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Cyclostationarity-Based Spectrum Sensing for Wideband Cognitive Radio

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Abstract

This paper addresses the problem of cyclostationary detection when the signal spectrum is partly intercepted. The signal model for partial interception of spectrum is presented. Cyclostationary feature of signal is analyzed in this scenario and cyclic spectrum present region is also defined. An improved cyclic spectrum estimator as well as detection strategy for unknown feature location is proposed. Simulation results verify that performance of proposed algorithm can satisfy the requirement of feature detection.

1. Introduction

Spectrum sensing is one of the most critical components of cognitive radio (CR) technology. Reliable spectrum sensing functionality needs to be equipped for CR users. Cyclostationary detector has been introduced for detecting weak signal in cognitive radio [6][5][9], since it has desirable performance under low signal-to-noise ratio (SNR) and can be used for signal recognition and classification.

A CR system should provide invisible spectrum access over a wide frequency range covering multiple communication standards thus wideband spectrum sensing as an important feature is required for CRs[7]. A tunable narrowband bandpass filter(BPF) or a filterbank composed of several narrowband filters can be employed as radio frontend according to spectrum usage for wideband sensing[8]. Existing signal types and their frequency locations are usually unknown to CR over a wide range of frequency (above 100MHz), therefore signal spectrum may be intercepted partly by bandpass filter. Current research of cyclostationary sensing are based on assumptions that signal spectrum is fully intercepted and center frequency can be captured. However none of previous works concerns cyclostationary sensing when signal spectrum is partly intercepted.

In this paper, we concern cyclostationary sensing when signal spectrum is partly intercepted. We introduce a signal model for partial interception of signal spectrum. With this model, we analyze effects of partial interception of signal spectrum on cyclostationary feature of signal and cyclic spectrum estimator. By applying weighting factor, we propose an improved cyclic spectrum estimator and a detection strategy when feature location is unknown. Simulation results demonstrated desirable performance of the estimator and detection strategy are presented.

2. Signal Model for Partial Interception of spectrum

Suppose that several spectrum bands whose frequency boundaries locate at $f_0 < f_1 ... < f_N$ are to be detected for wideband CR. The n-th band is defined as $B_n : \{f \in B_n, f_{n-1} < f < f_n\}, n = 1, 2, ...N$. The bandwidth of narrowband BPF is assumed to be B_w. When the tunable narrowband BPF is employed to search over wideband sequentially or the filterbank formed by multiple BPFs is applied to detect wide spectrum at a time[8], signal spectrum can be intercepted partly by BPF inevitably. The PSD structure of a wideband signal is illustrated in Fig.1, where the n-th band centered by $f_{c,n}$ is intercepted partly by the BPF. The assumptions are adopted that the width of n-th band is $B_n = f_n - f_{n-1}$, with center frequency at $f_{c,n} = (f_n + f_{n-1})/2$. After signal spectrum is intercepted partly by BPF, the width of n-th band remains in BPF is $B_p = f_H - f_{n-1}$, where (f_L, f_H) is passband of BPF. And only one signal band is captured by BPF but its location is unknown to CR. The bandpass representation of the signal can be defined as

$$s(t) = Re[s_{l,n}(t)e^{j2\pi f_{c,n}t}] \tag{1}$$

where $s_{l,n}(t)$ is the lowpass representation of the signal. After signal spectrum is intercepted partly, the signal can

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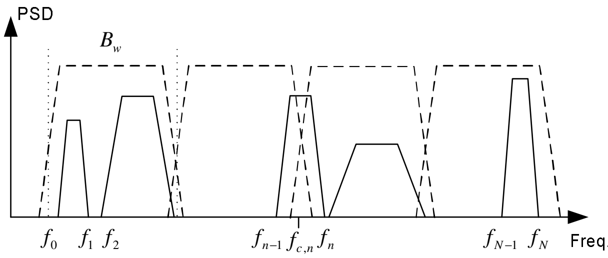

Figure 1. The PSD structure of a wideband signal

be described by

$$s_p(t) = s(t) \otimes h_{BP}(t) \tag{2}$$

where $\otimes$ denotes convolution and $h_{BP}(t)$ the impulse response of BPF. For the simplicity of analysis, we may approximate frequency response as

$$H_{BP}(f) = e^{-j\pi f M}, f_L < |f| < f_H \tag{3}$$

where M denotes the filter order. When f locates at other values, $H_{BP}(f)$ remains zero. Equivalent lowpass representation of signal whose spectrum is partly intercepted can be expressed as

$$\begin{aligned} s_{lp}(t) &= [s(t) \otimes h_{BP}(t) \otimes h_+(t)]e^{-j2\pi f_{cBP} t} \\ &= s_+(t)e^{-j2\pi f_{cBP} t} \end{aligned} \tag{4}$$

where $s_+(t)$ denotes the analytical signal, $h_+(t)$ the impulse response of Hilbert transform, and f_{cBP} the center frequency of BPF, $(f_H - f_L)/2$.

