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SCF Based Cyclostationary Spectrum detection for Mobile Radio signals

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Abstract — Spectrum sensing problem is one of the most challenging issues in Cognitive Radio (CR) systems in licensed as well as unlicensed bands. It basically determines the vacant bands and makes use of these available bands in an opportunistic manner. CR may be exploited to design wireless sensor nodes to form wireless sensor networks (WSNs), which are traditionally assumed to employ fixed spectrum. A CR Sensor Node (CRSN) can access the mobile radio channel as long as it does not cause interference to the primary users who have the priority to access the channel with a specific license to communicate over the allocated band. Signal detection for spectrum sensing is one of the major functionalities distinguishing CRSNs from traditional WSNs. In this paper authors present a method of detection and identification of mobile radio signals using the concept of cyclostationary spectral analysis based on Spectral Correlation Density (SCD) function. SCD functions of several signals used for mobile radio communication like BFSK, BPSK, GMSK and CDMA have been simulated in MATLAB and analysis have been made based on the results, which can be used to classify and identify these signals for identifying underutilized frequency bands.

Index Terms — Cognitive Radio, cyclostationary Spectral Analysis, Cyclic Spectrum, Digital Modulation, Mobile Radio Communications, Spectral Correlation Density, Signal Processing, Wireless Sensor Network.

INTRODUCTION

SPECTRUM is an essential functionality of mobile communication system [1]. A certain number of frequency bands remain underutilized enormously at certain times and locations. So spectrum sensing is basically a procedure tosearch these empty frequency bands, which is an essential functionality of Cognitive Radio Sensor Node (CRSN) since these nodes can operate on spectrum bands of the licensed primary users in an opportunistic manner. The objective of spectrum sensing is to make a decision on the binary hypothesis testing based on the received signal. The two hypotheses which are defined as H0 and H1 are modeled as:

(1) H_0: the frequency band is empty and the received signal is noise only:

$y(t) = n(t)$

(2) H_1: the frequency band is occupied and the received signal is PU signal interfered by noise.

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where y(t), x(t), and n(t) denote the received signal ,the signal transmitted by primary user and the noise respectively.

In general, there can be three types of spectrum sensing techniques, which include: Energy Detection [2], Matched Filter Coherent Detection [3], and cyclostationary Feature Detection [4]. Energy detection is highly susceptible to in-band interference and changing noise levels.Cyclostationary detection is superior to simple energy detection and match filtering process. The idea behind the theory of cyclostationary is that man made signals possesses hidden periodicities like chip rate and carrier frequency that may be reproduced by sine-wave extraction operation which produces features at frequencies that depend on these periodicities.Since second-order cyclostationarity is based on quadratic non-linearities, two frequency parameters are used for sine-wave extraction function. As a result, Spectral Correlation Density (SCD) is obtained, which can be represented in bi-frequency plane. The spectral correlation characteristic of cyclostationary signals gives a richer domain signal detection method. The detection process is done by searching the cyclic frequencies of different kinds of modulated signals. In addition, information such as carrier frequency, chip rate could be

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calculated according to cyclic frequencies. This spectral correlation based method is popular due to the fact that it is robust against noise and interference.

The organization of the paper is as follows. After the introduction in section I, section II provides an overview of cyclostationary signal processing followed by SCD functions of several digital modulated mobile radio signals. Simulation environment and results are provided in section III. Section IV concludes the paper with some highlights on future works.

II.CYCLOSTATIONARY SIGNAL PROCESSING

A. Overview

As introduced by Gardner, the second order cyclostationarity uses quadratic non-linearities to extract sine-waves from a signal. A continuous-time signal x(t) is said to be cyclostationary (in wide sense), if it exhibits a periodic auto-correlation function which is given by

$$R_x(t,\tau) = E\,[\,x(t)\,x^*(t-\tau)\,] \quad \text{----------(1)}$$

where, E[.] represents statistical expectation operator. Since $R_x(t,\tau)$ is periodic, it has the Fourier series representation

$$R_x(t,\tau) = \Sigma_\alpha R^\alpha{}_x(\tau)\, e^{j\,2\pi\,\alpha\,t} \quad \text{-------------(2)}$$

$$R_x^\alpha(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} x(t)x^*(t-\tau)e^{-j2\pi\alpha t}dt$$

