Implementation Issues in Spectrum Sensing for Cognitive Radios

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Abstract- There are new system implementation challenges involved in the design of cognitive radios, which have both the ability to sense the spectral environment and the flexibility to adapt transmission parameters to maximize system capacity while co-existing with legacy wireless networks. The critical design problem is the need to process multi-gigahertz wide bandwidth and reliably detect presence of primary users. This places severe requirements on sensitivity, linearity, and dynamic range of the circuitry in the RF front-end. To improve radio sensitivity of the sensing function through processing gain we investigated three digital signal processing techniques: matched filtering, energy detection, and cyclostationary feature detection. Our analysis shows that cyclostationary feature detection has advantages due to its ability to differentiate modulated signals, interference and noise in low signal to noise ratios. In addition, to further improve the sensing reliability, the advantage of a MAC protocol that exploits cooperation among many cognitive users is investigated.

I. Introduction

It is commonly believed that there is a spectrum scarcity at frequencies that can be economically used for wireless communications. This concern has arisen from the intense competition for use of spectra at frequencies below 3 GHz. The Federal Communications Commission's (FCC) frequency allocation chart indicates overlapping allocations over all of the frequency bands, which reinforces the scarcity mindset. On the other hand, actual measurements taken in downtown Berkeley are believed to be typical and indicate low utilization, especially in the 3-6 MHz bands. Figure 1 shows the power spectral density (PSD) of the received 6 GHz wide signal collected for a span of 50μs sampled at 20 GS/s [12]. This view is supported by recent studies of the FCC's Spectrum Policy Task Force who reported [1] vast temporal and geographic variations in the usage of allocated spectrum with utilization ranging from 15% to 85%. In order to utilize these spectrum 'white spaces', the FCC has issued a Notice of Proposed Rule Making (NPRM – FCC 03-322 [2]) advancing Cognitive Radio (CR) technology as a candidate to implement negotiated or opportunistic spectrum sharing.

Wireless systems today are characterized by wasteful static spectrum allocations, fixed radio functions, and limited network coordination. Some systems in unlicensed frequency bands have achieved great spectrum efficiency, but are faced with increasing interference that limits network capacity and scalability. Cognitive radio systems offer the opportunity to use dynamic spectrum management techniques to help prevent interference, adapt to immediate local spectrum availability by creating time and location dependent in "virtual unlicensed bands", i.e. bands that are shared with primary users. Unique to cognitive radio operation is the requirement that the radio is able to sense the environment over huge swaths of spectrum and adapt to it since the radio does not have primary rights to any pre-assigned frequencies. This new radio functionality will involve the design of various analog, digital, and network processing techniques in order to meet challenging radio sensitivity requirements and wideband frequency agility.

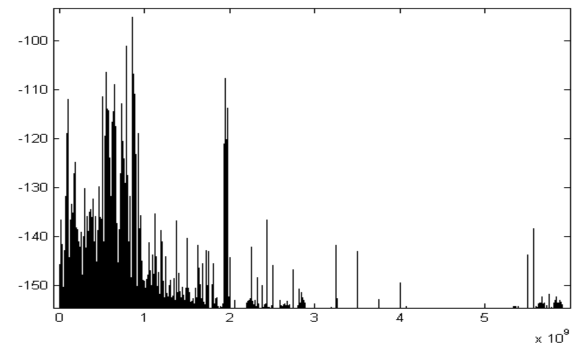


Figure 1. Measurement of 0-6 GHz spectrum utilization at BWRC

Spectrum sensing is best addressed as a cross-layer design problem. Cognitive radio sensitivity can be improved by enhancing radio RF front-end sensitivity, exploiting digital signal processing gain for specific primary user signal, and network cooperation where users share their spectrum sensing measurements.

The paper is organized as follows; Section II defines spectrum sensing function and proposes a cross-layer approach for its implementation. Section III considers RF front-end and A/D requirements for spectrum sensing and analog techniques for feasible implementations. In section IV we investigate digital signal processing techniques that can improve radio sensitivity and detect primary users' presence. Section V presents the results from a cooperative sensing scheme, achievable gains and implementation issues. Finally, conclusions are presented in Section VI.

