Physical Layer Design Issues Unique to Cognitive Radio Systems

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Abstract- **Cognitive radio systems offer the opportunity to improve spectrum utilization by detecting unoccupied spectrum bands and adapting the transmission to those bands while avoiding the interference to primary users. This novel approach to spectrum access introduces unique functions at the physical layer: reliable detection of primary users and adaptive transmission over a wide bandwidth. In this paper, we address design issues involved in an implementation of these functions that could limit their performance or even make them infeasible. The critical design problem at the receiver is to achieve stringent requirements on radio sensitivity and perform signal processing to detect weak signals received by a wideband RF front-end with limited dynamic range. At the transmitter, wideband modulation schemes require adaptation to different frequency bands and power levels without creating interference to active primary users. We introduce algorithms and techniques whose implementation could meet these challenging requirements.**

I. INTRODUCTION

It is commonly believed that there is a crisis of spectrum availability at frequencies that can be economically used for wireless communications. This misconception is strengthened by a look at the FCC frequency chart [1] that indicates multiple allocations over all of the frequency bands. As a result, there is fierce competition for the use of spectra, especially in the bands below 3 GHz. However, actual measurements taken in an urban setting reveal a typical utilization of 0.5% in the 3-4 GHz frequency band [2]. The utilization drops to 0.3% in the 4-5 GHz band. Thus, we actually have spectrum abundance, and the spectrum shortage is in partially an artifact of the regulatory and licensing process.

The current approach for spectrum sharing is regulated so that wireless systems are assigned fixed spectrum allocations, operating frequencies and bandwidths, with constraints on power emission that limits their range. Therefore, most communications systems are designed so that they achieve the best possible spectrum efficiency within the assigned bandwidth using sophisticated modulation, coding, multiple antennas and other techniques. The most advanced systems are approaching Shannon's channel capacity limit [3], so further increase in capacity would require additional system bandwidth. On the other hand, the discrepancy between spectrum allocation and spectrum use suggests that this spectrum shortage could be overcome by allowing more flexible usage of a spectrum. Flexibility would mean that radios could find and adapt to any immediate local spectrum availability. A new class of radios that is able to reliably sense the spectral environment over a wide bandwidth, detect the presence/absence of legacy users (primary users) and use the spectrum only if the communication does not interfere with primary users is defined by term *cognitive radio* [4].

Cognitive radios could provide a paradigm shift in the way that spectra is regulated and used. However, the novelty of this approach makes it difficult to leverage the experience of present wireless systems. There are many challenges across all layers of a cognitive radio system design, from its application to its implementation. A systematic framework for a cognitive radio system design needs to be addressed at the very early stage, so that system functions, models, and requirements can have corresponding metrics and that key questions could be addressed across a larger research community.

This paper presents some design issues of unique physical layer functions inside a wideband cognitive radio including radio RF/analog front-end, sampling circuits, and digital signal processing. The main focus is on the core functionality for cognitive approach to spectrum access: 1) reliable sensing of spectrum environment for primary user detection; 2) adaptive transmission in wide bandwidths without causing interference to any primary user. In addition, algorithms addressing hardware implementations for these unique functions are proposed together with metrics for their evaluation.

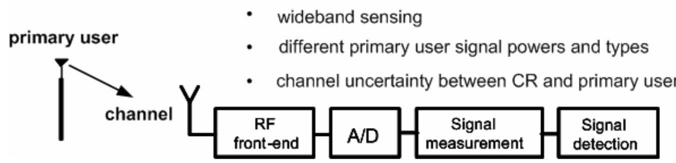
The paper is organized as follows: Section II defines unique physical layer functions of interest and introduces main challenges in their implementation. Section III discusses issues involved in algorithms and architectures for reliable detection of weak primary user signals. Section IV addresses a modulation scheme for cognitive radio wideband transmission.

II. UNIQUE PHYSICAL LAYER FUNCTIONS

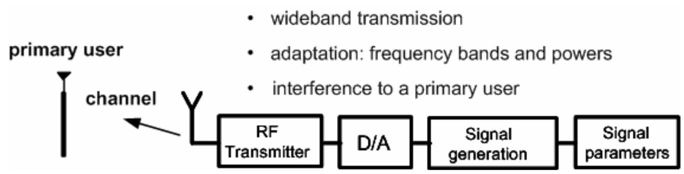
Conventional communications systems are defined and standardized using seven ISO/OSI layers, where physical layer functions realize signaling for the specific medium. Physical layer functions are interfaced with a data/link layer through a handshaking protocol. Even though cognitive radios are quite different from traditional wireless radios, it is reasonable to assume that a cognitive radio framework would be based on ISO/OSI layering methodology. A further advantage of layering approach could be to leverage a cognitive radio system design by enhancing existing layers of conventional radios with unique cognitive functionalities. First and foremost, one should start from cognitive functions on a physical layer in order to understand capabilities and limitations of their implementation so that upper layers can be designed using realistic models.

