Experimental detection Using Cyclostationary Feature Detectors for Cognitive Radios

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Abstract —Signal detection is widely used in many applications. Some examples include Cognitive Radio (CR) and military intelligence. Without guaranteed signal detection, a CR cannot reliably perform its role. Spectrum sensing is currently one of the most challenging problems in cognitive radio design because of various factors such as multi-path fading and signal to noise ratio (SNR). In this paper, we particularly focus on the detection method based on cyclostationary feature detectors (CFD) estimation. The advantage of CFD is its relative robustness against noise uncertainty compared with energy detection methods. The experimental result present in this paper show that the cyclostationary feature-based detection can be robust compared to energy-based technique for low SNR levels.

Keywords — Cognitive Radio, Cyclostationary detectors, Power spectral density, Spectral correlation function.

I. INTRODUCTION

The spectrum scarcity is driven by regulatory and license processes for spectrum allocation and not by the fundamental lack of spectrum [1]. Realizing the fact that the licensed spectrum remains unused most of the time [2]. A key function of cognitive radio is to prevent the harmful interference with licensed users and identify the available spectrum for improving the spectrum's utilization. To mitigate the impact of these issues, detection algorithms has been shown to be an effective method to improve the detection performance, which must be both precise and computationally efficient—precise, because an error will increase the risk of wireless interference to a licensed user, and computationally efficient to be implemented on cognitive radio nodes of limited processing and power resources. Wireless signal detection can be performed using many different techniques. Some of the most popular include matched filters, energy detectors and Cyclostationary Feature Detectors (CFD). Most of the previous published results about spectrum sensing rely on theoretical analysis and numerical simulations. The results published by UC Berkeley's BWRC [3] and [4] give good insights on the challenges regarding the implementation of spectrum sensing and cognitive radio. Spectrum sensing at low SNR conditions is critical to mitigate the hidden node problem and to enhance spectrum awareness. Cyclostationary feature detectors are considered to be one of the most robust detectors under noise uncertainties. In this paper, we evaluate the performance of CFD estimation from a practical implementation point of view.

The rest of the paper is organized as follows. Application field of spectrum detection is discussed in Section 2. In Section 3, we briefly discuss the stat of art detector. In Section 4, we present cyclostionary detection process and present the proposed algorithm. The experiment setup and experiment result is presented in Section 5. We conclude the paper and point out future work in Section 6.

II. APPLICATION FIELD

The development of spectrum sensing techniques can be applied to a range of applications. The two main applications region are CR networks [5] and maritime security [6]. CR network involves TV white spaces, Cellular networks and Emergency networks. The applications of CR in TV band, cellular networks and ISM band emerging in recent years. To consider CR deployment in sub band as TV band and cellular networks we consider performing spectrum sensing to learn the white space availability in the related frequency bands. The applicability of CR concepts and principles in TV band are more vast way than other systems. One reason could be that the main case study for CR is related to digital TV white spaces, where the base stations of the primary users are terrestrial and fixed. Cellular networks are another application. To overcome the indoor coverage problem and adapt to traffic growth, the concept of small cells, such as femtocells, has been proposed. Another important aspect in this area is interference mitigation. Mitigation of interference is very important issue in wireless communication because the degradation in signal quality may have an impact on the revenue of radio operators. In [7], spectrum sensing based on cyclostationary detection is identified as one of the main interference avoidance techniques. It is pointed out that the performance of the spectrum sensing technique is limited by received signal strength of the primary user, which may be severely degraded in multi-path fading and shadowing environment. As a consequence, it is important to provide experimental results (as presented in this paper), which quantify the performance of spectrum sensing techniques in various conditions. A quantitative study of the performance of the spectrum sensing technique such as presented in this paper could be a useful input in the design of the terrestrial secondary user systems.

III. STATE-OF-ART DETECTORS

One of the key challenges of CR technology is to

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reliably detect the presence or absence of primary users at very low signal-to-noise ratio. Spectrum sensing can be implemented by several detection methods. Different techniques serve different purposes based on their principles. Various methods for signal detection are mentioned in this section. However, cyclostationary detector will be described in next section. The matched filter-based detector gives better detection probability compared to other detector. However as mentioned [8], it requires the complete signal information and needs to perform the complete receiver operations in order to detect the signal. Energy sensing is an optimal detector when the noise power is known to the sensing node. The energy-based detection algorithm is easy to implement and has low complexity, but at the same time, it has some limitations such as the SNR wall [9].