II. Spectrum sensing

A "Cognitive Radio" is a radio that is able to sense the spectral environment over a wide frequency band and exploit this information to opportunistically provide wireless links that best meet the user communications requirements [2]. While many other characteristics have also been discussed as possible additional capabilities, we will use this more

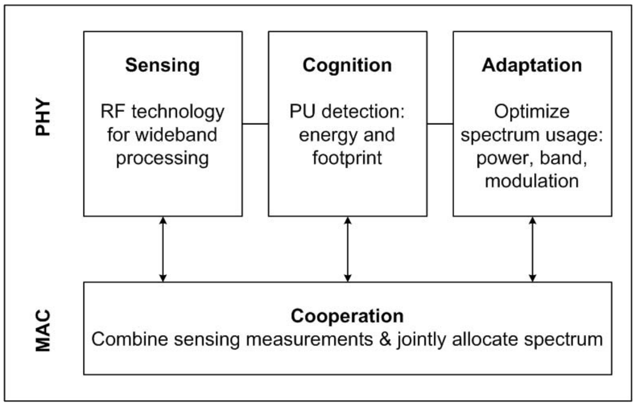


Figure 2. Cross layer functionalities related to spectrum sensing

restricted definition and consider physical (PHY) and medium access control (MAC) functions that are linked to spectrum sensing as illustrated in Figure 2.

Since cognitive radios are considered lower priority or secondary users of spectrum allocated to a primary user, a fundamental requirement is to avoid interference to potential primary users in their vicinity. On the other hand, primary user networks have no requirement to change their infrastructure for spectrum sharing with cognitive networks. Therefore, cognitive radios should be able to independently detect primary user presence through continuous spectrum sensing. Different classes of primary users would require different sensitivity and rate of sensing for the detection. For example, TV broadcast signals are much easer to detect than GPS signals, since the TV receivers' sensitivity is tens of dBs worse than GPS receiver.

In general, cognitive radio sensitivity should outperform primary user receiver by a large margin in order to prevent what is essentially a *hidden terminal problem*. This is the key issue that makes spectrum sensing very challenging research problem. Meeting the sensitivity requirement of each primary receiver with a wideband radio would be difficult enough, but the problem becomes even more challenging if the sensitivity requirement is raised by additional 30-40 dB. This margin is required because cognitive radio does not have a direct measurement of a channel between primary user receiver and transmitter and must base its decision on its local channel measurement to a primary user transmitter. This type of detection is referred to as *local spectrum sensing* and the worst case hidden terminal problem would occur when the cognitive radio is shadowed, in severe multipath fading, or inside buildings with high penetration loss while in a close neighborhood there is a primary user whose is at the marginal reception, due to its more favorable channel conditions. Even though the probability of this scenario is low, cognitive radio should not cause interference to such primary user.

The implementation of the spectrum sensing function also requires a high degree of flexibility since the radio environment is highly variable, both because of different types of primary user systems, propagation losses, and interference. The main design challenge is to define RF and analog architecture with right trade-offs between linearity, sampling rate, accuracy and power, so that digital signal processing techniques can be utilized for spectrum sensing, cognition, and adaptation. This also motivates research of signal processing techniques that can relax challenging requirements for analog, specifically wideband amplification, mixing and A/D conversion of over a GHz or more of bandwidth, and enhance overall radio sensitivity.

III. COGNITIVE RADIO FRONTEND

There are two frequency bands where the cognitive radios might operate in a near future: 400-800 MHz (UHF TV bands) and 3-10 GHz. The FCC has noted that in the lower UHF bands almost every geographical area has several unused 6 MHz wide TV channels. This frequency band is particularly appealing due to good propagation properties for long-range communications. Furthermore, given the static TV channel allocations, the timing requirements for spectrum sensing are very relaxed. The FCC approval of UWB underlay networks in 3-10 GHz indicates that this frequency range might be opened for opportunistic use. Furthermore, this band has very low spectral utilization, as indicated in Figure 1.

Regardless of operating frequency range, a wideband front-end for a cognitive radio could have an architecture as depicted in Figure 3. The wideband RF signal presented at the antenna of a cognitive radio includes signals from close and widely separated transmitters and from transmitters operating at widely different power levels and channel bandwidths. As a result, detection of weak signals must frequently be performed in the presence of very strong signals. Thus, there will be extremely stringent requirements placed on the linearity of the RF analog circuits as well as their ability to operate over wide bandwidths. In order to keep the requirements on the final analog to digital (A/D) converter at a reasonable level in a mostly digital architecture, front-end design needs a tunable notch analog processing block that would provide a dynamic range control.

