Cyclostationary Beacon for Assisting Spectrum Sensing in Opportunistic Spectrum Access

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ABSTRACT:
Cognitive radio is a promising solution to the problem of spectrum scarcity by means of allowing secondary radio networks access the spectrum opportunistically. One of the most important issues in cognitive radio is how to detect existing over-the-air signals reliably. Not a few literatures have reported that signals could be detected via their inherent or embedded properties. However, this approach may not be reliable and flexible enough for all kinds of signals with different modulation types. In this paper, we propose a type of multitone beacon signal carrying cyclostationary signatures, which is able to enhance the reliability and efficiency of signal detection at low cost of spectrum overhead. This beacon not only can indicate the presence or absence of user signal but also can reveal some other information helpful to opportunistic spectrum access through the information bits carried on its cyclostationary signatures. It could be applied to device/network identification, indication of spectrum allocation and spectrum rendezvous, both for primary and secondary users. Based on our previous work, the generation and detection algorithm of the beacon signal are extended with improved spectral efficiency. Performance is discussed with both computer simulation and testbed validation.

KEYWORDS: cognitive radio, beacon signal, spectrum sensing, spectrum rendezvous, cyclostationary detection

1. INTRODUCTION

Nowadays, one of the key problem challenging the wireless innovators and policy makers is the seeming spectrum scarcity caused by traditional inefficient command-and-control spectrum regulation [2]. In this regulation, the electromagnetic spectrum is divided into frequency bands and exclusively assigned to various entities without considering their utilization of these bands. Along with the rapid deployment of radio applications the available electromagnetic spectrum suitable for wireless communication seems to be nearly exhausted. However, several measurement studies [3] have proved that the spectrum is in fact significantly underutilized.

Cognitive radio is becoming a promising solution to this issue by allowing secondary radio networks access the underutilized spectrum in an opportunistic sharing manner. The concept of cognitive radio was firstly introduced by J. Mitola in [4], where secondary user can access the licensed frequency band under the constraint of causing no harmful interference to primary user. Therefore, it is of fundamental importance for secondary devices to sense its radio environment and percept the situation of other devices so as to behave properly.

By far, most sensing reported techniques are based on exploiting the inherent or embedded properties of primary user's signals, which imposes great challenge in efficiency and reliability [5]. In this paper, we propose a multitone beacon signal carrying cyclostationary signatures to enhance the reliability and efficiency of spectrum sensing. The beacon signal is relatively independent of user signal transmission and doesn't rely on the modulation types of user signal. So it may be flexibly used with all kinds of wireless system in opportunistic spectrum access.

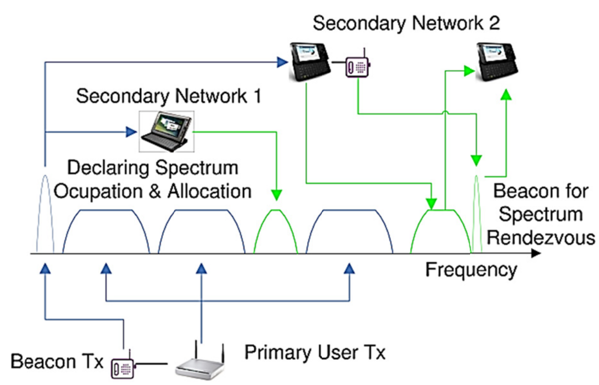

Fig. 1. Beacon signal for primary user detection and spectrum rendezvous

The beacon signal could be applied in the following two context which are shown in Fig.1: 1) It can be transmitted by primary users or networks to declare their occupation and spectrum allocation of certain frequency band and notify secondary users to avoid interference to them. It should be noted that as the proposed beacon is transmitted by an independent device in a small piece of band adjacent to user signal. Therefore, no technical changes is required for primary user's protocols and devices. 2) According to secondary users, the operating band may change dynamically following the presence of primary users. When a common control channel is impractical, the proposed beacon could be used as an indicator helping secondary devices to discover and synchronize to their peer devices, thus the so-called spectrum rendezvous [6].

In the proposed scheme, cyclostationary signal detection [7] which is optimal in blind signal analysis at low Signal-to-Noise Ratio (SNR) is applied for detecting the beacon signal. Moreover, as the bandwidth of the beacon signal is much smaller than that of broadband user signal, higher power spectral density and hence SNR as well as low spectrum overhead can be achieved.

