Energy Detector Prototype for Cognitive Radio System

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Abstract Spectrum sensing has been identified as a key enabling functionality to ensure that cognitive radios would not interfere with primary users by reliably detecting the primary user channels when they are not being used by the primary systems. In a cognitive radio system, signal detection mechanism is required for spectrum sensing in order to identify occupied and vacant TV channels and hence to detect the availability of the vacant spectra. In this paper the prototype for detection of the spectrum holes is discussed using energy detection mechanism. System parameters are analyzed and their relationship to each other and to the overall signal processing has been explored.
Key words Cognitive Radio, Energy detector, spectrum sensing, ISDB-T signal, NTSC signal

1. Introduction

The electromagnetic radio spectrum is a precious and an expensive resource. New wireless technologies are being introduced at a progressively increasing pace. So, the spectrum demand of such systems is also rapidly increasing. However many current technologies do not seem to utilize the allocated spectrum fully and efficiently. So, dynamic access and utilization of the spectrum is necessary. Cognitive radios have been proposed as a possible solution to improve spectrum utilization via opportunistic spectrum sensing. A conceptual and comprehensive definition of cognitive radio is provided in [1]. Cognitive radios are the secondary users of the spectrum allocated for the primary user. The first application of spectrum sensing was studied by IEEE 802.22 standard Working Group [2]. The IEEE 802.22 WG proposed to standardize a fixed wireless access system based on cognitive radio technology to enable spectrum access and sharing by the secondary system [2] [3]. This standard is called IEEE 802.22 Wireless Regional Area Network (WRAN). The IEEE 802.22 WRAN aims to provide the wireless broadband access to rural areas as well as to sub-urban areas where the spectrum utilization rate is quite low. The core concept is the coexistence of the IEEE WRAN system with the existing TV systems via spectrum sharing provided that the secondary system will not interfere the primary systems. The key challenge of spectrum sensing is the detection of weak signals in presence of noise and interference with a very small probability of misdetection.

Different detection schemes have been proposed for this purpose. Energy detector is one of them. The authors have done quite some work in this area including performance analysis of energy detector and its comparison with other detectors such as replica correlation detector and cyclo-stationary detector through simulations [4] [5]. However there is a lack of the experimental study about the performance of the detection system under real noise and interference conditions. So, it is the motivation of the authors to attempt to establish a frame work about the experimental system for spectrum sensing and detection issue.

Small size, light weight and cheap receivers are quite common in electronic markets for almost all general systems these days. However the detection scheme discussed in this paper uses off-the-shelf instruments as the parts of the receiver for specific purposes of frequency downconversion and analog to digital conversion. Their requirement arises from the fact that the detection mechanism needed for cognitive radio system is different than that for normal communication systems. The cognitive radio transceiver unit is supposed to be capable of performing the dual duty i.e. it needs not only to receive the signal but also to transfer data to the Base Station (BS) through spectrum sensing informing it about the availability of the spectrum holes.

In this paper, the prototype to implement the energy detection mechanism is discussed. This detection mechanism mainly focusses on discovering the vacant spectra from the analog TV (NTSC) system and from the digital TV (ISDB-T) system of Japan. In addition the authors have attempted to highlight some important parameters of the discussed system that will affect the experiment.

The rest of the paper is organized as following. Section 2 is about energy detection mechanism. In section 3, the physical perspective of the cognitive radio detection prototype to implement energy detection mechanism is discussed. In section 4, the important parameters of the system which can have very significant effect on sensing and analysis of the real TV signal are explained. Section 5 is about the future work on energy detector. Section 6 concludes the paper.

2. Energy Detector

Energy detection is a the signal detection mechanism based on Neyman-Pearson approach [6] [7]. The concept of energy detection mechanism is quite simple. The detector computes the energy of the received signal and compares it to certain threshold value to decide whether the desired signal is present or not.

The energy of the signal is preserved in both time domain and frequency domain. The time domain representation of this mechanism is shown in Figure 1. The frequency domain representation of this mechanism is shown in Figure 2. Theoretically, whichever representation is used for signal detection and analysis, makes no difference in result. However in the former representation a pre-filter matched to the bandwidth of the signal is required. This need makes this representation quite inflexible compared to the frequency domain representation. So, it is intended to use the second representation in near future for analyzing the received signal via simulation.

