Experimental Study of Energy Detector Prototype for Cognitive Radio System

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Abstract With the ever-increasing demand for bandwidth due to the current and emerging wireless services, spectrum scarcity has reached its peak. For the alleviation of this issue, cognitive radio systems have been proposed. The fundamental principle of this solution approach is the concept of spectrum sharing in order to dynamically utilize the precious spectrum. As the idea of cognitive radios emerged, the need of a key enabling functionality has also been identified so as to ensure that cognitive radios would not interfere with primary users. That functionality is spectrum sensing. Various mechanisms have been proposed to detect the spectrum of the primary systems. Energy detector is one of them. In this paper the results of the primitive experiment that was carried out to study the implementation of energy detector for cognitive radios for ISDB-T signal in Japan is presented and different aspects of further related experiments are discussed.

Key words Cognitive Radio, Energy detector, spectrum sensing, ISDB-T signal

1. Introduction

Along with the increasing pace of the development of new wireless technologies, the demand of these systems for spectrum is also rising up. On the other hand, the available spectral resources are limited. The available spectrum has been sufficiently assigned to and used by the existing systems. However, the available spectrum is not fully utilized by many of the current technologies. Therefore, it is still possible to maintain a balance between what is available and what is needed provided that the mechanisms of dynamic access and utilization of the spectrum are deployed. Cognitive radios have been proposed as a possible solution approach to the current low usage of radio spectrum. They are the secondary users of the spectrum allocated for the primary user via opportunistic spectrum sensing. Cognitive radio is the key technology that will enable flexible, efficient and reliable spectrum use by adapting the radio’s operating characteristics to real-time conditions of the environment. Cognitive radios have the potential to utilize the large amount of unused spectrum in an intelligent way while not interfering with other incumbent devices in frequency bands that are already licensed for specific uses.

A conceptual and comprehensive definition of cognitive radio is provided in [1]. The emergence of the concept of spectrum sharing was basically inspired by the measurements carried out in [2] for the frequency bands below 3 GHz and conducted from January/2004 to August/2005. The measurement implied that on an average, only about 5.2% of the spectrum is annually in use in the United States at any given time. Interestingly, those measurements reveal that heavy spectrum utilization often takes place in unlicensed bands while licensed bands often experience low (e.g. TV bands) or medium (e.g. some cellular bands) utilization. Even though the situation may not necessarily be the same in Japan, this revelation can prove to be one motivation for the necessity of continuous measurement in Japan too. The first application of spectrum sensing was studied by IEEE 802.22 Working Group [3]. 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 [3] [4]. 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. 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.
The concept of cognitive radio systems is often compared with a wireless local area network (WLAN) in the sense that the individual users use the channel on an opportunistic basis in the similar manner as in WLAN. However, care must be taken to distinguish cognitive radio systems from WLAN. The difference lies in the fact that the possibility of the proposed coexistence of cognitive radio systems with TV systems is entirely based upon the interference prohibition mechanisms provided for the primary system by the secondary system. In case of WLANs however, the resource sharing is within the users of the same network and the WLAN itself is responsible for avoiding interference. In addition, it is also important to understand the core differences between 802.22 and 802.16 (WiMax) [5] as confusion often arises between these two projects. 802.22 is primarily targeted at rural and remote areas and its coverage range is considerably larger than that of 802.16. The details are explained in [3].

Different detection schemes have been proposed for spectrum sensing of the primary system. 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 [6] [7]. However there is a lack of 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. The prototype to implement the energy detection mechanism for spectrum sensing for cognitive radio systems has been proposed in [8]. In addition, some important parameters of the system that are likely to affect the experimental study have also been discussed as well.

