A SURVEY ON SPECTRUM SENSING TECHNIQUES FOR COGNITIVE RADIO

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Abstract: *The paper refers to the increased demand for a new approach to efficiently use the available mobile communications spectrum resources. The current static assignment of spectrum often exceeds the available bandwidth. Cognitive Radios (CR), self-learning, adaptive and intelligent radios with the capacity to sense the radio environment and to adapt to the current conditions like available frequencies and channel properties, can use the spectrum in a more flexible way. The spectrum sensing capacities of the CR rely on advanced signal processing techniques and can be enhanced by using cooperative sensing.*

Keywords: *Cognitive radio, Spectrum Sensing, Digital Signal Processing.*

1. Introduction

The current situation on the field of telecommunication looks nowadays very promising in terms of emerging wireless technologies and systems. Bandwidth is perceived as the key item for progress in this area, the current approach in frequency band assignments as fixed bands with transmission power limits. In this manner, the medium utilization factor of some frequency bands is low, both for the inefficient geographical allocation as well as for being underused by the licensed services, the "primary users". A more flexible approach to the use of the radio resource implies the use of more intelligent radio terminals, so called "cognitive radios" equipped with spectrum sensing facilities for discovering the unused part of the radio spectrum, with the ability to change frequencies and to adapt to transmission in large bands and with the possibility to vary the transmission power in order to avoid interferences. The cognitive radio approach can affect decisively the future of spectrum regulations, a good example in this sense is the initiative IEEE 802.22 to define a new WRAN (Wireless Regional Area Network) interface for wideband access in rural and remote areas with cognitive radio techniques working in the guard bands (so called "white space") of TV channels not in use, taking advantage of the good propagation characteristics in the VHF3 and in the lower part of the UHF4 bands.

One of the aspects not yet regulated of the dynamic and distributed radio access is spectrum sensing which consists of a sensing technique, a sensing algorithm for fast and robust detection of incumbent signals and coordination and communication protocols for distributed radio access.

2. Signal processing techniques for spectrum sensing

2.1 Matched Filter

The optimal way for any signal detection is a matched filter, since it maximizes received signal-to-noise ratio [2]. However, a matched filter effectively requires demodulation of the signal of the licensed user, the primary user. This means

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that cognitive radio has a priori knowledge of primary user signal at both PHY and MAC layers, e.g. modulation type and order, pulse shaping, packet format. These data can be pre-stored in CR memory, but for performing demodulation it has to perform timing and carrier synchronization, even channel equalization. This is still possible since most primary users have pilots, preambles, synchronization words or spreading codes that can be used for synchronization.

If $X[n]$ is completely known to the receiver then the optimal detector for this case is

$$T(Y)=\sum_{n=0}^{N-1} Y[n]X[n] \underset{H0}{\overset{H1}{\lessgtr}} \gamma \qquad (1)$$

If γ is the detection threshold, then the number of samples required for optimal detection is:

$$N=[Q^{-1}(P_D - Q^{-1}(P_{FD})]^2 (SNR)^{-1}$$
$$N = O(SNR)^{-1} \qquad (2)$$

where P_D and P_{FD} are the probabilities of detection and false detection respectively.

The main advantage of the matched filter is that due to coherency it requires less time to achieve high processing gain since only $O(SNR)^{-1}$ samples are needed to meet a given probability of detection constraint. The most significant disadvantage of a matched filter is that a cognitive radio would need a dedicated receiver for every type of primary user.

2.2 Energy Detector

One approach for improving matched filtering is to perform non-coherent detection through energy detection, a sub-optimal technique extensively used in radiometry. An energy detector can be implemented similar to a spectrum analyzer by averaging frequency bins of a Fast Fourier Transform (FFT), as outlined in figure 1. Processing gain is proportional to FFT size N and observation/averaging time T. Increasing N improves frequency resolution which helps narrowband signal detection. Also, longer averaging time reduces the noise power thus improves SNR.

