Key-Words: - Spectrum sensing, energy detection, GNU Radio

1 Introduction

With the rapid increasing demand on wireless communication services, the spectrum resource becomes scarcer in supply. The current spectrum management mainly adopts static allocation, which results in low spectrum utilization [1]. To resolve the issues of low spectrum utilization and spectrum scarcity, spectrum sensing technology plays an effective role to detect the idle spectrum for dynamic spectrum access.

There are many methods proposed for spectrum sensing, including the source detection [2], interference detection and cooperative detection [3]. Energy detection method is a simple signal source detection algorithm firstly proposed by Urkowitz [4]. This method has the advantages that no required priori information and low calculation cost [5].

GNU Radio is an open source software development toolkit to implement software-defined radios. It provides a wide range of information processing module library, and it can realize signal processing process with software. Its accompanied hardware part, USRP (Universal Software Radio Peripheral), acts as the RF front-end system. It can convert the RF signal to the medium frequency, and convert the medium frequency signal to baseband signal with A/D, D/A converter, and FPGA. The GNU Radio software running on the PC deals with the baseband signal, and realize the functions of communications and other signal processing functions. The application of GNU Radio and USRP in the establishment of an experimental platform was introduced in [6]. GNU Radio has wideband spectrum sensing capability with example software program. The approach of wideband spectrum sensing in GNU Radio is based on the multistep frequency-domain energy detection, which will be described later. The spectrum sensing with energy detection based on GNU radio and USRP was introduced in [7]. An experimental study of OFDM implementation utilizing GNU radio and USRP was presented in [8]. The experimental study only gives the performance study under specific scenarios. There still lacks performance analysis and threshold determination method for general usage on spectrum sensing with GNU Radio. Though there are other methods proposed for wideband energy detection such as using wavelet transform [9] [10], the approach of wideband spectrum sensing in GNU Radio has relatively low calculation complexity. In order to improve the detection performance of GNU Radio in practice, we study its approach of wideband spectrum sensing, i.e., multistep frequency-domain energy detection by simulation in this paper.

We first analyze the wideband spectrum sensing procedure of GNU Radio achieved by multistep frequency-domain energy detection, and we give a detailed analysis of function and implementation details of each module in the wideband spectrum sensing procedure. Then, we simulate the whole procedure of its wideband spectrum sensing by using MATLAB. With the simulation results, we obtain the detection performance (detection probability and false alarm probability) of spectrum sensing in one step, and we discuss the factors influencing the decision threshold of energy detection in each step including windowing, SNR (Signal to Noise Ratio), sensing time. Moreover, we propose a method to determine the decision threshold. Finally, we discuss the accuracy of wideband spectrum sensing, especially the edge detection performance. The results presented in this paper can be used for setting parameters of GNU Radio to achieve more precise spectrum sensing.

The organization of this paper is as follows. The principle of energy detection is introduced in section 2. The wideband spectrum sensing procedure of GNU Radio is analyzed in section 3. The simulation and discussions are presented in section 4. Section 5 concludes this paper.

2 Principle of Energy Detection

The principle of energy detector is finding the energy of the received signal and compares that with a threshold for deciding whether the signal exists or not. Energy detection can be performed either in the time-domain or in the frequency-domain. In the time domain, the signal $x(t)$ is transmitted through a radio channel, and in the energy detector the signal is firstly passed through a bandpass filter (BPF) with bandwidth W; Then the filtered signal is sampled and its energy is calculated and compared to a predefined threshold. The primary user is decided to be present if the energy is above the threshold, or else absent [5]. The signal detection can be formulated as a binary hypotheses testing problem as follows,

$$H_0: \quad y(n) = x(n) \qquad n = 1,2,3,...,N$$

$$H_0: \quad y(n) = h(x(n)) + w(n) \qquad n = 1,2,3,...,N \quad (1)$$

where and represents the hypothesis "primary signal absent", and the hypothesis "primary signal present", respectively; $x(n)$ is a sample of the primary signal to be detected; $w(n)$ is a noise sample; $y(n)$ is a received signal sample; N is the total number of samples collected in the sensing time *T*; $h(\cdot)$ denote the channel fading process, and is a possibly random linear time-varying operator.