3. Cyclostationary Detection for partial interception of signal spectrum

Cyclostationary feature can be described by cyclic spectrum which measures the density of spectral correlation, that is, the density of correlation between widely separated spectral components. When the spectrum is intercepted partly, cyclic spectrum will be deformed.

3.1. Cyclostationary Feature for partial interception of signal spectrum

Based on Linear Periodically Time-Variant transformation (LPTV) model [4], we can obtain cyclic spectrum of the equivalent baseband signal in equation (4):

$$S^{\alpha}_{s_{lp}}(f) = S^{\alpha}_{s_+}(f + f_{cBP}) \tag{5}$$

where α is cyclic frequency of the signal. Since narrowband BPF and Hilbert transform are time invariant, considering $h(t) = h_{BP}(t) \otimes h_+(t)$ as impulse response function of LPTV system, we can arrive at

$$\begin{aligned} S^{\alpha}_{s_+}(f) &= H_+(f+\alpha/2)S^{\alpha}_{s_{BP}}(f)H^*_+(f-\alpha/2) \\ &= H_+(f+\alpha/2)H_{BP}(f+\alpha/2)S^{\alpha}_s(f) \\ &\times \; H^*_{BP}(f-\alpha/2)H^*_+(f-\alpha/2) \end{aligned} \tag{6}$$

where $H_+(f) = 2u(f)$ is unit step function and also the frequency response of Hilbert transform, $*$ complex conjugate. Besides, cyclic spectrum of baseband signal satisfies its spectral support region [2]. Thus cyclic spectrum of equivalent baseband signal for partial spectrum interception is bandlimited to $|f| < B_p - |\alpha|/2$, which is

$$\begin{aligned} S^{\alpha}_{s_{lp}}(f) &= H_{BP}(f + f_{cBP} + \alpha/2)S^{\alpha}_s(f + f_{cBP}) \\ &\times \; H^*_{BP}(f + f_{cBP} - \alpha/2) \end{aligned} \tag{7}$$

while $S^{\alpha}_{s_{lp}}(f) = 0$ for $|f| \geq B_p - |\alpha|/2$.

We note that cyclic spectrum for partial spectrum interception depends on how much the signal spectrum is captured. When signal spectrum is fully covered, its whole cyclostationarity can be presented. However, as width of signal spectrum cut off by BPF increases, the present cyclic spectrum is deformed. In spectral support region, width of intercepted spectrum is

$$\begin{aligned} B_{lp} &= f_H - f_{n-1} \\ &= f_H - f_{c,n} + B_n/2 \end{aligned} \tag{8}$$

while the cyclic frequency which can be present satisfies

$$|\alpha| < f_H - f_{c,n} + B_n/2 \tag{9}$$

That is, when width of captured signal spectrum equals to $(f_H - f_{c,n} + B_n/2)$, cyclic spectrum locating at $|\alpha| > f_H - f_{c,n} + B_n/2$ disappears. The present cyclic spectrum of partly intercepted signal spectrum is illustrated in Fig.2.

The diamond region with dashed line shows the spectral support region of signal moved to baseband from center frequency f_{cBP} while solid line denotes the spectral support region of equivalent baseband signal captured by BPF. When signal spectrum can be fully covered, the dashed diamond should be contained by the solid one. As captured signal spectrum reduces, the dashed diamond moved out of solid one along the f axis. The intersection of dashed and solid diamond demonstrates present area of cyclic spectrum for partial spectrum interception and can be defined as cyclic spectrum present region.