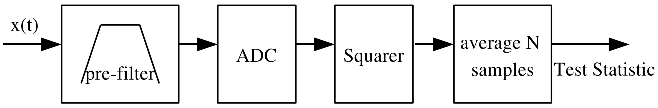

Figure 1 Time domain representation of energy detection mechanism

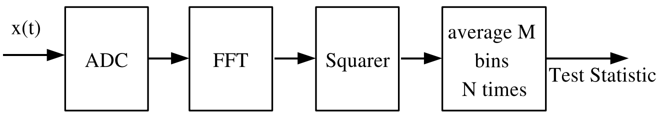

Figure 2 Frequency domain representation of energy detection mechanism

In order to measure the signal energy, the received signal is first sampled, then converted to frequency domain taking FFT followed by squaring the coefficients and then taking the average. The decision making strategy of energy detector is the test of two hypotheses H_0 and H_1 [6] [7]. As described in [4], the decision value of the energy detector to compare with the threshold γ is given by

$$T = \sum_{n=0}^{N-1} |x[n]|^2; \; n = 0, 1, 2, ..., N-1, N \tag{1}$$

The averaged signal energy is then subjected to the test of the two hypotheses. H_0 is the null hypothesis meaning that the received signal comprises of the noise only. If H_0 is true as shown in (2), then the decision value given by (1)will be less than the threshold γ. So the detector will conclude that there is no availability of the vacant spectrum. On the other hand, if H_1 is true as shown in (3) i.e. received signal has both signal and noise, the decision value will be larger than the threshold γ. So the detector concludes that the vacant spectrum is available. The threshold value is chosen so as to control the parameters such as probability of false alarm and probability of detection, a comprehensive analysis of which is given in [6].

$$H_0 : x[n] = w[n]; \; \text{signal is absent} \tag{2}$$

$$H_1 : x[n] = s[n] + w[n]; \; \text{signal is present} \tag{3}$$

where $n = 0, 1, 2, ..., N-1, N$ is the sample index, $w[n]$ is the noise and $s[n]$ is the primary signal required to detect.

3. Physical System to Implement Energy Detector

Despite the authors' ongoing research activities regarding spectrum sensing for cognitive radio system [4] [5], a lot of work is yet to be done to implement the ideas in real scenario. The main target of this work is to perform experimental study that shows the feasibility and practical performance limits of the energy detector approach under real noise and interference conditions in wireless channels. The detector model discussed in this paper for that purpose comprises of off-the-shelf instruments such as spectrum analyzer and oscilloscope [8] [9] as shown in Figure 3.

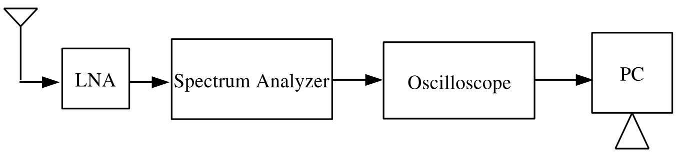

Figure 3 Block diagram of the prototype to implement energy detector

In this prototype, the spectrum analyzer functions as a frequency down-converter while the oscilloscope is a sampling unit. PC is the data acquisition system.

In order to have a slight insight to signal processing aspects of the system, the block diagram shown in Figure 3 can be redrawn as shown in Figure 4.

The oscilloscope comprises of the analog to digital converter. So, it can be used as a sampling unit. However if the RF signal be directly fed to the oscilloscope, the sampling frequency is supposed to be very high. So, the received

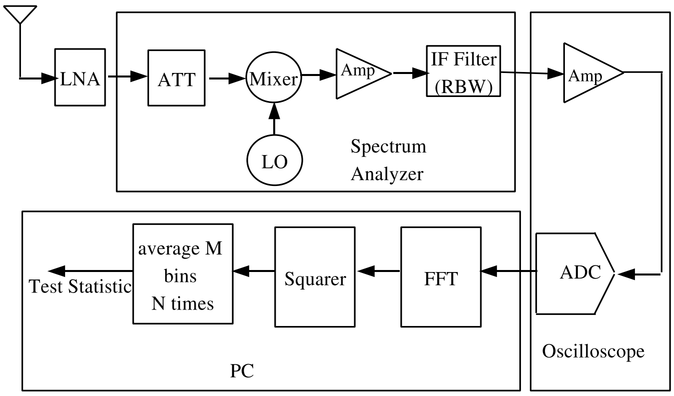

Figure 4 Insight to signal processing architecture

signal is first subjected to the spectrum analyzer. The spectrum analyzer contains the frequency converting unit i.e. the mixer which generates the intermediate frequency (IF) signal. This signal will then be fed to the oscilloscope so that the sampling frequency needed is practically feasible.