---------------(3)

where sum is taken over integer multiple of fundamental cycle frequencies, α. The term $R^\alpha{}_x(\tau)$ in (2) is known as cyclic autocorrelation function, which is defined as:

Consider a time series of length T, the expectation in the definition of auto-

$$R_x^\alpha(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} R_x(t,\tau)e^{-j2\pi\alpha t}dt$$

correlation can be replaced by time average so that

Therefore, a signal exhibits second-order cyclostationarity in the wide-sense when its cyclic auto-correlation function, $R^\alpha{}_x(\tau)$, is different from zero for some non-zero α.

Signals usually exhibit distinctive features in frequency domain that may not be present in the time domain. Those features help to detect the presence of those signals. For example, a sine-wave added with a noise, cannot be detected easily, by just looking at its time-domain representation. But the same signal can easily be detected in the frequency domain by making the integration time sufficiently long. Hence, it is very useful to determine the amount of correlation between frequency shifted versions of x(t) in the frequency domain.The spectral correlation density (SCD) function is defined as the Fourier transform of cyclic auto-correlation function of x(t).The SCD of a signal x(t) is given by,

$$S_x^\alpha(f) = \int_{-\infty}^{\infty} R_x^\alpha(\tau)e^{-j2\pi f\tau}dt \quad \text{----(5a)}$$

The spectral correlation is an important feature of the second order cyclostationary signals. If the signal x(t) exhibits cyclostationarity with cyclic frequency α, in time domain, then it also exhibits spectral correlation at shift α in frequency domain. So the SCD could be measured by the normalized correlation between two spectral components of x(t) at frequencies (f + α/2) and (f - α/2) over an interval T as given by

$$S_x^\alpha(f) \triangleq \mathcal{F}\{R_x^\alpha(\tau)\} = \lim_{T\to\infty} \frac{1}{T} X_T\left(f+\frac{\alpha}{2}\right) X_T^*\left(f-\frac{\alpha}{2}\right)$$

------------(5b)

Where F transform operator, $X_T(f) = \int_{-\frac{T}{2}}^{\frac{T}{2}} x(u)e^{-j2\pi f u}\,du$

B. SCD of Different Signals

Cyclic spectral analysis is a very useful tool for signal classification due to the following reasons:

Different types of modulated signals (FSK, BPSK, GMSK, DS-CDMA) with overlapping power spectral densities have highly distinct SCDs.There is no spectral correlation exhibited by stationary noise.The spectral correlation density function contains phase and frequency information related to timing parameters in modulated signals (carrier frequencies, pulse rates, chipping rates in spread spectrum signaling, etc.)SCD of several digital modulated signals used in mobile communications have been described in this section.

i) Binary Frequency Shift Keying (FSK)

An FSK signal is represented as follows [6]:

$$x[n] = \sum_{k=-\infty}^{\infty} \cos\left(2\pi\left(f_c - f(n)\right)n\right) h(n - kT_b) \quad (6)$$

$$f(n) = \sum_{m=1}^{M} \delta_m(n) f_m \quad (7)$$

$$S_x^\alpha(f) = 1/4T \sum_{m=1}^{M} W_m [G\left(f - f_m - f_c + \frac{\alpha}{2}\right) G^*\left(f - f_m - f_c - \frac{\alpha}{2}\right) + G\left(f + f_m + f_c + \frac{\alpha}{2}\right) G^*\left(f + f_m + f_c - \frac{\alpha}{2}\right) \quad (8)$$

The SCD function of an FSK signal is given by [6]:ii) Binary Phase Shift Keying (BPSK)A BPSK signal is defined as follows [7]:

$$x(t) = a(t)\cos(2\pi f_0 t + \varphi_0) \quad (9)$$

where, $\Phi o \in (0,\pi)$ and a(t) is the amplitude . The SCD of above signal is given by

iii) Direct Sequence - Code Division Multiple Access(DS-CDMA)In DS-CDMA system, a pseudo random code (also known as PN code) is directly modulated with the data signal. If the datasignal d(t) has rate $1/T_b$ and the code signal c(t) has rate 1/Tc the resulting spread spectrum signal has spreading factor ,$G_p = T_b/T_c$ [8].Let us consider a DS/SS signal x(t) with x(t)=d(t)c(t). Here

$$c(t) = \sum_{m=-\infty}^{\infty} C_m\, q(t - mT_c) \quad (11)$$

where q(t) is a pulse shape and Cm has values within ±1.The cyclic auto-correlation function is given by