Reducing the in-band interference to a manageable level is a critical design problem, since the traditional strategy of narrow band analog frequency selective filtering to avoid the wide dynamic range of interfering signals is not viable. The ultimate solution to this problem would involve a combination of techniques, including adaptive notch filtering such as employed in UWB designs, banks of on chip RF filters possibly using MEMS technology such as FBAR's, and spatial filtering using RF beam-forming through adaptive antenna

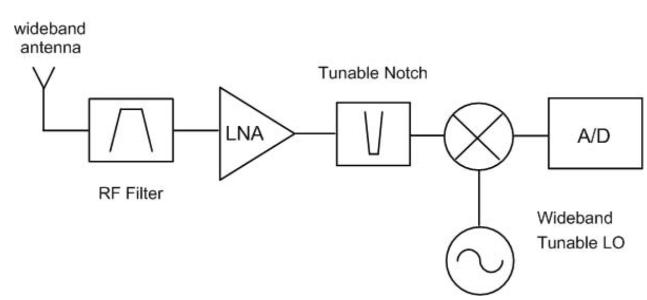


Figure 3. Wideband RF/analog front-end architecture for cognitive radio

arrays. Other more sophisticated approaches could involve active cancellation, because in the situation in which the interfering signal is extremely strong, it is then possible to decode the signal and provide an active canceling signal before the A/D conversion process. While the active cancellation approach will consume significantly more hardware, it has the important advantage of ultimately being more flexible.

The spatial dimension provides several new opportunities. The sensitivity of the sensing receiver can be increased by the exploitation of multiple antennas through diversity increase and range extension, which in effect could make it much more sensitive than the primary users which it is trying to detect.

IV. SIGNAL PROCESSING TECHNIQUES FOR SPECTRUM SENSING

A key advantage of CMOS integration is that digital signal processing can be used to assist the analog circuits. In case of spectrum sensing the need for signal processing is two-fold: improvement of radio front-end sensitivity by processing gain and primary user identification based on knowledge of the signal characteristics. In this section we discuss advantages and disadvantages of three techniques that are used in traditional systems: matched filter, energy detector and cyclostationary feature detector.

A. Matched Filter

The optimal way for any signal detection is a matched filter [4], since it maximizes received signal-to-noise ratio. However, a matched filter effectively requires demodulation of a primary user signal. This means 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. Such information might be pre-stored in CR memory, but the cumbersome part is that for demodulation it has to achieve coherency with primary user signal by performing 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 coherent detection. For examples: TV signal has narrowband pilot for audio and video carriers; CDMA systems have dedicated spreading codes for pilot and synchronization channels; OFDM packets have preambles for packet acquisition. The main advantage of matched filter is that due to coherency it requires less time to achieve high processing gain since only $O(1/SNR)$ samples are needed to meet a given probability of detection constraint [5]. However, a significant drawback of a matched filter is that a cognitive radio would need a dedicated receiver for every primary user class.

B. Energy Detector

One approach to simplify matched filtering approach is to perform non-coherent detection through energy detection. This sub-optimal technique has been extensively used in radiometry. An energy detector can be implemented similar to

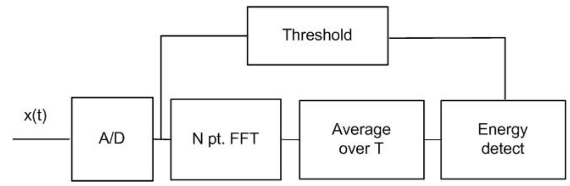


Figure 4. Implementation of an energy detector using Welch periodogram averaging

a spectrum analyzer by averaging frequency bins of a Fast Fourier Transform (FFT), as outlined in Figure 4 [3]. 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. However, due to non-coherent processing $O(1/SNR^2)$ samples are required to meet a probability of detection constraint [5].

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. Even if the threshold would be set adaptively, presence of any in-band interference would confuse the energy detector. 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: direct sequence and frequency hopping signals, for which more sophisticated signal processing algorithms need to be devised. In general, we could increase detector robustness by looking into a primary signal footprint such as modulation type, data rate, or other signal feature.

C. Cyclostationary Feature Detection

Modulated signals are in general coupled with sine wave carriers, pulse trains, repeating spreading, hoping sequences, or cyclic prefixes which result in built-in periodicity. Even though the data is a stationary random process, these modulated signals are characterized as *cyclostationary*, since their statistics, mean and autocorrelation, exhibit periodicity. This periodicity is typically introduced intentionally in the signal format so that a receiver can exploit it for: parameter estimation such as carrier phase, pulse timing, or direction of arrival. This can then be used for detection of a random signal with a particular modulation type in a background of noise and other modulated signals.