Another essential feature of the proposed beacon signal is that bits containing information about the corresponding device or network can be carried on the cyclostationary signatures generated by multiple cross-correlated tones. This may greatly increase the flexibility and efficiency in spectrum sensing. These bits could be used to, for example: 1) declare the occupation of certain spectra band and system type of primary user; 2) indicate the band allocation and bandwidth of a primary network to unlicensed devices - as long as the band allocation is acquired via the beacon signal, it's not necessary to scan the whole band searching for licensed signals; 3) identify a secondary user or network in the context of spectrum rendezvous, etc. It is to be noted that the idea of carring information bits in cyclostationary signatures is not limited to the independent beacon signal and could be extended to other schemes where signatures are embedded in user signal, which is similar to the ideal in [6].

In [6] and [8], the authors proposed an scheme for spectrum rendezvous and network identification for Orthogonal Frequency Division Multiplexing (OFDM) based systems when common control channel is impractical. This is achieved via embedding signatures on part of the sub-carriers. The proposed beacon signal could also accomplished the same purposes through its flexibly allocated signatures. However, the modulation of user signal is not limited to OFDM and it could be applied to existing systems as the beacon transmission is actually independent of user signal.

The remainder of this paper is structured as follows. An overview of cyclostationary signal detection is given in Section 2. In Section 3, the generation of the multitone beacon and its cyclostationary detection algorithm is introduced. Section 4 presents some simulation results in order to discuss the performance with practical issues considered, such as noise uncertainty and carrier frequency offset. In Section 5, the beacon signal and its detection algorithm is validated using a real-word testbed and over-the-air transmissions. Conclusion is drawn in Section 6.

2. CYCLOSTATIONARY ANALYSIS

Many of the communication signals in use today exhibit inherent cyclostationary features arising from their underlying periodicity, such as repeating pilot or preambles, sinusoid carriers and spread coding, etc. This periodicity can result in special pattern of correlation in frequency domain, which is insensitive to noise and hence make the detection and classification of signals at low SNR possible.

A signal $x(t)$ is defined to be wide-sense cyclostationary if its mean and autocorrelation are periodic with period T_0:

$$\begin{aligned} M_x(t) &= E\{x(t)\} = M_x(t+T_0), \\ R_x(t,\tau) &= E\{x(t-\tau/2)x^*(t+\tau/2)\} \\ &= R_x(t+T_0,\tau). \end{aligned} \tag{1}$$

Such periodicity in t with period T_0 can be expressed as a Fourier series [9]:

$$R_x(t,\tau) = \sum_{\alpha} R_x^{\alpha}(\tau) e^{j2\pi\alpha t} \tag{2}$$

where $\alpha = m/T_0$ and m is an integer. The Fourier coefficient can be then obtained by,

$$R_x^{\alpha}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} R_x(t,\tau) e^{-j2\pi\alpha t} dt \tag{3}$$

The cyclic Wiener relation states [3] that the spectral correlation function (SCF) can be obtained from the Fourier transform of the cyclic autocorrelation in 3,

$$S_x^{\alpha}(f) = \int_{-\infty}^{\infty} R_x^{\alpha}(\tau) e^{-j2\pi\alpha\tau} d\tau \tag{4}$$

Practically, the spectrally smoothed cyclic periodogram is used to approximate SCF:

$$S_{x_T}^{\alpha}(t,f) = \frac{1}{T} X_T(t, f+\alpha/2) X_T^*(t, f-\alpha/2), \tag{5}$$

where X_T is the time-variant Fourier transform defined as:

$$X_T(t,f) = \int_{f-T/2}^{f+T/2} x(u) e^{-j2\pi f u} du. \tag{6}$$

The SCF can be then estimated by frequency smoothing of the cyclic periodogram together with increasing observation time and reducing smoothing window size:

$$S_x^{\alpha}(f) = \lim_{\Delta f\to 0} \lim_{T\to\infty} \frac{1}{\Delta f} \int_{f-\Delta f/2}^{f+\Delta f/2} S_{x_T}^{\alpha}(t,u) du. \tag{7}$$

An example of QPSK signals SCD is shown in

Fig.2. The advantages of cyclostationary signal analysis over other approaches lie in the spectral correlation features which can be revealed with SCF and is insensitive to noise. As these features are specific to the modulation type and bandwidth of signals, signal identification and classification could also be achieved. And the spectral correlation features can be intentionally embedded in the signal in order to assist spectrum sensing.