$$T(Y)=\sum_{n=0}^{N-1} Y^2[n] \underset{H0}{\overset{H1}{\lessgtr}} \gamma \qquad (3)$$

$$N = 2[(Q^{-1}(P_{Fd} - Q^{-1}(P_D))(SNR)^{-1} - Q^{-1}(P_D)]$$

$$N = O(SNR)^{-2} \qquad (4)$$

Based on the above formula, due to non-coherent processing, $O(SNR)^{-2}$ samples are required to meet a probability of detection constraint. There are several drawbacks of energy detectors that might diminish their simplicity in implementation. First, a threshold used for primary user detection is highly susceptible to unknown or changing noise levels. Furthermore, in frequency selective fading it is not clear how to set the threshold with respect to channel notches. Second, energy detector does not differentiate between modulated signals, noise and interference. Since it cannot recognize the interference, it cannot benefit from adaptive signal processing for canceling the interferer. Furthermore, spectrum policy for using the band is constrained only to primary users, so a cognitive user should treat noise and other secondary users differently. Lastly, an energy detector does not work for spread spectrum signals like direct sequence and frequency hopping signals, for which more sophisticated signal processing algorithms need to be devised. Generally, detector robustness can be increased by looking into a primary signal footprint such as modulation type or data rate.

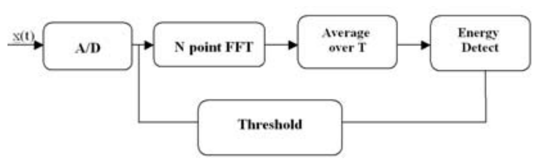

Figure 1: Block diagram of a matched filter detector

2.2.1 Parallel MRSS Sensing

An important drawback of the classical energy detection method are the long sensing times and, consequently, a lower average data throughput, which is further degraded if the system bandwidth is large (e.g., 3-10GHz) or if the necessary sensing resolution must be very fine. The total sensing time can be reduced using a multi-resolution spectrum sensing (MRSS) technique wherein the total system bandwidth is first sensed using a coarse resolution. A fine resolution sensing is then performed over a small range of frequencies. This technique not only reduces the total number of blocks that must be sensed, it also allows the cognitive radio to avoid sensing the entire system bandwidth at the maximum resolution.

One approach using the multi-resolution sensing techniques is described in [6] using an FFT-based energy detector. In addition to multi-resolution sensing, parallel sensing can be employed to further reduce the total sensing time. It requires multiple data-chains at the receiver and, hence, is amenable to multiple-antenna receivers. In the case of an *M* antenna receiver, the total sensing time is reduced by an approximate factor of *M*. This parallel approach to multiple resolution sensing has shown that for a large number of antennas, a smaller coarse resolution sensing bandwidth results in faster sensing times, whereas for a small number of antennas, a larger coarse resolution sensing bandwidth is preferred.

2.2.2 MRSS Sensing with wavelet

Another MRSS approach with less hardware efforts to implement (antennas and ADC blocks) relies on analog wideband spectrum sensing and reconfigurable RF front end [3]. In order to provide the multi-resolution sensing feature the wavelet transform was adopted. This type of transformation is applied to the input signal and the resulting coefficient values stand for the representation of the input signal's spectral contents with the given detection resolution. The spectral components of the incoming signal are then detected by the Fourier Transform performed in the analog domain. In this way, bandwidth, resolution and center frequency can be controlled by wavelet function. A block diagram of this sensing method is presented in figure 2. The building components are an analog wavelet waveform generator where the wavelet pulse is generated and modulated with I and Q sinusoidal carrier with the given frequency and a Hann window with 5 MHz bandwidth is selected as the wavelet. The received signal and the wavelet are multiplied using an analog multiplier. The analog integrator computes the correlation of the wavelet waveform with the given spectral width, i.e. the spectral sensing resolution and the resulting correlation with I and Q components of the wavelet waveforms are inputted to ADC where the values are digitized and recorded. If the correlation values are greater than a certain threshold level, the sensing scheme determines the reception of an interferer.

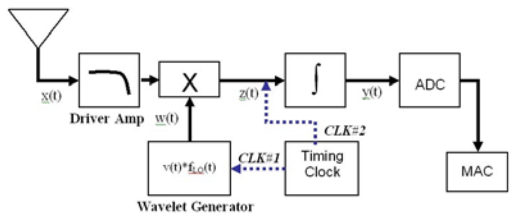

Figure 2: MRSS with analog wideband spectrum sensing

Since the analysis is performed in the analog domain, high-speed operation and low power consumption can be achieved. Furthermore, by applying the narrow wavelet pulse and a large tuning step size of the frequency of the local oscillator, the MRSS is able to examine a very wide spectrum span in the fast and sparse manner. On the contrary, very precise spectrum searching is realized with the wide wavelet pulse and the delicate adjusting of the local oscillator frequency. In this manner, by virtue of the scalable feature of the wavelet transform, multi-resolution is achieved without any additional digital hardware burdens.

The disadvantages of this sensing method consist in the difficulty of knowing the frequency information of received signals, which imply relatively complicated hardware comparing to FFT method.