3.2. Cyclic Spectrum Estimator for Partial Interception of spectrum

Considering received signal model, $x(t) = s(t) + n(t)$, cyclic spectrum estimator [3] can be given by

$$\hat{S}^{\alpha}_x(f) \;=\; \frac{1}{MT}\sum_{\upsilon=-(M-1)/2}^{(M-1)/2} X_T(f + \alpha/2 + \upsilon F_s)$$

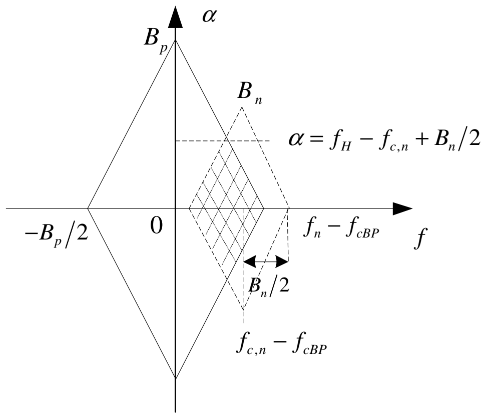

Figure 2. The present cyclic spectrum of partly intercepted signal spectrum

$$\times \quad X_T^*(f - \alpha/2 + \upsilon F_s) \tag{10}$$

where T denotes observation length, M spectral smoothing length, F_s frequency sample interval, $X_T(f)$ short-time Fourier transform $X_T(f) = \sum_{t=0}^{T-1} x(t)e^{-j2\pi ft}$.

Suppose that when signal spectrum is intercepted partly, frequency bins locating at $f \in (f-\alpha/2-(M-1)F_s/2, f-\alpha/2-(M-1)F_s/2+\Delta MF_s)$ are cut off and their valves are assumed to be estimation errors, $X_T(f) = \varepsilon_f$. Then conventional estimator computes cyclic spectrum at certain (f, α) as

$$\begin{aligned}\hat{S}_x^\alpha(f) &= \frac{1}{MT}[\sum_{\upsilon=-M'}^{\Delta M-M'} X_T(f+\alpha/2+\upsilon F_s) \\ &\times \quad \varepsilon^*_{f-\alpha/2+\upsilon F_s} + \sum_{\upsilon=\Delta M+1-M'}^{M'} X_T(f+\alpha/2+\upsilon F_s) \\ &\times \quad X_T^*(f-\alpha/2+\upsilon F_s)] \\ &= \frac{1}{MT}[\sum_{\upsilon=\Delta M+1-M'}^{M'} X_T(f+\alpha/2+\upsilon F_s) \\ &\times \quad X_T^*(f-\alpha/2+\upsilon F_s) + \xi]\end{aligned} \tag{11}$$

where ξ is accumulation of spectral correlation at frequency bins cut off and $M' = (M-1)/2$. Note that spectral correlation exhibits at $(M - \Delta M)F_s$ frequency bins. Conventional estimator averages over MF_s frequency bins with unknown locations of cut off ones, thus the estimated result is reduced.

The reduction of the feature due to cut off frequencies can be improved by weighted spectral correlation. Smoothing window is used for smoothed correlation with window length L. Two adjacent windows have P overlapped frequency samples. The number of smoothing group is defined as $Q = \lceil \frac{M-L}{L-p} + 1 \rceil$. The smoothed spectral correlation of q-th group is

$$\begin{aligned}\tilde{I}_q &= \frac{1}{T}\sum_{\upsilon=q'}^{q'+L-1} X_T(f+\alpha/2+\upsilon F_s) \\ &\times \quad X_T^*(f-\alpha/2+\upsilon F_s)\end{aligned} \tag{12}$$

where $q' = (L-P)q - (M-1)/2$ is the start subscript of frequency sample for each group. Then weight factors are applied for averaging over Q groups. Let $\mathbf{w}_{Re} = [w_{Re,1}, ..., w_{Re,q}, ...w_{Re,Q}]$ and $\mathbf{w}_{Im} = [w_{Im,1}, ..., w_{Im,q}, ...w_{Im,Q}]$ represent weight factors for real and imaginary parts of spectral correlation of Q groups respectively. Weight factors for real parts are provided by

$$w_{Re,q} = \frac{(Re\{\tilde{I}_q\})^2}{\sum_{q=1}^{Q}(Re\{\tilde{I}_q\})^2} \tag{13}$$

For imaginary parts, weight factors can be obtained in a similar way. The improved cyclic spectrum estimator can be expressed as

$$\hat{S}_x^\alpha(f) = \mathbf{w}\tilde{\mathbf{I}}^T \tag{14}$$

where

$$\begin{aligned}\tilde{\mathbf{I}} &= [\tilde{\mathbf{I}}_{Re}, j\tilde{\mathbf{I}}_{Im}] \\ &= [Re\{\tilde{I}_1\}, ..., Re\{\tilde{I}_Q\}, jIm\{\tilde{I}_1\}, ..., jIm\{\tilde{I}_Q\}]\end{aligned}$$

Note that weight factor for each group is set in proportion to its spectral correlation. Low correlation leads to high possibility of presence of frequency bin cut off and relates to a low weight factor.