Common analysis of stationary random signals is based on autocorrelation function and power spectral density. On the other hand, cyclostationary signals exhibit correlation between widely separated spectral components due to spectral redundancy caused by periodicity [6]. By analogy with the

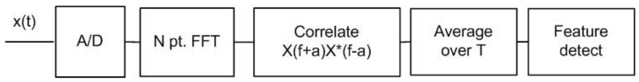


Figure 5. Implementation of a cyclostationary feature detector

definition of conventional autocorrelation, one can define spectral correlation function (SCF):

$$S_x^{\alpha}(f)=\lim_{T\to\infty}\lim_{\Delta t\to\infty}\frac{1}{\Delta t}\int_{-\Delta t/2}^{\Delta t/2}\frac{1}{T}X_T\left(t,f+\alpha/2\right)X_T^{*}\left(t,f-\alpha/2\right)dt \qquad (1)$$

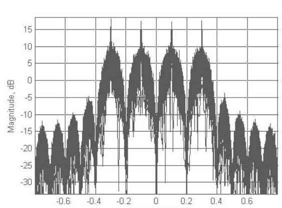
where finite time Fourier transform is given by:

$$X_T(t,v)=\int_{t-T/2}^{t+T/2}x(u)e^{-j2\pi vu}du \qquad (2)$$

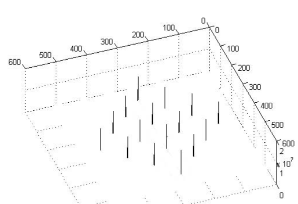
Spectral correlation function is also termed as *cyclic spectrum*. Unlike PSD which is real-valued one dimensional transform, the SCF is two dimensional transform, in general complex-valued and the parameter α is called cycle frequency. Power spectral density is a special case of a spectral correlation function for α=0.

The distinctive character of spectral redundancy makes signal selectivity possible. Signal analysis in cyclic spectrum domain preserves phase and frequency information related to timing parameters in modulated signals [6]. As a result, overlapping features in the power spectrum density are non-overlapping feature in the cyclic spectrum. Different types of modulated signals (such as BPSK, QPSK, SQPSK) that have identical power spectral density functions can have highly distinct spectral correlation functions. Furthermore, stationary noise and interference exhibit no spectral correlation.

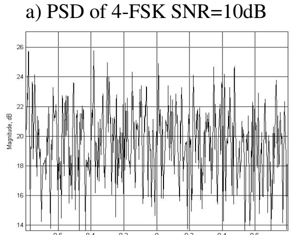
Implementation of a spectrum correlation function for cyclostationary feature detection is depicted in Figure 5. It can be designed as augmentation of the energy detector from Figure 4 with a single correlator block. Detected features are number of signals, their modulation types, symbol rates and presence of interferers. Figure 6 illustrates the advantages of cyclostationary detection versus energy detection for continuous phase 4-FSK modulated signals. Distinct pattern of 4-FSK modulation in a spectral correlation function is preserved even in low SNR=-20dB while energy detector is limited by the large noise.



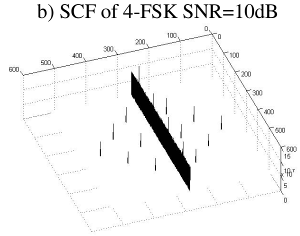
a) PSD of 4-FSK SNR=10dB



b) SCF of 4-FSK SNR=10dB



c) PSD of 4-FSK SNR=-20dB



d) SCF of 4-FSK SNR=-20dB

Figure 6. Detection of a continious-phase 4-FSK using energy detection and cyclostationary feature detection.

Signal processing techniques studied in this paper motivate the need to study other feature detection techniques that can improve sensing detection and recognize modulation, number and type of signals in a low SNR regimes.

V. Cooperative spectrum sensing

In previous sections we have reviewed RF and Digital Signal Processing techniques to increase the probability of primary user detection. The performance of these techniques is limited by received signal strength which may be severely degraded due to multipath fading and shadowing. Digital TV measurements report standard deviations of 2.0 to 4.0 for log-normal shadowing effects [8]. In such a scenario cooperative sensing may alleviate the problem of detecting the primary user by reducing the probability of interference to a primary user. In cooperative sensing we rely on the variability of signal strength at various locations. We expect that a large network of cognitive radios with sensing information exchanged between neighbors would have a better chance of detecting the primary user compared to individual sensing.

There are three main questions regarding cooperative sensing:

(a) How much can be gained from cooperation?
(b) How can cognitive radios cooperate?
(c) What is the overhead associated with cooperation?