The major purpose of the detection unit is to detect very weak signals but also not to overload on strong signals. That is why the spectrum analyzer comprises of the attenuator which prevents overloading in case of strong signals. The mixer multiplies the received signal with the carrier signal from the local oscillator. So, the frequency of the received signal is shifted. Then the band pass filter selects the signal component with specific center frequency and specific bandwidth. In this case, the band pass filter selects the frequency band of the specified IF and specified bandwidth. Once the RF signal is converted to IF signal, all the signal processing can be done for IF range only.

The low noise amplifier is fundamentally to process the signal in between the antenna (that picks up the signal from air, which is very weak) and the spectrum analyzer. It amplifies the signal so that the spectrum analyzer can detect it.

4. System Parameters

Our fundamental objective is to use the system shown in section 3 to receive the ISDB-T signal and NTSC signal to accomplish the decision making process for the availability of the spectrum holes, record the data and then carry out simulations to analyze the stored data.

Before starting to capture the real signal, the important thing is to understand and analyze the signal processing mechanism. So, in this section some important parameters that can significantly affect the performance of the system are highlighted.

4.1 Average signal power

The required field strength of the ISDB-T signal in Japan for the receiver unit is given by [10] as

$$E = E_{\min} + M \tag{4}$$

where E is the required field strength in dBμV/m, E_{min} is the minimum field strength in dBμV/m and M is the place and time margin in dB.
With $E_{\min} = 51$ dBμV/m [10] and $M = 9$ dB [10], the value of E becomes 60 dBμV/m. The received power level in W is given by

$$P = S \cdot A \tag{5}$$

where S is the power flux density in W/m^2 and A is the effective area of the receiver antenna in m^2. The power flux density S is given by

$$S = \frac{E^2}{120\pi} \tag{6}$$

where E is the required field strength in V/m. The effective area of the receiver antenna is given by

$$A = \frac{\lambda^2 G}{4\pi} \tag{7}$$

where λ is the wavelength of the propagating waves given by $\lambda = \frac{c}{f}$, where c is the velocity of light and f is the frequency of the propagating waves and G in (7) is the antenna gain of the TV receiver. In the prototype an omnidirectional antenna explained in the next subsection is used. From (5), (6), and (7), the received power level can be written as

$$P = \frac{E^2}{120\pi}\frac{\lambda^2 G}{4\pi} \tag{8}$$

Taking c as 3×10^8 m/sec, f as 600 MHz and G as 9 dB [10] and putting all the variable values including E in (8), the value of P becomes -63 dBm. This value is important because we can use it to figure out the tentative signal level that the detector system should be capable of detecting. So, the point is that our detector should be capable of sensing signals below -63 dBm.

4.2 Antenna parameters

The omnidirectional compact discone aerial antenna DA753G from AOR Ltd. [11] will be used for the experiment. In general, the major parameters of an antenna for any receiver system is its gain and directivity. In this prototype, as the antenna is omnidirectional, the important parameter is its gain only. The typical gain values of the receiver antennas are in the range of 2 dBi-4 dBi including the cable loss.

4.3 Insertion loss of the cable

A coaxial cable of about 10 meters will be used in the experiment. According to the technical specification provided for the cable (model MWX221 from Junkosha Inc.), the insertion loss for the required frequency range (upto about 1000 MHz) is around 2.5 dB. So, if the antenna gain is taken as unity, the signal level at the input of the low noise amplifier will be about 2.5 dB less than the received signal level. However, the antenna gain generally overshades the insertion loss.

4.4 Gain of the low noise amplifier

The gain of the low noise amplifier that will be used in the experiment is in the range 22 dB to 32 dB and its noise figure is below 4 dB. The operating input level of the low noise amplifier is about −45 dBm to −41 dBm. The tentative input signal level to the low noise amplifier which is theoretically below −63 dBm, will be amplified by the low noise amplifier by its gain.