2.3 Cyclostationary Feature Detector

Another method for the detection of primary signals is Cyclostationary Feature

Detection [4] in which modulated signals are coupled with sine wave carriers, pulse trains, repeated spreading, hopping sequences, or cyclic prefixes. These modulated signals are characterized as cyclostationary because their mean and autocorrelation exhibit periodicity, which is introduced in the signal format at the receiver so as to exploit it for parameter estimation such as carrier phase, timing or direction of arrival. These features are detected by analyzing a spectral correlation function, which has the main advantage that it differentiates noise from modulated signal energy due to the fact that noise is a wide-sense stationary signal with no correlation. The spectral correlation function (SCF) can be defined as:

$$S_x^{\alpha}(f) = \lim_{\tau\to\infty} \lim_{\Delta t\to\infty} \frac{1}{\Delta t} \int_{-\Delta t/2}^{\Delta t/2} \frac{1}{\tau} X_{\tau}(t, f+\alpha/2) X_{\tau}^{*}(t, f-\alpha/2) dt \tag{5}$$

Spectral correlation function is also known as cyclic spectrum. While power spectral density (PSD) is a real valued one-dimensional transform, SCF is a complex valued two-dimensional transform. The parameter α is called the cycle frequency and if $\alpha = 0$ then SCF gives the PSD of the signal. Because of the inherent spectral redundancy, signal selectivity becomes possible. Analysis of signal in this domain retains its phase and frequency information related to timing parameters of modulated signals. Due to this, overlapping features in power spectral density are non overlapping features in cyclic spectrum. Hence different types of modulated signals that have identical power spectral density can have different cyclic spectrum.

Figure 3: Block diagram of a cyclostationary feature detector

Implementation of a spectrum correlation function for cyclostationary feature detection is depicted in figure 3. It can be defined as an augmentation of the energy detector from figure 1 with a single correlator block. Detected features are number of signals, their modulation types, symbol rates and presence of interferers.

The cyclostationary detectors work in two stages. In the first stage the signal *x(k)*, that is transmitted over channel *h(k)*, has to be detected in presence of AWGN *n(k*). In the second stage, the received cyclic power spectrum is measured at specific cycle frequencies. The signal S_j is declared to be present if a spectral component is detected at corresponding cycle frequencies α_j.

$$S_x^{\alpha}(f) = \begin{cases} S_n^0(f), & \alpha = 0, \text{signal absent} \\ |H(f)|^2 S_s^0(f) + S_n^0(f), & \alpha = 0, \text{signal present} \\ 0, & \alpha \neq 0, \text{signal absent} \\ H(f+\frac{\alpha}{2}) H^{*}(f-\frac{\alpha}{2}) S_s^{\alpha}(f), & \alpha \neq 0, \text{signal present} \end{cases} \tag{6}$$

The advantages of the cyclostationary feature detection are robustness to noise, better detector performance even in low SNR regions, signal classification ability and operation flexibility because it can be used as an energy detector in $\alpha = 0$ mode. The disadvantage is a more complex processing than energy detection and therefore high speed sensing cannot be achieved. The method cannot be applied for unknown signals because an a priori knowledge of target signal characteristics is needed. Finally, at one time, only one signal can be detected: for multiple signal detection, multiple detectors have to be implemented or slow detection has be allowed.

2.4 Mixed Mode sensing schemes

Since cyclostationary feature detection is in a certain way complementary to the energy detection, performing better for narrow bands, a combined approach is suggested in [3], where energy detection could be used for wideband sensing and then, for each detected single channel, a feature detection could be applied in order to make the final decision whether the channel is occupied or not. Such a decisional architecture is presented in figure 4. First a coarse energy detection stage is performed over a wider frequency. Subsequently the presumed free channel is analyzed with the feature detector in order to take the decision.

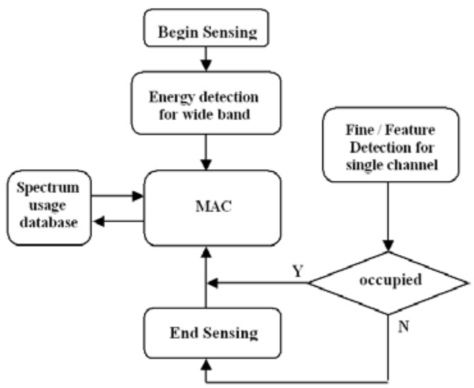

Figure 4. Combined decision scheme based on wideband energy detection with feature detection for a single channel

3. Cooperative Spectrum Sensing

Detection of primary user by the secondary system is critical in a cognitive radio environment and it is rendered more difficult due to the challenges in accurate and reliable sensing of the wireless environment. Secondary users might experience losses due to multipath fading, shadowing, and building penetration which can result in an incorrect judgment of the wireless environment, which can in turn cause interference at the licensed primary user by the secondary transmission. This arises the necessity for the cognitive radio to be highly robust to channel impairments and also to be able to detect extremely low power signals. These requirements pose a lot of challenges for building CR networks.