To answer the first of these questions we designed a simulation environment where a group of cognitive radios attempt to detect a TV transmitter in the 700MHz band. Each radio may transmit if it decides (either individually or in cooperation with other users) that a primary user is not present. We do not assume any particular medium access scheme used by this radio group and are interested in the maximum interference caused by any potential cognitive radio transmitter.

Digital TV receivers are required to receive signals as low as -83 dBm without significant errors with a typical CNR of 15 dB [9, 10]. We assumed that any interference from the cognitive radio network would appear as white noise to the TV receiver and interference levels in the order of -98 dBm (minimum received signal – typical CNR = -83-15 = -98dBm) would significantly degrade receiver performance. We assumed a cognitive radio network spread out in a circle of radius 100m, located in a building 200m in height. Each radio can transmit with a power of 20dBm. The TV receiver was located at a height of 3m, 10 km from the radio network. This allowed us to use the standard Hata-Okumura model for suburban environments [11]. Each cognitive radio performs local sensing and decides on the presence of primary user using sensing results from a certain fraction of cognitive radios in the network. Figure 7 shows the probability of interference to the TV receiver from the cognitive radio network. The fraction of the network consulted by each cognitive radio is varied between 0 (no cooperation), 10% and 20%. From the figure we see a drastic reduction in probability of interference as the fraction of radios consulted is increased. A particularly noteworthy aspect is the reduction in probability of interference as the number of cognitive radios in the network is increased.

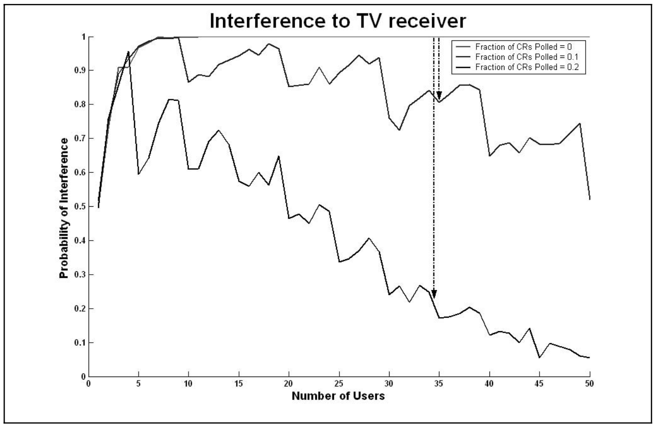


Figure7 Probability of Interference to TV receiver by a cognitive radio network with individual sensing and cooperative decision making

While we can minimize interference to the primary receiver by never transmitting, more sophisticated cooperation schemes have to be designed to achieve optimal tradeoff between network capacity and probability of interference. In [7] a centralized network is proposed where the access point collects sensing results from all users. The access point sounds the channel and then performs channel allocation so as to meet the requested data rates of each user. The overhead associated with this scheme is in providing sensing results to the access point every time the channel conditions change. If channel coherency time is small, increment updates need to be performed so as to reduce bandwidth requirements on the control channel. A distributed cooperation scheme (as used in the simulation environment presented in Figure 7) where neighbors are chosen randomly may be easier to implement but may not achieve the capacity of the centralized scheme.

One of the problems in cooperation is in combining the results of various users which may have different sensitivities and sensing times. Some form of weighted combining needs to be performed in order to take this into account.

Cooperation also introduces the need for a control channel. A control channel can either be implemented as a dedicated frequency channel or as an underlay UWB channel. Wideband RF frontend tuners/filters can be shared between the UWB control channel and normal cognitive radio reception/transmission. Furthermore, with multiple cognitive radio groups active simultaneously, the control channel bandwidth needs to be shared. With a dedicated frequency band, a CSMA scheme may be desirable. For a spread spectrum UWB control channel, different spreading sequencing could be allocated to different groups of users.

VI. Conclusion

In the paper, we explore the new field of cognitive radios with a special emphasis on one unique aspect of these radios - spectrum sensing. We motivate the strong need for sophisticated sensing techniques and established sensing to be a cross-layer function. Firstly, we identify two key issues related to the cognitive radio frontend - dynamic range reduction and wideband frequency agility. Primary user detection can be further improved by advanced feature detection schemes like cyclostationary detectors which utilize the inherent periodicity of modulated signals. Further, individual sensing is not adequate for reliable detection of primary users due to shadowing and multipath effects. In such a case cooperative decision making is the key to reducing the probability of interference to primary users.

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