The test statistic of the detector is given by

$$T = \sum_{n=0}^{N} \left(y(n)\right)^2 \qquad (2)$$

and it is compared with a predefined threshold λ for hypothesis testing.

In the frequency-domain energy detection, $x(t)$ is firstly passed through a band-pass filter whose band is *W*, and then is transformed into frequency-domain via FFT. Then, the energy of the transformed signal is calculated in the frequency domain and then it is compared to a predefined threshold for hypothesis testing.

In theory, the energy value obtained in the energy detector is equivalent in the time-domain and in the frequency-domain. However, the implementation details are different in the time-domain energy detection and in the frequency-domain. Thus, the corresponding detection performance is different and the decision threshold should be determined respectively.

3 Wideband Spectrum Sensing Procedure of GNU Radio

The GNU Radio package has an example program for wideband spectrum detection, usrp_spectrum_sense.py, which is written in Python language. The GNU Radio software employs Python and C++ mixed programming method. Due to the high execution efficiency, C++ is used to a variety of signal processing module. Python is used to writing scripts that connect the modules of the signal processing flow.

Through the analysis of the example program, the wideband spectrum sensing of GNU Radio is implemented through multistep frequency domain energy detection. In each step, a narrow band is sensed by energy detection in the frequency domain. The process of spectrum sensing in one step is shown in Fig. 1. First of all, the baseband signal is obtained through USRP sampling; the sampled signal is converted to vector in the s2v module, passed through Blackman-Harris window filter for reducing the side lobe and spectrum leakage. Then the signal is transformed into frequency domain via FFT, and the magnitude of energy is calculated by the c2mag module and converted into logarithmic value by the log module.

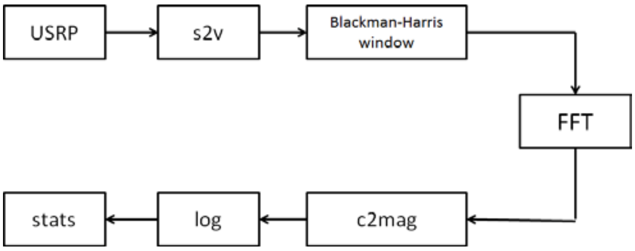

Fig. 1. Frequency-domain energy detection of GNU Radio in one step

Then we analyze the module functions and the implementation details of the frequency-domain energy detection of GNU Radio in one step. The initialization of USRP mainly config.s ADC sampling rate, power, gain, etc. using Python scripts usrp.py. In usrp_spectrum_sense.py, the self.connect (self.u, s2v, fft, c2mag, log, stats) obtains data from USRP, and connects the functions of self.u, s2v, fft, c2mag, log and stats. Among them, s2v transfers the sampled signal into vector by gr.stream_to_vector. The module of Mywindow adds window on the signal by window.Blackman-Harris. The FFT module implements FFT transform by gr.fft_vcc to transform the signal to the frequency domain. The complex signal is truned to mean square value by the function gr.complex_to_mag_ squared. The log module convert the energy value to logarithmic valueby the function gr.nlog10_ff. The stats module obtains the statistical data by function gr.bin_statistics_f.

When the A/D sampling rate (adc_rate) of USRP is set to 64 MBbytes per second and the hardware default settings of the extraction rate (decim) is 16, the maximum detection bandwidth of USRP is adc_rate/decim = 4 MHz. When the spectrum to be detected is larger than the maximum detection bandwidth in the default settings, the USRP cannot sense the whole spectrum in one step. For such wideband spectrum sensing in the GNU radio, the approach of multistep frequency domain energy detection is employed. The procedure of wideband spectrum sensing of GNU Radio by multistep frequency domain energy detection is shown in Fig. 2.