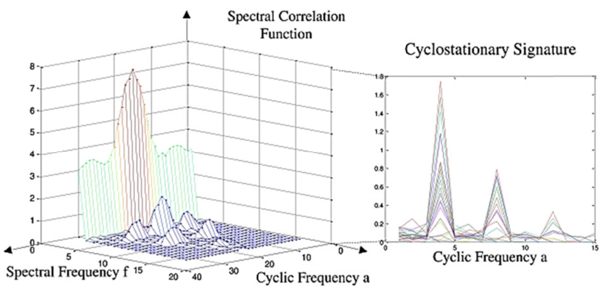

Fig. 2. Spectral correlation function of QPSK

3. BEACON SIGNAL GENERATION AND DETECTION

Section II introduces the general model of analyzing the cyclostationary features within a signal. These features are revealed by means of correlation between different spectral components of the signal. Based on this model, in this section, the novel approaches of generating, detecting the proposed beacon signal are presented from the practical points of view.

3.1. Generation of Beacon Signal

In our previous work of cyclostationary beacon signal [1], the values of tones are randomized and only the tones belong to the same bit are identical in order to produce unique correlation pattern, i.e. cyclostationary signature. The well-known windowing techniques in OFDM is borrowed for suppressing both out-of-band emission as well as inter-tone interferences. In this study, we found that it's not necessary to use randomized values for tones and there are two benefits of applying identical values:

- The cross correlation among tones belonging to different bits can generate extra signatures in SCF, which can be also used to decode the signal. Only one tone for each bit is enough, but in previous study [1], multiple (≥ 2) tones is required for generating signatures for one bit. Hence, the spectral efficiency can be improved to 1 bit/tone which is at least two times of previous one.
- As each tone is a pure sine wave in this case, idealy there are no out-band power leakages. Therefore, the suppression techniques such as windowing is not needed here.

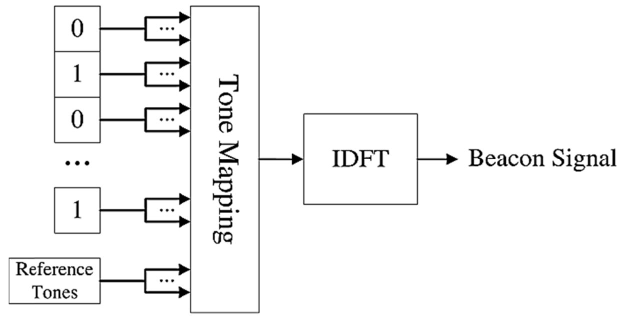

Fig. 3. Beacon signal generation

The process of generating the beacon signal is illustrated in Fig.3. Each of the information bits is mapped on one or several tones in frequency domain and the spectral correlation is hence produced. In this study, only one tone for each bit is considered and robustness can be enhanced by channel coding or more tones for 1 bit which will be discussed in next section. The frequency carriers of these correlated tones are predetermined so that the location of their corresponding signatures in SCF can be calculated by detector. The tones are then converted to time domain signal with Inverse Discrete Fourier Transform (IDFT), which is similar to Orthogonal Frequency Division Multiplexing (OFDM). This is a convenient way of sculpturing the spectrum of beacon signal tone by tone and arranged spectral correlations explicitly in frequency domain.

The reference tones are used to detect the existence of beacon signal itself and help decoding bits carried by the tones. There frequency should be fixed so that the signatures' location of SCF is known to receiver and used to test beacon's existence.

Assuming there are K information bits $\{b_k \mid k = 1,2,\ldots,K\}$ to be carried on the beacon and each bit are mapped onto L tones. So the total number of signature tones is $K \times L$. In this study, we only consider the case $L = 1$. When additional robustness is required from correlation, as was in [1], larger L should be used.