The prototype for detection is shown in Figure 1 [8]. The basic idea is to receive the ISDB-T signal, process it so as to make it suitable for analysis and then to analyze it based on the concept of energy detection [9]. The detection prototype discussed uses off-the-shelf instruments as the parts of the receiver for specific purposes of frequency downconversion and analog to digital conversion. In fact, the cognitive radio transceiver unit is supposed to be capable of performing the dual duty i.e. it needs not only to sense the spectrum of the primary system but also to inform the Base Station (BS) about the availability of spectrum holes. The details about spectrum holes can be found in [1]. According to IEEE 802.22 WRAN specification, an omnidirectional antenna is used for spectrum sensing while a directional antenna is required to transmit the information to the transmitter side in order to avoid interference. However, the prototype in [8] addresses the first task only i.e. it is a prototype designed to detect the TV spectrum and to analyze it so as to determine the availability of the vacant spectra.

In this paper, the ISDB-T signal is detected. The spectrum of the received signal and the ideally stipulated spectrum of the broadcasted ISDB-T signal are compared. As energy detection is based on comparing the received signal with an appropriate threshold to determine whether the spectrum was actually being utilized or not, noise floor of the system is very important. So, the average noise floor is determined and the signal to noise ratio (SNR) is calculated in the band of concern.

The rest of the paper is organized as following. Section 2 is about ISDB-T signal in Japan. The experimental set up is explained in section 3. In section 4, the results of the experiment are presented and analyzed. The future work is discussed in section 5. Section 6 concludes the paper.

2. ISDB-T signal

As explained in section 1, the licensed bands such as TV bands often experience low or medium spectrum utilization. So, ISDB-T signal was chosen for the detection experiment. The detection of ISDB-T signal may have to be considered if IEEE 802.22 WRAN will be deployed in Japan in future. The detailed description of ISDB-T signal including its structure, channel coding scheme, different modes etc. is provided in [10]. ISDB-T basically comprises of a group of data segments that includes multiple transport stream packets (TSPs) defined in MPEG-2 Systems. These data segments are subjected to required channel coding. Then, pilot signals are added to data segments in the OFDM framing section to form an OFDM framing segment (with a bandwidth of 6/14 MHz). A total of 13 OFDM segments are converted to OFDM transmission signals collectively by IFFT. Although there exists Mode 1, Mode 2 and Mode 3 for ISDB-T signal transmission, The commonly used mode is Mode 1. An example of an OFDM segment for Mode 1 is shown in Figure 2.
It comprises of 108 carriers with carrier separation of 4 KHz.
The total bandwidth of a segment is 6/14 MHz. The signal
arrangement for OFDM transmission segment that comprises
of 13 segments is shown in Figure 3 [10]. It comprises of 1405
carriers with the total bandwidth of 6 MHz.

The frequency bandwidth for digital terrestrial television
broadcasting is 5.7 MHz with 4 KHz spacings between car-
rier frequencies in Mode 1. The carrier frequency is the cen-
ter frequency of the frequency bandwidth. The transmission
spectrum mask of digital terrestrial television broadcasting
as stipulated in [10] is shown in Figure 4.

The ISDB-T frequency ranges from 470 MHz to 770 MHz.
There are 9 digital TV channels broadcasted in Tokyo, each
of them with a bandwidth of 6 MHz. A list of those channels
and the corresponding center frequency is shown in Table 1.

3. Experimental Set-up

An omnidirectional antenna was used for sensing. The signal
detected by the antenna was fed to the TV booster. The spectrum analyzer that follows, acted as a frequency down-
converter and hence the RF signal was converted into the
Intermediate frequency (IF) signal. This signal was sampled
by the analog to digital converter (ADC) in the oscilloscope.
The data acquisition and analysis was performed in the PC.

The experimental set up is depicted in Figure 5 and the
specification of the instruments used for the experiment are
shown in Table 2.

4. Results and analysis

Out of the 9 channels broadcasted in Tokyo, the one with
highest power level was chosen for illustration of the concept.
The measurement parameters are depicted in Table 3. The
received signal was subjected to the processing as explained
in section 3.