The basic reason for the need of the low noise amplifier in this system can be attributed to the noise figure (NF) of the spectrum analyzer. The noise figure of a device is given by

$$F = \frac{SNR_{\text{input}}}{SNR_{\text{output}}} \tag{9}$$

where both SNR_{input} and SNR_{output} are ratios. In practice however, the noise figure is mostly considered in dB as $10\log_{10} F$ and in such cases F is refered to as noise factor. The noise figure of the spectrum analyzer is quite high. However, the antenna picks up the signal in air which is very weak and is embedded on noise. So, if this signal is directly fed to the spectrum analyzer, then it will not be able to overcome the noise figure of the spectrum analyzer. That is why the need for the low noise amplifier arises. The low noise amplifier increases the input SNR which ultimately decreases the overall noise figure of the system. This phenomenon can be explained more clearly with the Friis equation (10) for n cascaded devices in the system as following:

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots + \frac{F_n - 1}{G_1 G_2 G_3 \cdots G_{n-1}} \tag{10}$$

where F_n is the noise factor for the nth device and G_n is the power gain of the nth device, both of them being the ratios. For the cascaded connection of the low noise amplifier and the spectrum analyzer, (10) will become

$$F = F_1 + \frac{F_2 - 1}{G_1} \tag{11}$$

Because the gain of the low noise amplifier G_1 is quite high, the second factor of (11) will be a very small quantity. Thus the overall noise figure of the system is reduced which improves the system performance.

4.5 Noise figure and noise level of the spectrum analyzer

The average noise level of the spectrum analyzer is given by [9] as

$$N = 10\log_{10}(kTB) + F \tag{12}$$

where, k is Boltzmann constant in J/K, T is the absolute temperature of the receiver in K, B is the receiver noise bandwidth in Hz and F is the noise figure of the receiver in dB. Considering the receiver temperature T as 290 K and the bandwidth B as 1 MHz, we get,
$N = -114$ dBm$+F$
The spectrum analyzer that will be in the experiment is Anritsu MS2665C [12] for which F is 24 dB. So, the value of N will be −90 dBm. In physical sense, N represents the minimum limit of the measurable input signal.

4.6 Intermediate frequency of the spectrum analyzer

The ISDB-T signal is transmitted in the UHF operating frequency band of 470 MHz to 770 MHz while the NTSC signal is transmitted in the range 90 MHz to 770 MHz. This range of frequency is quite high for the oscilloscope to directly sample. So, this signal is first passed through the spectrum analyzer. The spectrum analyzer generates an intermediate frequency signal of 10.69 MHz with the resolution bandwidth of 3 MHz. The oscilloscope that will be used in the experiment is Lecroy 9354TM the maximum sampling frequency of of which is 500 MHz. This sampling frequency is sufficient to sample the resulting signal.

4.7 Memory of the sampling unit

The waveform memory of the sampling unit i.e. the oscilloscope is another important parameter to consider. Because the ultimate goal is to detect the real time TV signal, store it (in terms of snapshots) and then perform the analysis of that data via simulation, the amount of data that can be stored is limited by the available memory of the sampling unit. The oscilloscope that will be used for the experiment has a waveform memory of about 32 MB. So, the data storage is supposed to be done accordingly.

5. Future work

The real time ISDB-T and NTSC signal is planned to be detected. It is intended to carry out the analysis of the response of the detection mechanism with respect to variations in the threshold parameter, probabilities of accurate detection etc. The analysis of the received signal will be implemented via simulations. The analysis will basically involve getting frequency domain coefficients of the signal and calculating the energy of the signal via those coefficients and then subjecting to the hypothesis test using a suitable threshold value.

6. Conclusion

Cognitive radios have been proposed as a solution approach for dynamic spectrum access and utilization via opportunistic sensing. Spectrum sensing is often considered as a simple detection problem. However the key challenge is the detection of the weak signal in real environment corrupted by noise and suffering from interference. Energy detector is one of the simplest detection mechanisms among those proposed so far. However despite considerable research work in cognitive radio detection mechanisms, experimental testing and verification of those mechanisms is yet in its infancy. In this paper, an insight to the physical aspect of the implementation of the energy detection mechanism has been presented by highlighting different parameters of the typical units used in the system that can significantly affect the system.

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