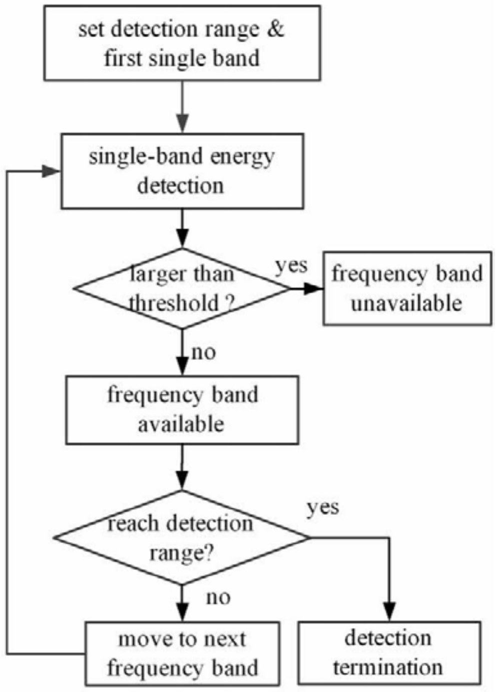

Fig. 2.The procedure of wideband spectrum sensing of GNU Radio by multistep frequency domain energy detection

In the multistep frequency domain energy detection, the equipment first sets up the spectrum range to be sensed, the RF board of USRP changes the central frequency step-by-step, the USRP performs energy detection for a narrow range of frequency in one step by comparing the testing result with a predefined detection threshold and determining whether the primary uses exists in the frequency band. Such a process is continued until the frequency is beyond the scope of testing range.

4 Simulation and Discussion

The wideband spectrum sensing of GNU Radio by the multistep frequency domain energy detection procedure shown in Fig. 2 is simulated using MATLAB.

First, we generate a wideband signal as shown in Fig. 3 by using MATLAB. In the simulation, a baseband signal of sinc waveform with 2 MHz bandwidth is generated first with BPSK modulation. One BPSK symbol duration is set to 0.5 μs . Then the baseband signal is modulated to carriers at 5 MHz and 15 MHz. With such parameters, the signal's occupied spectrum is within 4 MHz ~ 6 MHz and 14 MHz ~ 16 MHz. The spectrum to be sensed is set to 20 MHz. The sampling frequency is set to 40 MHz. The modulated signal is added with white gaussian noise to simulate the received signal at USRP. The spectrum diagram of the received signal without noise is shown in Fig. 3. The spectrum diagrams of the received signal at SNR (signal-to-noise ratio) = 5 dB and 10 dB is shown in Fig. 4 and Fig. 5, respectively. In our simulation, the signal power changes while the noise power is kept at different SNRs. The noise power at each sampling point is set to 1 for normalization.

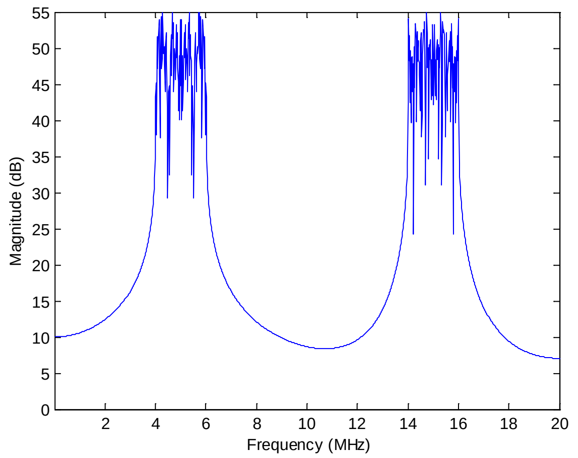

Fig. 3. The spectrum diagram of the received signal without noise

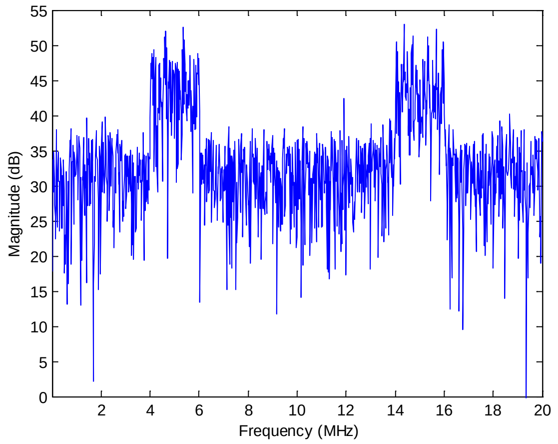

Fig. 4. The spectrum diagram of the received signal (SNR = 5 dB)