Let the set of the tones for the kth bit be

$$\begin{aligned} G_k &= \{a(i_l^k) \mid i_l^k \in I_k, l = 0,1,\ldots,L-1\} \\ k &= 0,1,\ldots,K-1 \end{aligned} \tag{8}$$

where I_k is the index set for the signature tones belonging to the kth bit, which is predetermined and also known by receiver. The values for the tones are assigned as follow:

$$a(i_l^k) = \begin{cases} 0, & b_k = 0 \\ A. & b_k = 1 \end{cases} \tag{9}$$

Obviously, the values of the tones belonging to bit 1 are all equal to A while that belonging to bit 0 are all zeros. The complex envelope of the beacon signal can be then presented as

$$x(t) = \sum_{k=1}^{K} \sum_{l=1}^{L} a\,(i_l^k) e^{j \cdot 2\pi \Delta f i_l^k t} \tag{10}$$

where Δf is the frequency spacing between adjacent tones. Obviously, the signal generation can be easily implemented with IDFT.

3.2. Cyclostationary Detection of Beacon Signal

In order to decode the information carried on proposed beacon signal by taking the advantage of cyclostationary properties, a low complexity detector is designed for practical implementation. The detector is essentially an estimator of SCF, by which different spectral components are cross correlated and cyclostationary signatures at various cyclic frequencies α and spectral frequency f coordinate are extracted for detection.

The detection is based on the cyclic periodogram introduced in Section 3.1 thanks to its low complexity. First, DFT is applied to the received samples $x(n)$:

$$X_q(n) = \sum_{p=0}^{RN-1} x\,(qRN+p)W(p)e^{-j\cdot 2\pi pn/RN} \qquad (11)$$

where q is the index of DFT window, N is the total number of tones on the signal and R is a positive odd number. $W(n)$ is the window function used to suppress power leakages in SCF estimation. The simulation result presented in next section will show the performance gain of applying hamming window when carrier frequency offset (CFO) presents. The DFT size is odd times of the number of tones, which can help mitigating the CFO problem and will be proved in the next section.

As each signature spans R bins for a fixed cyclic frequency, the maximum values of these bins in SCF are picked up for detection:

$$\begin{aligned} \hat{S}_x(m,n) &= \frac{1}{Q}\max_i\{\,|\sum_{q=0}^{Q-1} X_q\,(nR+i)X_q^*(nR+i-mR)|\} \\ m &= 0,1,\dots,N-1;\ n=0,1,\dots,N-1; \\ i &= 0,1,\dots,R \end{aligned} \qquad (12)$$

An example of a beacon signal's SCF and Power Spectrum Density (PSD) are presented in Fig.4. There are twenty bits with one tone for each of them. Two reference tones are placed at the lower and higher edges of the signal's spectrum and there corresponding signatures on SCF is marked in the figure. It's also shown that the plane in SCF where cyclic frequency $\alpha = 0$ (i.e. $m = 0$) is actually the signal's PSD.

After the signal's SCF is estimated by $\hat{S}_x(m,n)$, we can first test the existence of beacon signal with the signature generated by reference tones. Let the spectral frequency and cyclic frequency indexes of the signature be (n_{ref}, m_{ref}), which are known to receiver as was illustrated in Section 3.1. The test results is:

$$\begin{aligned} H_0 &: \quad \hat{S}_x(m_{ref}, n_{ref}) < \lambda(p_{FA}) \\ H_1 &: \quad \hat{S}_x(m_{ref}, n_{ref}) \geq \lambda(p_{FA}) \end{aligned} \qquad (13)$$

where H_1 and H_0 are the hypothesizes of the signal detected or not detected respectively. $\lambda(p_{FA})$ is detection threshold which is related with probability of false alarm p_{FA}, We obtain the threshold simply by applying the detection algorithm to gaussian noise, sort the detected values and choose the threshold according to intended p_{FA}.