As shown in Figure 1 [8], the basic algorithm intended to
be used for analysis is the energy detection principle. The

Table 1 TV channels in Tokyo

<table>
<thead>
<tr>
<th>Channel no.</th>
<th>Center frequency (MHz)</th>
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<tbody>
<tr>
<td>20</td>
<td>515</td>
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<tr>
<td>21</td>
<td>521</td>
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<tr>
<td>22</td>
<td>527</td>
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<td>26</td>
<td>551</td>
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<tr>
<td>27</td>
<td>557</td>
</tr>
<tr>
<td>28</td>
<td>563</td>
</tr>
</tbody>
</table>

Table 2 Specification of the instruments used for the experiment

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Specification</th>
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<tbody>
<tr>
<td>Antenna (DA753G) [11]</td>
<td>Frequency range 75 MHz - 3 GHz</td>
</tr>
<tr>
<td>Booster [12]</td>
<td>Gain 22 dB - 32 dB</td>
</tr>
<tr>
<td></td>
<td>Noise figure &lt; 4 dB</td>
</tr>
<tr>
<td>Spectrum analyzer [13]</td>
<td>Frequency range 9 KHz - 21.2 GHz</td>
</tr>
<tr>
<td></td>
<td>Noise figure -90 dBm</td>
</tr>
<tr>
<td></td>
<td>IF 10.69 MHz</td>
</tr>
<tr>
<td></td>
<td>RBW 30 Hz - 3 MHz</td>
</tr>
<tr>
<td>Oscilloscope [14]</td>
<td>Sampling rate 50 KSpS - 500 MSpS</td>
</tr>
<tr>
<td></td>
<td>No. of quantization bits 8</td>
</tr>
<tr>
<td></td>
<td>Memory size 5 MB</td>
</tr>
</tbody>
</table>
concept of energy detection mechanism is quite simple. The detector computes the energy of the received signal and compares it with the threshold value (the noise floor) to decide whether the primary signal is present or not. As described in [6], the energy of the received signal, also termed as the decision value of energy detector, is given by

$$T = \sum_{n=1}^{N} |x[n]|^2,$$  \hspace{2cm} (1)

where $x[n]$ is the received signal and $N$ is the number of its samples in the band of concern.

This decision value is then subjected to the test of two hypotheses $H_0$ and $H_1$. $H_0$ is the null hypothesis meaning that the received signal comprises of noise only. If the decision value given by (1) is less than threshold, $H_0$ is true as shown in (2). On the other hand, if the decision value is larger than the threshold, i.e. the received signal comprises of both signal and noise, $H_1$ is true as shown in (3).

$$H_0 : x[n] = w[n]; \text{ signal is absent}$$ \hspace{2cm} (2)

$$H_1 : x[n] = s[n] + w[n]; \text{ signal is present}$$ \hspace{2cm} (3)

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

However, the complete analysis of the detected signal is yet to be accomplished for which the energy detection algorithm will be rigorously implemented. What has been done so far is the initial study only so as to prepare for the real scanning of the data.

The received ISDB-T signal captured for 1 ms is shown in Figure 6. The corresponding spectrum is shown in Figure 7. In the same figure, the ideal ISDB-T spectrum is also shown for the purpose of comparision. As the receiver noise floor plays a vital role for analysis of the detected signal, it was also measured. In order to measure noise floor, no signal input was provided to the spectrum analyzer but the oscilloscope was connected to it. The amplitude range of the oscilloscope was kept from $-25$ mV to $+25$ mV. Under these conditions, the noise floor was detected and the noise spectrum is shown along with the the signal spectrum and the gaussian spectrum in the band of concern in Figure 8.

As can be seen from Figure 7 and Figure 8, the level of the received signal is around $-45$ dBm, while the noise floor level is around $-76$ dBm. The average signal to noise ratio was calculated around IF within the range of the RBW (3 MHz) using (4) and it was found to be $+30.88$ dB. In fact, the initial study was done with the antenna inside the experiment room in non-line-of-sight (NLOS) condition. In future, it is intended to carry out the experiment in line-of-sight (LOS) condition which will definitely result higher SNR.

$$SNR = \sum_{i=1}^{N} \frac{(Re(P_s[i])^2 + (Im(P_s[i])^2)}{Re(P_n[i])^2 + (Im(P_n[i])^2)}$$  \hspace{2cm} (4)

where $SNR$ is the average signal to noise ratio in the band of concern, $P_s$ is the signal power, $P_n$ is the noise power and $N$ is the number of samples in the band of concern.