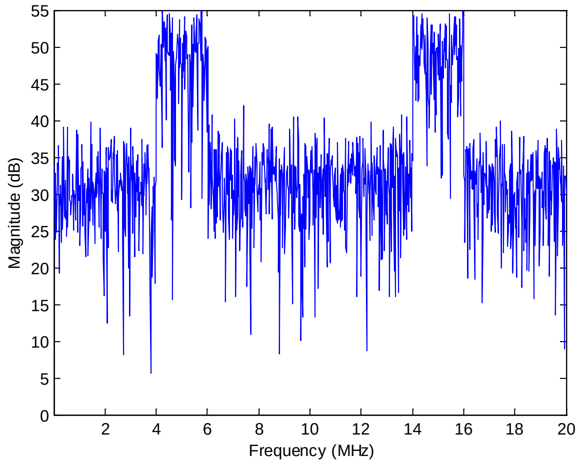

Fig. 5. The spectrum diagram of the received signal (SNR = 10 dB)

In the simulation, one-step 200 KHz narrowband energy detection is realized first. It is implemented by a 200 KHz bandpass filter with 500-order Hamming window. The wideband spectrum sensing is realized by by changing the central frequency of the 200 KHz bandpass filter step-by-step until the 20 MHz spectrum is detected. Thus, the step frequency is 200 KHz in the multistep frequency domain energy detection. The number of sensed BPSK symbols at each 200 KHz narrowband is set to 100.

The initialization of data is realized by using BPSK modulation to simulate the self.u and s2v functions. The data transmission rate is set to 200 Kbps. The modulated signal is sampled with a sampling frequency 40 MHz, the FFT is performed on the sampled data to simulate the self.connect (fft) module. After FFT, the calculations of square sum and logarithm are used to simulate the c2mag and log functions. Then, the calculated result is compared with a threshold for energy detection in each 200 KHz step.

Fig. 6 shows the detection probability P_d versus the decision threshold λ (in logarithmic value) when the SNR is 5 dB and 10 dB, respectively. With the Blackman-Harris window, to satisfy a certain detection probability, for example $P_d \geq 0.9$, the required maximum value of decision threshold λ increases from 56.0 to 61.7 when the SNR increases from 5 dB to 10 dB; Without the Blackman-Harris window, the required maximum value of decision threshold λ increases from 62.0 to 67.1. Thus, the decision threshold is reduced about 6 at the same SNR with the Blackman-Harris window than that without the Blackman-Harris window. Note that the signal power changes while the noise power is kept at different SNRs in our simulation. The relation of P_d with the SNR does not hold for the case if the signal power is kept and noise power changes at different SNRs.

Fig. 7 shows the false-alarm probability P_f versus the decision threshold λ (in logarithmic value) when the SNR is 5 dB and 10 dB, respectively. It can be seen that, to satisfy a certain false-alarm probability, for example $P_f \leq 0.1$, the required minimum value of decision threshold λ increases from 42.0 to 46.8 with the Blackman-Harris window than that without the Blackman-Harris window. Thus, the decision threshold is reduced about 6 with the Blackman-Harris window than that without the Blackman-Harris window. It can be observed that the required minimum value of decision threshold to satisfy a certain false-alarm probability is irrelevant to the SNR. Note that the signal power changes while the noise power is kept at different SNRs in our simulation. The relation of P_f with the SNR does not hold for the case if the signal power is kept and noise power changes at different SNRs.

From Fig. 6 and Fig. 7, it can be seen that the decision threshold λ influences the performance of the detection probability P_d and the false alarm probability P_f. Thus, the decision threshold increases with the increase of SNR to achieve the same detection probability. In addition, whether Blackman-Harris window is used or not has impact on the the decision threshold. To achieve certain detection probability P_d or false alarm probability P_f, the decision threshold is smaller at the same SNR with the Blackman-Harris window than that without the Blackman-Harris window. Since the Blackman-Harris window can reduce the sidelobe and spectrum leakage, the spectrum energy is more concentrated with the Blackman-Harris window. Hence, the corresponding decision threshold method is smaller with the Blackman-Harris window.