Cyclostationarity in manmade communications signals is due to signal processing operations used in the construction and/or subsequent processing of the signal, such as modulation, sampling, scanning, multiplexing and coding operations. It uses non-random periodic statistic of these signals to detect and possibly even classify a signal of interest. Cyclic detection is a robust spectrum sensing technique since it relies on what are called cyclostionary processes. A random process can be classified as wide sense cyclostationary if its mean and autocorrelation vary periodically in time [10]. Modulated information is a cyclostationary process, while nose is not. As result, cyclic detectors can successfully operate in extremely low SNR environment using mathematical equations we could extracts the cyclic features of the signal. Other alternative spectrum sensing methods are proposed in [11].

IV. CYCLOSTATIONARY DETECTION PROCESS

Cyclostationarity can be a perfect probabilistic approach to model wireless man-made signals. Cyclostationary feature detectors are based on the identification of second-order cyclostationary characteristics, which are present in most of the communication signals that contain pilot sequences, carrier tones and frame headers, which are transmitted on a recurrent basis. Wide-sense stationary refers to time-invariant moments (such as mean, variance and higher order moments), while Wide-sense cyclostationarity means that the mean and the autocorrelation function of the signal is periodic [12]. From mathematical point of view, if any higher order nonlinear transformation of a random signal generates a spectral line at cyclic frequencies other than zero, the signal is called cyclostationary [13]. Cyclostationary of signals are measured using Spectral Correlation Function (SCF). General properties of cyclostationary processes are derived starting from the Fourier series expansion of the autocorrelation function, which is periodical. The Fourier coefficient of the Fourier expansion of the periodic autocorrelation function of a cyclostationary signal is called the Cyclic Autocorrelation Function (CAF). The Fourier transform of CAF is called the Spectral Correlation Function (SCF). Mathematically, this can be found at [14]. Spectral correlation function has some properties which can be used in practical situation resulting in better performance compared to other methods of detecting such as power spectral density (PSD).

The detection algorithm based on cyclostationary detection has a high computational complexity in comparison to detection algorithm based on power sensing. There is need to identify more efficient algorithms, which are still based on the cyclic spectrum analyzer features, but they require less computational effort. As reported by Roberts [15], cyclic spectral analysis algorithms fall into classes: those that average in frequency (frequency smoothing), those that average in time (time smoothing). Although both classes of algorithms produce similar approximations to cyclic spectrum, time smoothing with an FFT accumulation method (FAM) and Strip Spectral Correlation Algorithm (SSCA) are considered to be more computationally efficient. See [14] and [15] for further details about FAM and SSCA. A comparison of the performance of energy sensing and cyclostationarity-based spectrum sensing is described in [16]. In this paper, we will use a similar notation, but with real time measurement. In this paper, we implement SSCA algorithms.

A. Relationship between SCF and PSD

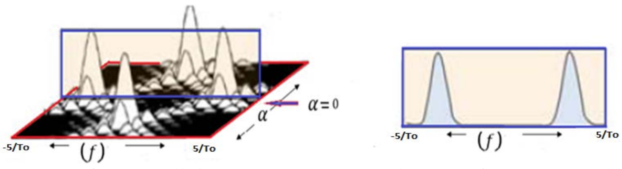
According to Wiener relation and Cyclic Wiener relation [17], PSD is from Fourier transform of autocorrelation and SCF is from Fourier transform of the CAF. Autocorrelation is special case of CAF when cyclic frequency (α=0). Thus, it is intuitively assumed that PSD is special case of SCF when α = 0. As mentioned above, PSDs, that is, SCF at α = 0, of BPSK, QPSK are same, whereas SCFs at α ≠ 0 have distinct features. Figure 1 shows the relation between SCF and PSD. PSD on the right is a part of SCF when α=0 (rectangular in the left), which means that SCF is a generalization of PSD. In mathematical expression, from Equation derivate by [17], PSD are derived as below.

$$\alpha = 0; S_x^0(f) = \int_{-\infty}^{\infty} R_x^0(\tau) e^{-j2\pi f\tau} d\tau$$

$$\alpha = 0; S_x^0(f) = \frac{1}{T_0 T} \int_{-T/2}^{T/2} X_{T_0}(t, f + \frac{1}{\alpha}) X_{T_0}^*(t, f - \frac{1}{\alpha}) dt$$

$$= \frac{1}{T_0 T} \int_{-T/2}^{T/2} \left| X_{T_0}(t, f) \right|^2 dt$$

Where $X_{T_0}(t, f + 1/\alpha)$ & $X^*{}_{T_0}(t, f - 1/\alpha)$ are the complex demodulates inputs for FFT, $S_x^0(f)$ is spectral correlation function of signal at α=0, $R_x^0(\tau)$ is cyclic autocorrelation at α=0 and $T_0 T$ is observation time.