3.3. Cyclic Spectrum Detector for Partial Interception of spectrum

When signal spectrum is intercepted partly, location of cyclic spectrum are unknown to CR. Thus to detect cyclostationary feature at specific (f, α) is not feasible. We need to identify location of cyclic spectrum. We search for maximum spectral correlation at certain cyclic frequency over (f_{start}, f_{end}) with search interval Δf according to

$$\hat{k} = \arg \max_{0<k\le K} [|S_x^\alpha(f_k)|] \tag{15}$$

where f_k denotes k-th frequency bin. From equation (15), we can also obtain several locations with higher spectral correlation.

Let a test vector for K' frequency bins at certain α is composed of

$$\begin{aligned}\hat{\mathbf{s}}_x^\alpha = [&Re\{\hat{S}_x^\alpha(f_{k,1})\}, ..., Re\{\hat{S}_x^\alpha(f_{k,K'})\}, \\ &Im\{\hat{S}_x^\alpha(f_{k,1})\}, ..., Im\{\hat{S}_x^\alpha(f_{k,K'})\}]\end{aligned} \tag{16}$$

Given that the hypothesis H_0 represents the case where $x(t)$ does not exhibit cyclostationarity with the cyclic frequency α and H_1 represents the case where $x(t)$ does exhibit cyclostationarity, the following binary hypothesis testing problem can be formulated:

$H_0 : \forall\{f_{\hat{k},n}\}_{n=1}^{K'} \Rightarrow \hat{\mathbf{s}}_x^\alpha = \mathbf{\Delta}_x^\alpha$

H_1 : for some $\{f_{\hat{k},n}\}_{n=1}^{K'} \Rightarrow \hat{\mathbf{s}}_x^\alpha = \mathbf{s}_x^\alpha + \mathbf{\Delta}_x^\alpha$

where $\mathbf{\Delta}$ is the asymptotically normal distributed estimation error vector. The asymptotic complex normality of $\hat{\mathbf{s}}_x^\alpha$ [1] allows the formulation of the following generalized likelihood function as the test statistic for the binary hypothesis test:

$$\mathcal{T} = \hat{\mathbf{s}}_x^\alpha \hat{\mathbf{\Sigma}}_x^{-1} \hat{\mathbf{s}}_x^{\alpha(T)} \tag{17}$$

where $\hat{\mathbf{\Sigma}}_x$ denotes estimated covariance matrix of $\hat{\mathbf{s}}_x^\alpha$ [1].

Under null hypothesis, the distribution of the test statistic converges asymptotically to a central χ^2 distribution with $2K'$ degrees of freedom. Therefore, for a given false alarm probability P_f, we can obtain threshold from χ^2 distribution table and decide presence of cyclostationarity.

4. Simulation Results

In the following, the confidence of the proposed method has been investigated. OFDM signals are generated using quadrature phase shift keying (QPSK) modulated random data symbol. A 16-bin IFFT is used for the simplicity of analysis with subcarrier separation $1kHz$. Center frequency of bandpass OFDM signal is $25kHz$. Passband and bandwidth of BPF are $(f_L < f < f_H)$ and $B_w = 18kHz$. The width of intercepted spectrum can be adjust by changing passband of BPF.

Fig.3 and Fig.4 illustrate the cyclic spectrum present region when signal spectrum is fully captured and is partly intercepted respectively. For symmetry of cyclic spectrum, only $\alpha > 0$ are presented. We can observe that the cyclic spectrum present region is deformed or vanish moving along f axis as signal spectrum is discarded.

Fig.5 compares performance of improved estimator with conventional one and relationship between detection probability and SNR is plotted. Specific frequency location $f = 8kHz, \alpha = F_d = 1kHz$ is chosen. $L = 25$ is selected for smoothing window with overlapped length $P = L - 1$. Passband of BPF is set to be $(2kHz, 20kHz)$. The detection performance improves by the proposed estimator as expected for partial spectrum interception.

Fig.6 shows the detection reliability at different cyclic frequencies, $\alpha = F_d, 2F_d$. Two set of passbands $(7kHz, 25kHz)$ and $(2kHz, 20kHz)$are chosen for comparison. We can also note the performance improvement by our proposed estimator. And feature at $\alpha = 2F_d$ can be harder to detect than $\alpha = F_d$ when signal spectrum is discarded too much. Therefore, we should choose smaller α to detect for partial spectrum interception.