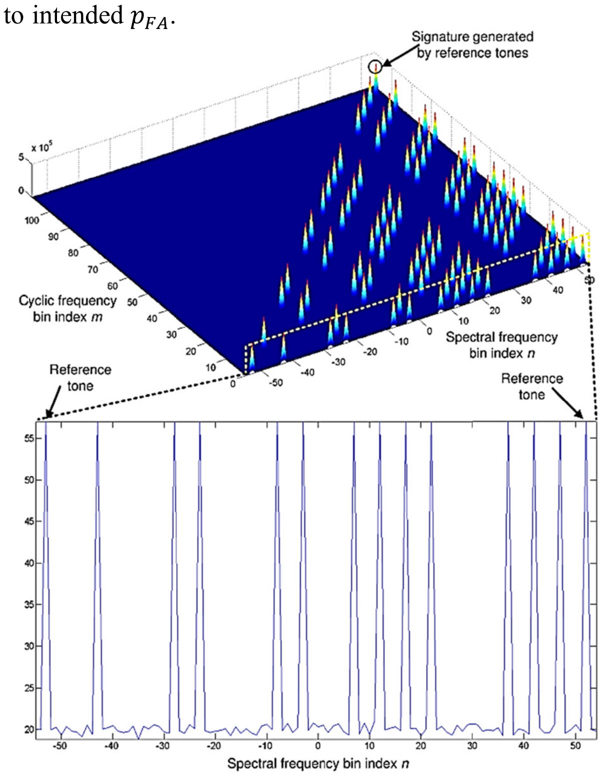

Fig. 4. An example of a beacon signal's SCF and PSD, *R=5 , N=22*

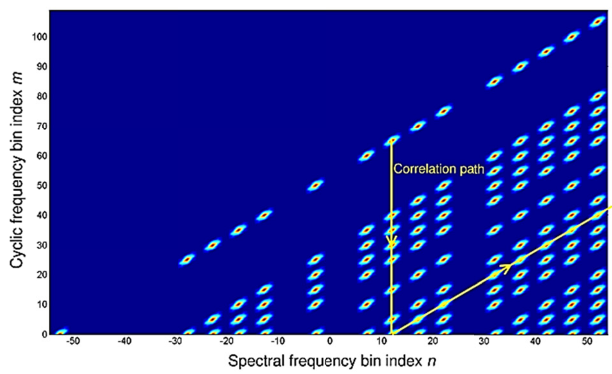

Fig. 5. An example of a beacon signal's SCF and PSD, *R=5 , N=22*

After the existence of beacon signal is detected, the next step is to decode the bits carried in the signal.Fig.5 indicated that all the signatures corresponding to a tone is along a path (the yellow lines), we name it correlation path. By validating the maximum correlation values along this path, the bit values can be detected as

$$\hat{b}_k = \begin{cases} 1, & \max\{\hat{S}_x(m^k_{path}, n^k_{path})\} \geq \gamma \hat{S}_x(m_{ref}, n_{ref}) \\ 0. & \max\{\hat{S}_x(m^k_{path}, n^k_{path})\} < \gamma \hat{S}_x(m_{ref}, n_{ref}) \end{cases} \qquad (14)$$

where (m_{path}^k, n_{path}^k) are the coordinates along correlation path for the kth bit. And γ is the boundary factor for differentiate the signatures for bit 1 from bit 0. Here we simply let it be 0.5, which means if the detected signature value of a bit is larger than half of the reference signature value, the decoded bit is one, otherwise it is zero.

4. SIMULATION RESULTS

We first simulate the performance of detecting reference tone, i.e. the existence of the beacon signal itself under noise uncertainty (NU) which is common in practical receivers. In [10], a typical NU value of 1 dB is estimated and two approaches of modeling NU are introduced: the robust statistics and the Bayesian statistics. The robust statistics approach use upper limit of noise power PSD to calculate probability of false alarm and use lower limit to calculate probability of misdetection, which models the worst case in NU. The result in 6 shows that by increasing number of averaging, thus the Q in equation (12), the sensing performances of both energy detector and the proposed cyclostationary detector are improved. However, when NU presents, the "SNR wall" phenomenon appears which prevent performance improvement by increasing number of samples for averaging. But cyclostationary detector is insusceptible to NU and outperforms energy detector.