(a)-SCF of BPSK (all α) *(b)-PSD of BPSK (α=0)*

Fig 1. SCF and PSD of BPSK

V. EXPERIMENTAL RESULTS

A. Experimental setup

The measurement setup employed in this study, shown in Figure 2, is modular and capable of performing cyclostionarity base on CFD of sensed signal. It consist of two main parts, IQ data acquisition (measurements part) and Post-processing (implementation of the algorithms needed for cyclostationarity based detection). The goal of the IQ data acquisition phase is twofold, gather sufficient measurement data at the chosen spectrum band and prepare it for processing. The IQ data acquisition consists of the pre-measurement and the actual measurements that result in a stream of complex IQ data. The Post Processing stage is MATLAB programs contain functions for importing data from measurement acquired in field and processing them. MATLAB post-processing program potentially aid in, processes the stream of measured complex baseband IQ data and is the central part of the cyclostationarity based detection. The Simulink blocks in Figure 3 describe how the data flows are analyzed inside MATLAB. The testbed setup uses the Strip Spectral Correlation Algorithm (SSCA) for CFD estimation. The SSCA algorithm is a computationally efficient algorithm suitable for practical implementations measurements of the received signal at different positions and different environment from transmitter. The measurement was conducted using two elements: Receiver platform and Transmitter platform. The receiver platform was conducted using two types of commercially available spectrum sensing equipment: Agilent N9030A PXA signal analyzer [18] and a USRP2 [19]. Although, the results presented in this section are based on the data collected with the USRP2, the validation of correct working of USRP2 was done by comparing the PSD of the transmitted signal from USRP2 with that from signal analyzer. The transmitter platform was representing by using Agilent E4438C Vector Signal Generator.

B. Result and analysis

In this section, we present the results of the experimental detection using cyclostationary sensing for 2.4 ISM signals as well Energy sensing. The signal transmitted from Vector Signal Generator with (carrier frequency 2.415 GHz, frequency deviation 20 kHz and modulation 2-FSK), and received by USRP2 under line of sight (LoS) and non-line of sight (NLoS) conditions. Figure 4, shows the received signal of FSK plot for signal transmitted by signal generator. Figure 4-a and 4-b depicts the CPS (cycle power spectrum) estimates for the cyclostationary sensing of ISM signal in LoS conditions with two different signal to noise ratio(SNR=12dB and SNR=4dB) at 1m distance and 6m distance from transmitter respectively. CPS is presented at frequency of 2.415 GHz for a bandwidth of BW = 36 kHz. From both figure, we clearly identify the different frequency and cyclic frequency components of the CPS. The cyclostationary feature is observed at the cyclic frequencies of α = ±20kHz, where α = 0 represents the standard power spectrum (Energy sensing) of the received signal with respect to frequency (*f*). Figure 4-c depicts the CPS estimates for the cyclostationary sensing of ISM band signal in NLoS conditions with SNR = -3 dB at 6 m distance from transmitter. In comparison to Figure 4-a, b and c we observe a similar cyclic feature of the spectrum but with a rough density surface due to signal fading and shadowing. Note that, although, the peaks signal become more indistinct as the SNR decreases, special at = 0, it is still can detect at cyclic frequencies of α = ± 20 kHz.