One of the very important parameters in the context of experimental set up is the spectrum sensing time. Obviously, the longer the spectrum can be sensed and detected, the more accurate would the results be and hence the probability of detection goes closer to unity. On the other hand, the sensing time is closely related to the signal to noise ratio. Besides, it was observed that there was an inverse relationship between sampling rate and the time interval for which the signal was detected at once. As attempts were made to increase the time interval, the sampling rate decreased. At maximum, an interval of 50 ms was detectable however, the sampling rate would then go down to 1 MSps. As the IF was 10.69 MHz and the RBW was 3 MHz, sampling at 1 MSps was not feasible. The compromise was therefore made at the sampling rate of 50 MSps. So, the current configuration of the instruments can only capture the samples within the interval of 1 ms. In fact, the authors plan to perform data acquisition at regular intervals and then to concatenate all the received data in near future so as to increase the effective sensing time and hence to improve the results and the analysis.

Another important point here is the bandwidth of the received signal. In fact, the bandwidth of the TV signal of each channel is around 6 MHz. However, the IF filter of the spectrum analyzer was Gaussian and the RBW, which at most could be set as 3 MHz, imposed a limitation to its output. Therefore the current apparatus can not capture the
The shape of the signal spectrum shown in Figure 7 differs from the ideal transmission spectrum mask shown in the same figure. The most significant factor for this is the RBW filter. The shape of this filter is not perfectly rectangular but Gaussian which results the signal spectrum also to deviate from what is ideally expected. The signal level is also much lower than in the stipulated mask. The received signal level was around $-69$ dBm which was amplified by the TV booster upto about $-40$ dBm. In addition, it can be seen from Figure 7 that the received signal is already a distorted version. The authors would like to measure the frequency distortion due to multipath to characterize the channels in future. For future experiment, it is predicted that the fading will be reduced in LOS condition and perhaps the signal level will also increase.

5. Future work

In this paper, the experimental prototype proposed as the receiver to cognitive radio system has been tested to detect the ISDB-T signal under real noise and interference conditions. However, the time interval of detection is 1 ms only. In future, the authors intend to capture the signal at regular intervals for a longer period and concatenate the data so that the effective interval of capturing will be larger. Then the measurement of the channel responses for channel modelling are planned to be conducted. As the noise floor has been calculated, the received signal will then be compared with the threshold level (noise floor) to determine the spectrum density profile of the ISDB-T signal in Japan. The authors also plan to analyze the effect of multipath in the received signal. Another issue is to study about the variation of the probability of detection with respect to the sensing time. Once, the ISDB-T signal is dealt with, the following step will be to play with the NTSC signal of Japan subjecting it to similar processing and analysis in order to determine the spectral density profile of NTSC system. In fact, the equipments used in our prototype and their current configurations have imposed many limitations. So, if possible, the authors also desire to deploy the new spectrum analyzer with the wider RBW. However, even if the spectrum analyzer with wider RBW is available, the problem of the length of memory still persists. So, the probable option for this issue may be to consider more specific system in future to capture the signal continuously such as the one in [15].

6. Conclusion

In this paper, the prototype proposed in [8] was implemented to detect the ISDB-T signal under real noise and interference conditions. The noise floor was determined, the signal was captured for 1 ms and the average SNR was calculated. The fundamentally governing motive of the authors to perform these measurements is to conduct the measurement.
of wideband channel response by utilizing scattered pilots in ISDB-T. In future, the ISDB-T signal spectrum is intended to be scanned for a longer duration at regular time intervals and then the authors intend to merge the received data to compare the energy of the received signal to the computed noise floor. Then the availability of the vacant spectra in ISDB-T system is planned to be explored. Since we are in the transient status from analog to digital terrestrial broadcasting, both should be equally targeted. So, the NTSC signal is aimed to be detected after the ISDB-T signal for similar analysis.

References