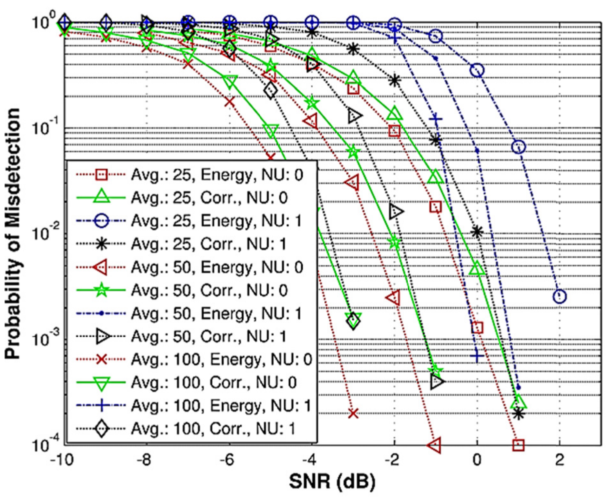

Fig. 6. Detection performances of energy detector and cyclostationary detector for reference tones with different detection length under noise uncertainty, $p_{FA} = 0.01$

Fig.7 presents the decoding performance under CFO. Probability of erroneous detection here means that the detection is erroneous if at least one bit on the signal is misdecoded. As transmit power for bit zero is actually zero, the signal power varies with the ratio between bit one and bit zero. In order to keep consistence, the SNR here and in the following means the power of a tone over noise within the tone spacing. CFO here is denoted by times of frequency spacing of adjacent. It is shown that when *R=1* (one DFT bin for each tone), the decoding performance is very vulnerable to CFO. Especially when CFO is 0.4 tone spacing, the detection is completely failed no matter how high SNR is. The reason is the frequency resolution is too low for *R=1* that frequency shift can produce significant power leakages in neighboring tones, which results a high false alarm probability for tones carrying bit zero. By increasing DFT size five times (*R=5*), the performance with and without CFO can be both improved. Comparing with use of rectangular window, using Hamming window is more robust against CFO. This is due to Hamming windowing's better suppression of power leakage in spectral estimation[11].

The decoding performance for CFO 0.3 is worse than that for CFO 0.4. This is because CFO 0.4 coincides with integral $R \times 0.4 = 2$ times FFT bin's spacing while CFO 0.3 is fractional 1.5 times. More power leakages to neighboring FFT bins are produced when signal is not centered at integral times of bin's spacing. Shown in Fig.8, for CFO 0.3 and rectangular window, the extra signature in light blue of the SCF reveals clearly the power leakage. When hamming window and higher FFT size are applied, the leakage is greatly suppressed resulting more robust decoding performance under CFO. It shows in Fig.7 that the performance divergence for different CFO is much smaller using Hamming window than using rectangular window.

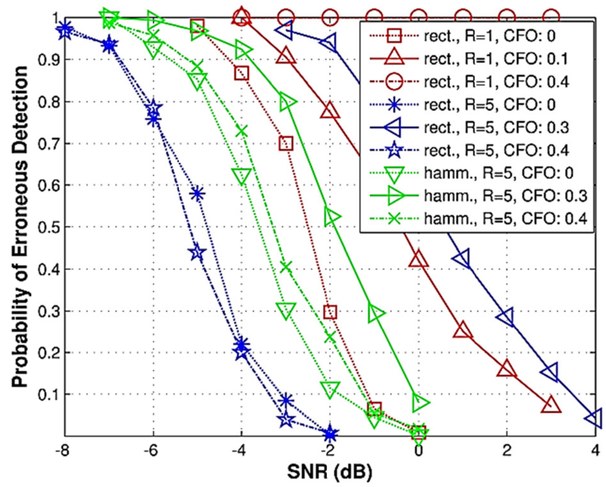

Fig.7. Decoding performance with different resolutions and window functions under carrier frequency offset (CFO), 20 bits, 2 reference tones, totally 22 tones, 2200 samples used for detection

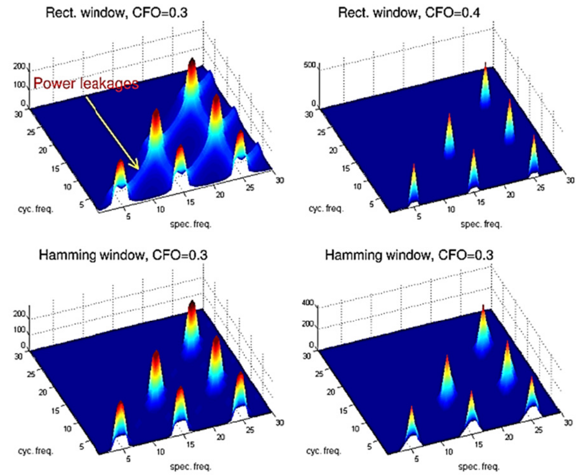

Fig. 8. SCF for CFO of 0.3 and 0.4 FFT bin spacing using rectangular window and hamming window, power leakage is clearly revealed for CFO 0.3 and rectangular window