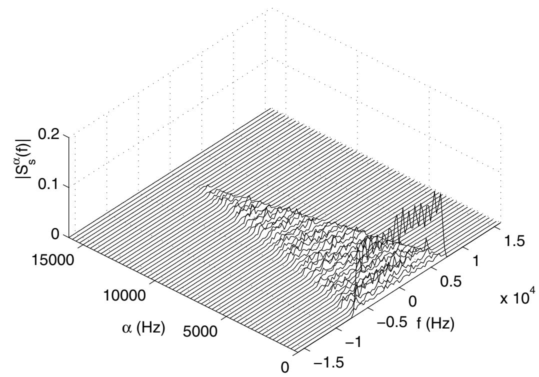

Figure 3. the cyclic spectrum present region when signal spectrum is fully captured

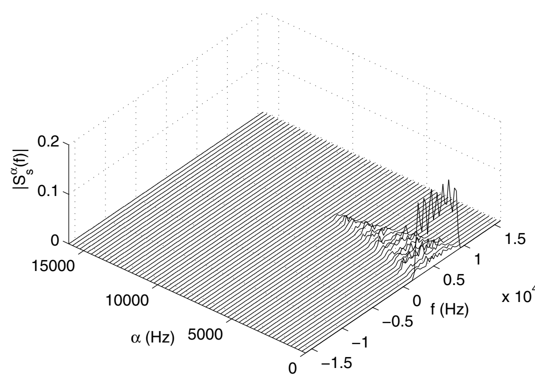

Figure 4. the cyclic spectrum present region when signal spectrum is partly intercepted

Fig.7 indicates performance of proposed detection method. f_{start} and f_{end} are set to be $4kHz$ and $8kHz$. And $\Delta f = 500Hz$. Passband $(2kHz, 20kHz)$, $(4kHz, 22kHz)$, $(7kHz, 25kHz)$ and $(12kHz, 30kHz)$ are considered. Similar performance can be observed when enough spectrum is intercepted. However performance decreases as captured spectrum reduces. Moreover, compared to detection at certain location, performance is more reliable considering multiple locations.

5. Conclusion

In this paper, a signal model for partial spectrum interception is presented. The effects on cyclostationary feature are exploited and cyclic spectrum present region is defined.

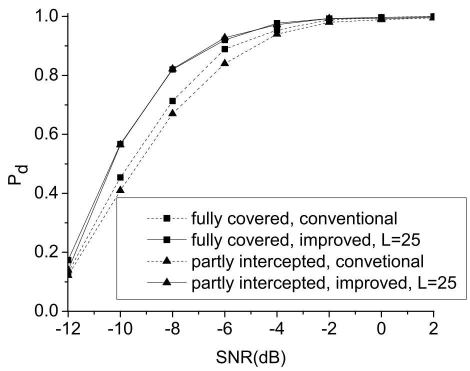

Figure 5. P_d vs SNR for comparing performance of improved estimator with conventional one

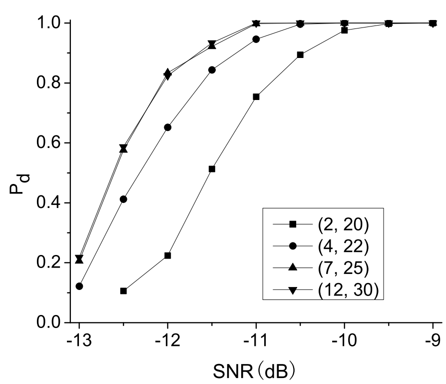

Figure 6. P_d vs SNR for comparing performance at different cyclic frequencies

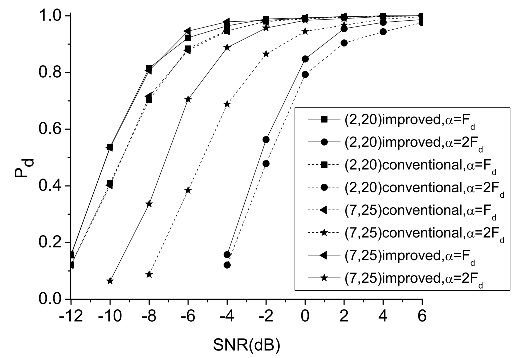

Figure 7. P_d vs SNR for proposed detection method

An improved cyclic spectrum estimator based on weighting and its detection strategy for unknown feature location are proposed. Simulation results verify that variation of cyclic spectrum coincides with our analysis. And improved detection performance is demonstrated. Smaller cyclic frequency exhibits more reliable performance when spectrum partly intercepted. By searching feature over a frequency range, detection performance can be enhanced desirably.

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