3.1 Cooperative techniques

High sensitivity requirements on the cognitive user can be alleviated if multiple CR users cooperate in sensing the channel. Various topologies are currently used [7], broadly classifiable into three regimes according to their level of cooperation.

Decentralized Uncoordinated Techniques: the cognitive users in the network don't have any kind of cooperation which means that each CR user will independently detect the channel, and if a CR user detects the primary user it would vacate the channel without informing the other users. Uncoordinated techniques are fallible in comparison with coordinated techniques. Therefore, CR users that experience bad channel realizations detect the channel incorrectly thereby causing interference at the primary receiver.

Centralized Coordinated Techniques: in these kinds of networks, an infrastructure deployment is assumed for the CR users. One CR that detects the presence of a primary transmitter or receiver informs a CR controller which can be a wired immobile device or another CR user. The CR controller notifies all the CR users in its range by means of a broadcast control message. Centralized schemes can be further classified in according to their level of cooperation into *Partially Cooperative* where networks nodes cooperate only in sensing the channel. CR users independently detect the channel inform the CR controller which then notifies all the CR users; and *Totally Cooperative Schemes* where nodes cooperate in relaying each others information in addition to cooperatively sensing the channel.

Decentralized Coordinated Techniques: this type of coordination implies building up a network of cognitive radios without having the need of a controller. Various algorithms have been proposed for the decentralized techniques, among which the gossiping algorithms [5], or clustering schemes [1] where cognitive users gather to clusters, auto-coordinating themselves.

The cooperative spectrum sensing raises the need for a control channel, which can be implemented as a dedicated frequency channel or as an underlay UWB channel. Wideband RF front-end tuners/filters can be shared between the UWB control channel and normal cognitive radio reception/transmission. For sharing the control channel bandwidth, a CSMA scheme may be applied. For a spread spectrum UWB control channel, different spreading sequencing could be allocated to different groups of users.

3.2 Benefits of cooperation

Cognitive users selflessly cooperating to sense the channel has a lot of benefits among which the **plummeting sensitivity**

requirements: channel impairments like multipath fading, shadowing and building penetration losses impose high sensitivity requirements inherently limited by cost and power requirements. Employing cooperation between nodes can drastically reduce the sensitivity requirements [7], up to -25 dBm reduction in sensitivity threshold were obtained by using this scheme; **agility improvement:** all topologies of cooperative networks reduce detection time compared to uncoordinated networks. However the totally cooperative centralized schemes have been shown to be most agile, over 35 % more compared tot the partially cooperative schemes [7].

3.3 Disadvantages of cooperation

Cooperative sensing in the aforementioned schemes is not trivial due to factors like **limited bandwidth:** CR users are low cost low power devices that might not have dedicated hardware for cooperation. Therefore data and cooperation information have to be multiplexed causing degradation of throughput for the cognitive user; **short timescales:** the CR user have to do sensing at periodic intervals as sensed information become obsolete fast due to factors like mobility, channel impairments etc. This considerably increases the data overhead; **large sensory data:** since the cognitive radio can potentially use any spectrum hole, it will have to scan a wide range of spectrum, resulting in large amounts of data, being inefficient in terms of data throughput, delay sensitivity requirements and energy consumption.

Even though cooperatively sensing data poses a lot of challenges, it could be carried out without incurring much overhead, because only approximate sensing information is required, eliminating the need for complex signal processing schemes at the receiver and reducing the data load. Also, even though a wide channel has to be scanned, only a portion of it changes at a time, requiring updating only the changed information and not the details of the entire scanned spectrum.

4. Conclusions

This paper presents an extensive analysis of the spectrum sensing techniques, an important issue for the development of the cognitive radio concept.

Besides the presented techniques, the authors are continuing the research on the topic of energy detection using Wavelet Packet Division Multiplexing (WPDM), a new and promising method for fast and reliable classification of unused spectrum, and an alternative method for transmitting and receiving signals simultaneously in one or more frequency bands.

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