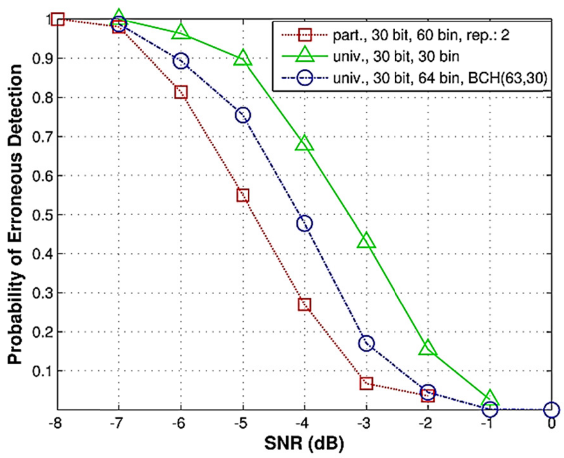

Fig. 9. Decoding performance using partial correlation method and universal correlation method combine with BCH code, 2 reference tones, *R=5*, averaging *Q=20*

In our previous work in [1], we partially specified two or more identical tones for each bit in order to generate cyclostationary signatures in SCF. The spectral efficiency of this approach is low as the number of bits can be carried is only half of the number of tones or even less. In this study, higher efficiency of 1 bit/tone can be achieved by utilizing the cross-correlations among tones from different bits universally. Fig.9 presents the decoding performance of using partial correlation method and universal correlation method for 30 bits. BCH(63,30) code is applied here to enhance the robustness. It is shown that for universal methods without BCH code, the performance is about only 1.5 dB worse than partial method with 2 tones for each bit, but the spectral efficiency is twice. When BCH(63,30) is applied, as the codeword is about two times of the bits, spectral efficiency is roughly as low as that of the partial method. However, the robustness enhancement by BCH code is worse than using partial method. Therefore, if extra robustness is required at the cost of reduced spectral effeciency, the partial method proposed in [1] is a better choice.

5. TESTBED VALIDATION

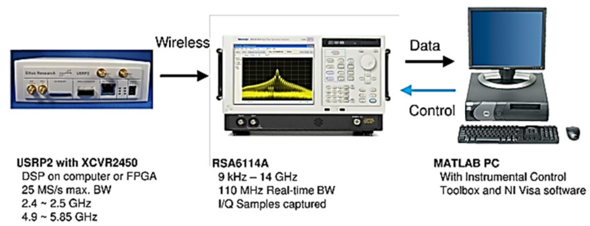

Fig. 10. Hardware components of the testbed for beacon transmission and receiving

In order to validate effectiveness and feasibility of the proposed beacon signal scheme, we further experiment the proposed cyclostationary beacon scheme with a testbed and over-the-air transmission, which is depicted in Fig.10. The signal is transmitted with a Universal Software Radio Peripheral 2 (USRP2) and received with a Tektronix RSA6114A spectrum analyzer. With the help of Instrument Control Toolbox, we can get the inphase/quadrature samples of received signal on computer and process it with our cyclostationary detector implemented in Matlab. Some key parameters of the beacon signal are listed in Table 1.

Table 1: Parameters of Transmitted Beacon Signal

Bits	98
Reference Tones	2
Tone Spacing	10 kHz
Bandwidth	1 MHz
Carrier Frequency	5.601 GHz
Detection Resolution	R=5
Detection Time	10 ms

For eliminating the interference from DC component transmitted by USRP2, we shift the transmitted signal by 1 MHz into its upper sideband. Since the low-cost oscillator in USRP2 produces a large CFO of 20 to 30 kHz at 5.601 GHz carrier, which is too high for the detector, we first estimate the CFO visually with the DC component from USRP2 received by spectrum analyzer and then compensated it by tuning CFO to below half the tone spacing: 5 kHz. Fig.11 shows the received beacon signal's PSD displayed by the analyzer and SCF estimated by the detector, which clearly reveals cyclostationary signatures.