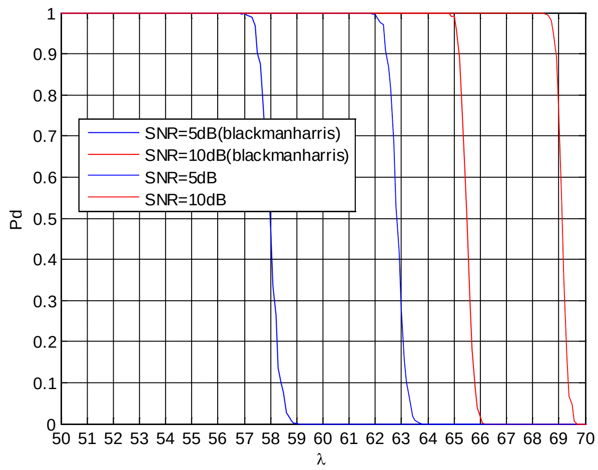

Fig. 6. Detection probability versus decision threshold with different SNRs and with and without Blackman-Harris window

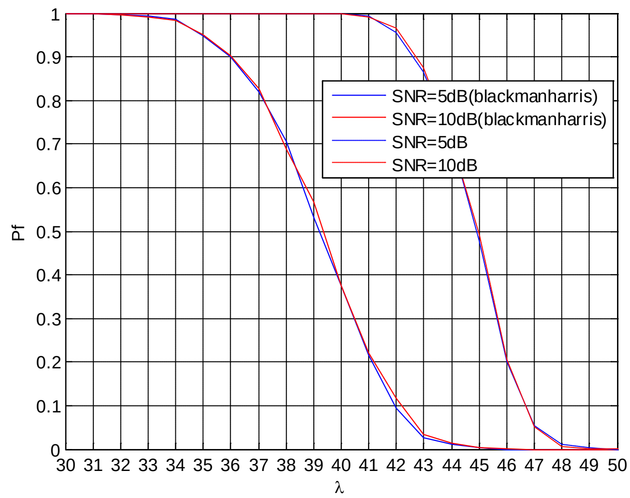

Fig. 7. False-alarm probability versus decision threshold with different SNRs and with and without Blackman-Harris window

The decision threshold for the energy detection in one step frequency of 200 KHz can be determined from the simulation results of Fig. 6 and 7. At SNR = 5 dB and without the Blackman-Harris window, the decision threshold λ should be less than 62.4 to satisfy the detection probability $P_d \geq 0.9$. Furthermore, the decision threshold λ should be greater than 46.8 to satisfy the false-alarm probability $P_f \leq 0.1$. Therefore, a value between 46.8 and 62.4 can be chosen as the decision threshold in one step spectrum sensing for the case that SNR= 5 dB and without the Blackman-Harris window. At SNR = 10 dB and without the

Blackman-Harris window, the decision threshold λ should be less than 69.9 to satisfy the detection probability $P_d \geq 0.9$. Furthermore, the decision threshold λ should be greater than 46.8 to satisfy the false-alarm probability $P_f \leq 0.1$. Therefore, a value between 46.8 and 69.9 can be chosen as the decision threshold in one step spectrum sensing for the case that SNR = 10 dB and without adding the Blackman-Harris window.

To sense the whole 20 MHz spectrum, there need totally 100 steps of 200 KHz spectrum sensing. Fig. 8 shows the detected energy in 100 steps for 20 MHz spectrum sensing by multistep frequency domain energy detection for the case that SNR = 5 dB and without the Blackman-Harris window. The value of 52 is chosen as the decision threshold in one step spectrum sensing for such a case.

It can be seen from Fig. 8 that the detected energy is continuously larger than 52 from the 21th to the 30th 200 KHz steps, and from the 71th to the 80th 200 KHz steps. Therefore, when determine the idle spectrum in the aggressive way, the occupied spectrum in 20 MHz bandwidth is from 4.0 MHz to 6.0 MHz and from 14.0 MHz to 16.0 MHz. The idle spectrum is the spectrum range except 4.0 MHz to 6.0 MHz and 14.0 MHz to 16.0 MHz in the 20MHz.