By taking Fourier transform of (12), we get the cyclic spectral density,

$$R_S^\alpha(\tau) = \lim_{T\to\infty} 1/T \int_{-T/2}^{T/2} E\left\{x\left(t + \frac{\tau}{2}\right) x^*\left(t - \frac{\tau}{2}\right)\right\} \quad (12)$$

$$= \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} C_m C_n^* R_d^{\alpha - \frac{m-n}{NT_c}}(\tau) e^{j2\pi \frac{m+n}{2NT_c}\tau} \quad (13)$$

in which s^β_d |is the cyclic spectral density of the data signal.With BPSK modulation

where d'(n)Є(-1,1), q'(t) is the pulse shape,

$$S_x^\alpha(f) = \sum_m \sum_n C_m C_n^* S_d^{\alpha - \frac{m-n}{NT_c}}\left(f - \frac{m+n}{2NT_c}\right) \quad (14)$$

$t_0$is the pulse delay, f_0 is the frequency of the carrier and Φ_o is its phase. s^β_d is given by,

$$d(t) = \{\sum_n d'(n) q'(t - nT_d - t_0)\} \cos(2\pi f_0 t + \varphi_0)\}, \quad (15)$$

$$S_d^\beta(f) = \frac{\sigma_{d'}^2}{T_d Q'\left(f + \frac{\beta}{2} + f_0\right) Q^*\left(f - \frac{\beta}{2+f_0}\right) e^{-j2\pi\beta t_0}} \delta\left(\beta - \frac{k}{T_d}\right) \quad (16)$$

with Q'(f)=F{[q'(t)]}It is observed from (18) that s^β_d has a non-zero value for β=K /Td . Therefore, s^α_x is also non-zero for $\alpha - 1/NT_C = \beta$ When the processing gain N is equal to the spread factor Tb/Tc, [8], α =

$$s(t) = \exp\left[j2\pi h \sum_{n=-\infty}^{\infty} d_n \int_{-\infty}^{t} g(\tau - nT_s) d\tau\right] \quad (17)$$

P/Td. So the data frequency, Fd =1/Td. This means that cyclic frequencies are multiples of data frequency.

$$g(t) = \frac{1}{T_s rect\left(\frac{t}{T_s}\right)} * p_{Gauss}(t) \quad (18)$$

iv) Gaussian Minimum Shift Keying (GMSK)

The complex envelope of a GMSK modulated signal is [9]:

$$R_S^\alpha(\tau) = \lim_{T\to\infty} 1/T \int_{-T/2}^{T/2} s^{lin}(t + \epsilon) s^{lin}(t + \tau + \epsilon) e^{-j2\pi\alpha t} dt \quad (19)$$

With the symbol sequence $d_n \in \{-1,1\}$, symbol rate $f_s = 1/T_s$ and frequency impulse g(t) given as

where ρ_{Gauss} (t)is a Gaussian impulse with the time bandwidth product ,BT_S.

The conjugate cyclic auto-correlation function due to the linear component of the signal can be expressed as

where Є is the unknown symbol timing. Therefore, the conjugate spectral correlation density is given by

$$S_S^\alpha(f) = \int_{-\infty}^{\infty} R_S^\alpha(\tau) e^{-j2\pi f\tau} d\tau \quad (20)$$

where R_s^α is given in (19).

III. SIMULATION ENVIRONMENT AND RESULTS

The simulations were restricted to the following signal types: BFSK, BPSK, GMSK, and DS-CDMA as they are the most widely used ones in mobile communications. In order to obtain the desired SCD functions of various digital modulated signals that are extensively used in mobile radio communications and to classify them according to certain parameters like frequency resolution (Δf), cyclic frequency resolution (Δα), carrier frequency (fc) and sampling frequency (fs) we have simulated the signals and passed them through spectral correlation analyzer by using FAM

algorithm in MATLAB version:7.5.0.342(R2007b).
The plots of SCD functions are shown in Fig. 1, Fig.2 & Fig.3 respectively.