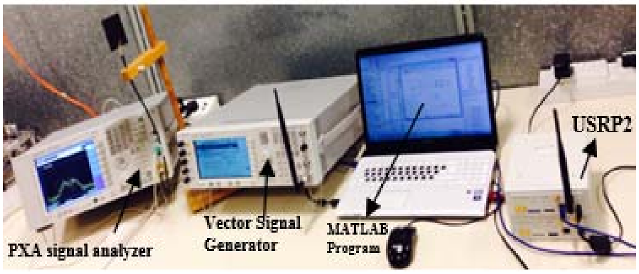


Fig. 2. Test bed for Experiments

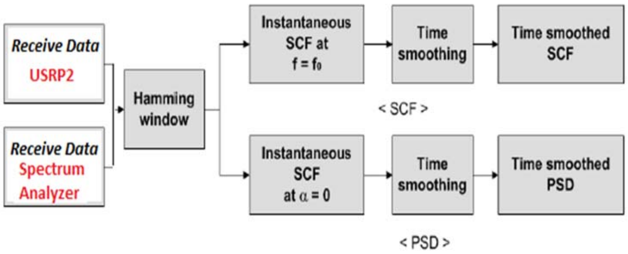


Fig. 3. Simulink block model

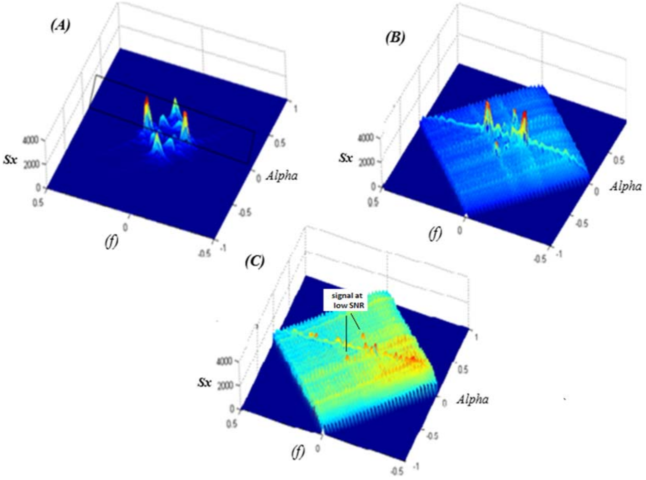


Fig.4. Received power vs frequency and cycle frequency

Figure 5 shows an example the power–distance relationship for the ISM band signal as measured with USRP2.Although enormous measurement done at University of Hull -UK to identify and characterize the difference between the energy detection and cyclostationary features under real world channel noise, only the measurement done inside PhD Room Researcher mentioned in this section according to space constraints in this paper. Channel noise involved path loss, shadowing and multipath under various locations and transmitter/receiver separations. PhD Researcher Room was chosen to model "obstructed in factories" environment. This model includes the statistics of multipath propagation characteristics for cases of light and heavy clutter in a factory.

Within each 4096 frame length from USRP2, a power ratio a level was calculated. Path loss experiments are executed at 14 different distance locations, varying distance between transmitter and receiver from 30 cm to 700 cm. The SCF and PSD are investigated at the same time to compare their path loss and SNR under same conditions. The magnitude of the PSD and SCF features in all locations as well as separation distances are presented in dB scale. To see the effects of noise environment, SNR and path loss of the features are analyzed.

The example results presented in figure 5 show that at practical values, the SCF feature has an advantage of typically 4-6dB lower compared to PSD referring to lower noise floor level at low SNR environment. In addition, Since the path loss exponent reflect the effect of shadowing and multipath, the calculated overall path loss exponent is slightly differ (by 0.10 as in Figure 5). That is, in general, the SCF yielded better performance than the PSD. Path loss exponents are obtained from the slope of the log-log path loss line. To fit measured data into the trend, Least Squares (LS) fit is used. It was found from experiment, that it is conclusive that the cyclostionary feature method is more robust to noise effects than the energy-based.

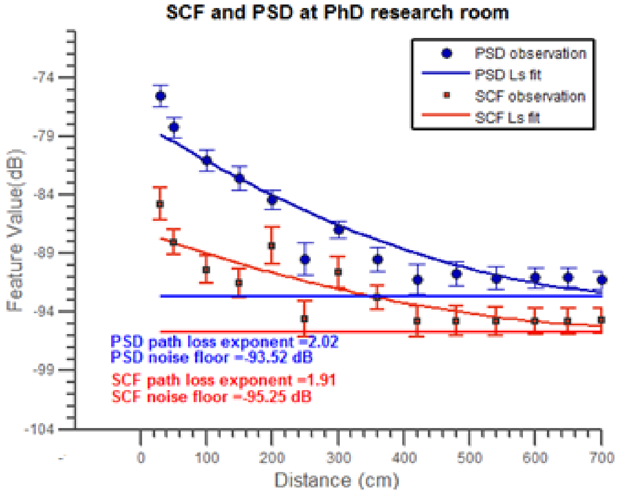


Fig. 5. SCF/PSD path loss at PhD Researcher Room

VI. CONCLUSION AND FUTURE WORK

Two different spectrum sensing techniques were used to detect ISM signal that transmitted from signal Vector Signal Generator at frequency 2.415 GHz and received using USRP2. The first spectrum sensing technique is based on an energy-based detector (SCF at $\alpha = 0$), which has low computation complexity but minimum probability of detection in case of low SNR. The cyclostationary technique (SCF at $\alpha \neq 0$), is more complex but has a better detection for low SNR. In summary, this paper provides experiment result and analysis of cyclostationarity sensing under practical signal and radio conditions, and proposes SSCA algorithm for a robust performance compared to energy based detection at low signal to noise ratio.

Future works may include testing the modified detectors and evaluating the impact of various implementations issues and adoption of cyclostationary analysis in collaborative spectrum sensing networks. Furthermore, since we look to improve the performance of SCF, changes in parameters used in this work would give more distinct features of the cyclostationary.

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