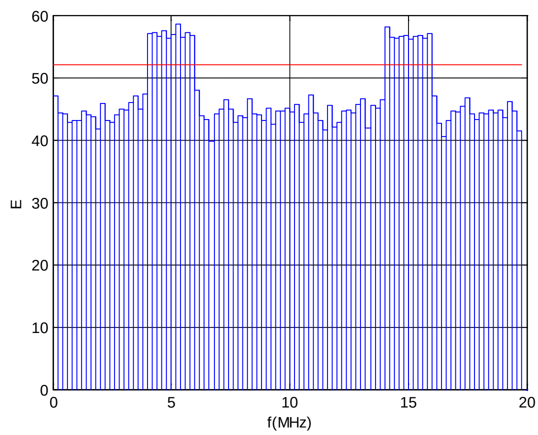

Fig. 8. Detected energy in 100 steps for 20 MHz spectrum sensing by multistep frequency domain energy detection (SNR= 5 dB & without Blackman-Harris window)

At SNR = 5 dB and with the Blackman-Harris window, the decision threshold λ should be less than 57.5 to satisfy the detection probability $P_d \geq 0.9$. Furthermore, the decision threshold λ should be greater than 42.0 to satisfy the false-alarm probability $P_f \leq 0.1$. Therefore, a value between 42.0 and 57.5 can be chosen as the decision threshold in one step spectrum sensing for the case that SNR= 5 dB and with the Blackman-Harris window. At SNR = 10 dB and with the Blackman-Harris window, the decision threshold λ should be less than 65.2 to satisfy the detection probability $P_d \geq 0.9$. Furthermore, the decision threshold λ should be greater than 42.0 to satisfy the false-alarm probability $P_f \leq 0.1$. Therefore, a value between 42.0 and 65.2 can be chosen as the decision threshold in one step spectrum sensing for the case that SNR= 10 dB and with the Blackman-Harris window.

Fig. 9 shows the detected energy in 100 steps for 20 MHz spectrum sensing by multistep frequency domain energy detection for the case that SNR= 5 dB and with the Blackman-Harris window. The value of 48 is chosen as the decision threshold in one step spectrum sensing for such a case.

It can be seen that from Fig. 9 the detected energy is continuously larger than 48 from the 21th to the 30th 200 KHz steps, and from the 71th to the 80th 200 KHz steps. Therefore, the occupied spectrum in 20 MHz bandwidth is from 4.0 MHz to 6.0 MHz and from 14.0 MHz to 16.0 MHz frequencies. The idle spectrum is the the spectrum range except 4.0 MHz to 6.0 MHz and 14.0 MHz to 6.0 MHz in the 20MHz.

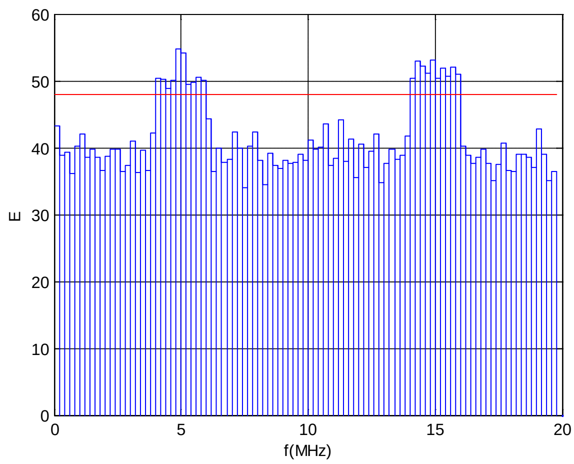

Fig. 9. Detected energy in 100 steps for 20 MHz spectrum sensing by multistep frequency domain energy detection (SNR= 5 dB & with Blackman-Harris window)

Lastly, we evaluate the sensing performance with different sensing time. Next, the number of sensed BPSK symbols at each 200 KHz narrowband is set to 200 (i.e., N=200) instead of 100 in the above investigation.