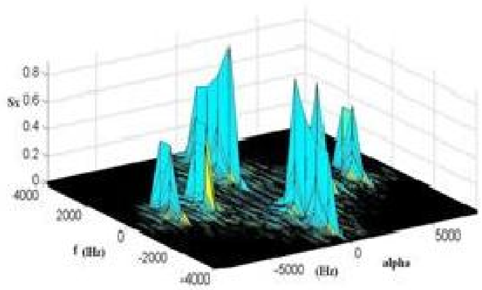

Fig. 1.SCD estimate of BFSK signal Parameters:Δf = 512 Hz, $\Delta\alpha$ = 16 Hz, fC1 = 1024 ,fC2 = 3048 and fs = 8192 Hz.

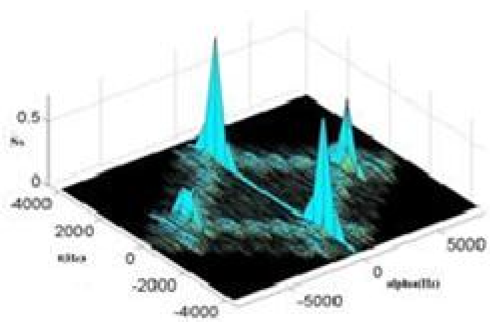

Fig.2.Surface plot of SCD estimate of BPSK signal Parameters:Δf = 512 Hz, $\Delta\alpha$ = 16 Hz, f.c= 2048 Hz and f_s = 8192 Hz.

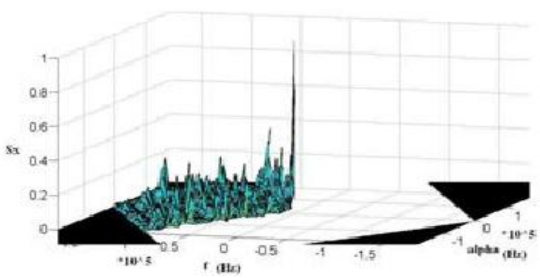

Fig.3. Surface plot of SCD estimate of GMSK signal Parameters:Δf = 512 Hz, $\Delta\alpha$ = 16 Hz, fC = 2048 and fs = 8192 Hz.

Fig.1 showing the SCD plot of BFSK has the envelope of the cyclic spectrum at carrier frequencies |f1| = 1900 Hz and $|f_2|$ = 2800 Hz for $\alpha = 0$. It is also found that the correlation exist at α = 3800 Hz and α = 5600 Hz, which is the twice of the carrier frequencies f1 and f2.Fig.2 shows the SCD plot of BPSK signal. For the zero frequency shift, the spectral correlation density is equivalent to standard power spectral density. Here $\alpha = 0$ line shows sinc2(x) at f =2400 Hz which is equal to carrier frequency. It is also clear from the figure that the greater correlation exist at almost twice the carrier frequency = 4900 Hz.
Fig.3 showing the SCD plot of GMSK signal highlights certain features. From the figure it is clear that the lobes are repeated after every 2/Tb sec.

IV. CONCLUSION

In this paper we showed that spectral correlation based detection method for spectrum sensing could be used to increase the spectral efficiency in mobile WSN. We performed MATLAB simulation of SCD functions of several digital modulated signals commonly used for mobile radio communications. As cyclostationarity is one of the properties of modulated signals, therefore, simulation results prove that it can be used as a measure for signal feature detection through spectral correlation density function. Unique signal feature properties of various digital modulated signals like BFSK,BPSK, GMSK and DS-CDMA modulated signals have been analyzed in this paper by using spectral correlation function. SCD of white noise shows no spectral correlation density, which provides an easy method of channel sensing and spectrum allocation. But, this detector suffers from highercomputational complexity which has just become manageable. Our future work is directed towards enhancement of this algorithm, which would lead to lower computational complexity and processing delay.

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