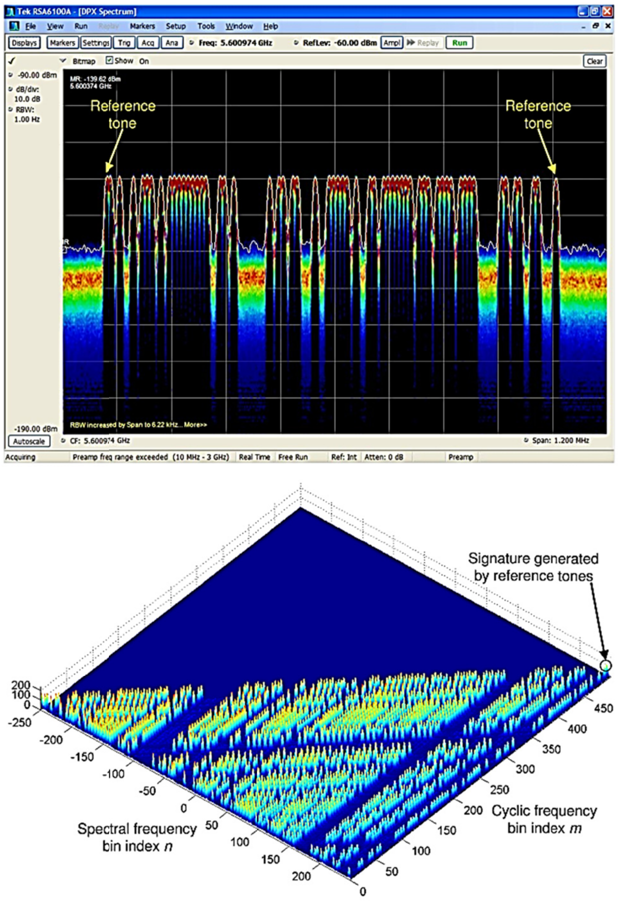

Fig. 11. Received real-world beacon signal's SCF and PSD with parameters in Table

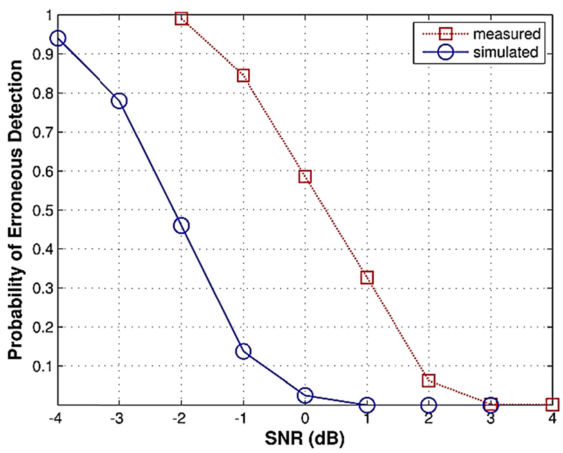

Fig. 12. Decoding performance for simulated and received real-world beacon signal with parameters in Table

Complete detection and decoding algorithm is implemented to process real samples from hardware. In order to produce a controllable SNR range for validating the decoding performance, noise are produced in Matlab and add to received signal. Fig.12 presents the decoding performance for both simulated and received signal. We believe the degradation of about 3 dB for received signal with the testbed is due to hardware imperfections such as residual CFO and unflatness of the receiver's frequency response. We observed there are maximum 0.5 dB differences at different locations of the RSA6114A's frequency response.

6. CONCLUSION

In this paper, based on our previous work in [1], an improved multitone beacon signal for assisting spectrum sensing in opportunistic spectrum access is proposed. Information bits can be carried on the cyclostationary signatures in this beacon signal, which make it versatile in declaring spectrum occupation for licensed devices, indication of frequency band allocation and network identification for spectrum rendezvous. The idea of carrying information bits on cyclostationary signatures can also be extended to other schemes where signatures are embedded in user signal. A low-complexity algorithm is proposed based on SCF revealing the cyclostationary signatures in spectral-cyclic frequency domain. Computer simulations are performed to evaluate the detection performance with analysis on practical issues such as noise uncertainty, CFO and suppression of power leakage. Then we further evaluate the beacon signal with real-world radio transmission using testbed with hardware imperfections. Both simulation and experiment show the beacon signal can be effectively detected under low SNR with practical constraints.

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