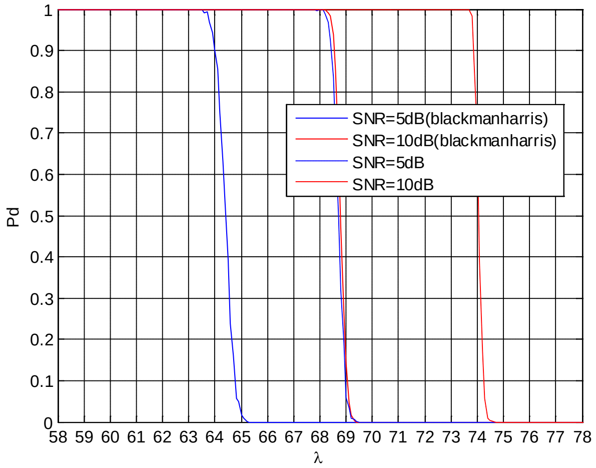

Fig. 10. Detection probability versus decision threshold with different SNRs and with and without Blackman-Harris window (N =200)

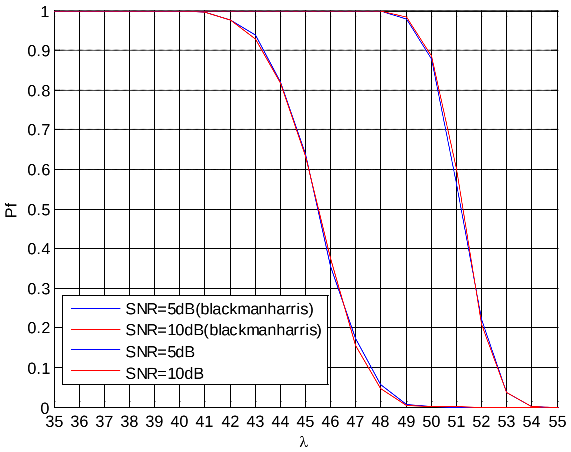

Fig. 11. False-alarm probability versus decision threshold with different SNRs and with and without Blackman-Harris window (N=200)

Fig. 10 shows P_d versus λ for N = 200 when the SNR is 5 dB and 10 dB, respectively. With the Blackman-Harris window, to satisfy $P_d \geq 0.9$, the required maximum value of decision threshold λ increases from 64.0 to 68.5 when the SNR increases from 5 dB to 10 dB; Without the Blackman-Harris window, the required maximum value of decision threshold λ increases from 68.4 to 73.8. Comparing Fig. 6 for the case N = 100, the required maximum value of decision threshold λ needs to be increased to satisfy $P_d \geq 0.9$. Fig. 11 shows P_f versus λ for N= 200 when the SNR is 5 dB and 10 dB, respectively. It can be seen that, to satisfy $P_f \leq 0.1$, the required minimum value of decision threshold λ increases from 47.6 to 52.6 with the Blackman-Harris window than that without the Blackman-Harris window. Comparing Fig. 7 for the case N = 100, the required minimum value of decision threshold λ needs to be increased to satisfy $P_f \leq 0.1$.

6 Conclusions

When the spectrum to be sensed is larger than the maximum detection bandwidth in the hardware settings, the sensing device cannot sense the whole spectrum in one step. For such wideband spectrum sensing, the GNU radio employs the approach of multistep frequency domain energy detection where a narrow band is sensed by energy detection in the frequency domain in one step. By simulating such a wideband spectrum sensing procedure of GNU Radio with MATLAB, we obtained the detection performance (detection probability and false alarm probability) of spectrum sensing in each step. We discussed the factors influencing the decision threshold of energy detection in each step including windowing, SNR (Signal to Noise Ratio), and sensing time. To determine the decision threshold, we proposed a method by considering both the requirements of detection probability and false alarm probability for practical usage. Simulation results show that the decision threshold increases with the increase of SNR to achieve the same detection probability. To achieve certain detection probability or false alarm probability, the decision threshold is smaller with the Blackman-Harris window than that without the Blackman-Harris window. In addition, the smaller sensing frequency step value, the higher accuracy of detection can be obtained. However, it leads to longer detection time. A proper value for each frequency advancing step can be a further research topic when using GNU Radio for spectrum sensing in practice.

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