Cognitive radio communication is strictly conditional on the reliable detection of unoccupied spectrum. This requirement establishes a new type of functionality on the physical layer for spectrum sensing over all available degrees of freedom (time, frequency, and space) in order to identify frequency bands currently available for transmission. The key challenge of spectrum sensing is the detection of weak signals in noise with a very small probability of miss detection. Spectrum sensing requires the radio to receive a wideband signal through an RF front-end, sample it by high speed analog-to-digital (A/D) converter, and perform measurements for detection of primary user signals, as illustrated in Figure 1a. The challenges in spectrum sensing are: 1) achieving sufficient RF front-end sensitivity for wideband signals; 2) accurately detecting dissimilar, frequency band dependent, primary signals at differing received power levels.

After identifying an available spectrum segment, a cognitive radio should use modulation schemes that provide best spectrum utilization and capacity while avoiding interference to any primary user. Furthermore, the desired transmission scheme should be flexible to allow assignments of any band to any user, and should be scalable with the number of users and bands. In the ideal case, this flexible wideband transmission would be realized by digital domain waveform synthesis, where a set of parameters specifies transmission bands and power control. Figure 1.b illustrates the top-level architecture of a wideband transmitter. The main challenge is to create a signal that, without external analog filters, adaptively changes the occupied bandwidth and without causing interference to any active primary users.



(a) Cognitive radio receiver



(b) Cognitive radio transmitter

Figure 1. System issues in unique cognitive radio physical layer functions

III. RELIABLE DETECTION OF PRIMARY USER SIGNALS

The importance of reliable detection of primary users is two fold: 1) it ensures that cognitive radios would not interfere with primary users, which permits secondary use of their spectrum; 2) creates spectrum opportunities for capacity increase of cognitive networks. In order to realize this function, cognitive radios must have significantly better sensitivity and wideband frequency agility than conventional radios [2]. Therefore, an implementation of spectrum sensing requires novel designs of not only wideband RF/analog circuits, but also digital signal processing and network cooperation techniques in order to meet such challenging requirements. In the next sections, we discuss the critical design issues in wideband sensing RF front-end and digital signal processing required to provide reliable detection of weak primary user signals in the presence of large noise or interferers.

A. *Wideband Sensing Front-end*

Figure 2 shows an architecture of wideband RF front-end capable of simultaneous sensing of several GHz wide spectrum. This architecture is commonly proposed for software-defined radios [5]. The wideband RF signal presented at the antenna of such a front-end includes signals from close and widely separated transmitters, and from transmitters operating at widely different power levels and channel bandwidths. One of the main limitations in a radio front-end's ability to detect small signals is its dynamic range, which also dictates the requirement for number of bits in analog-to-digital (A/D) converter. The wideband sensing requires multi-GHz speed A/D converters, which together with high resolution (of 12 or more bits) might be infeasible [6]. Therefore, reducing the strong in-band primary user signals, which are of no interest to detect, is necessary to receive and process weak signals. Commonly, this reduction would be achieved by filtering a strong signal through a notch filter. However, in the wideband implementation, strong primary user signals can be located anywhere in the frequency band requiring tunable filters, which might be too complex to implement.

An alternative approach for dynamic range reduction would be to filter a signal in the spatial domain rather than in the frequency domain using multiple antennas. This idea is inspired by recent theoretical work on multiple antenna channels identifying that spatially received signals occupy a limited number of directions or spatial clusters [7]. Therefore, signals can be selectively received or suppressed using antenna arrays through beamforming techniques [8]. In this application, signals received from multiple antennas must be

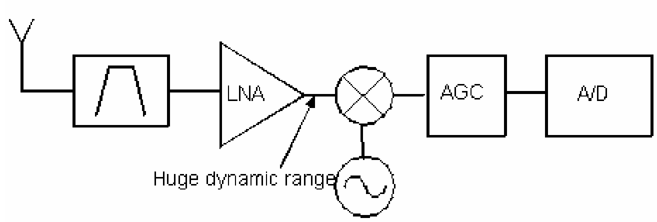


Figure 2. Wideband cognitive radio RF front-end

combined before the A/D converter. As a result, multiple antenna processing must be done in the analog domain before the automatic gain control circuits that would properly amplify reduced dynamic range signal for the best utilization of number of bits in the A/D converter.

The architecture of the wideband RF front-end, enhanced with an antenna array for spatial filtering, is presented in Figure 3. This architecture could be implemented as a phased antenna array where the antenna array coefficients are computed in the digital domain and fed back to adjust the gains and phases of the antenna elements. A simple algorithm for computation of coefficients could be derived by noticing that strong primary users occupy distinct frequency bands and spatial directions of arrival. By applying an FFT on a wideband signal at the output of the A/D, a power profile in frequency domain is measured. In order to obtain the estimate of angles of arrivals, the antenna array coefficients must sweep through many directions. Given M antenna elements, any set of $K>M$ independent array coefficients is sufficient to obtain the estimation of spatial distribution. Let set of K array coefficients be denoted as:

$$A = [\underline{a}(1)^T \ \underline{a}(2)^T \ldots \underline{a}(K)^T]_{MxK} \tag{1}$$

$$\underline{a}(k) = \left[a_1(k) a_2(k) \ldots a_M(k)\right] \tag{2}$$

where $a_i(k)$ is the coefficient for the *ith* antenna in the *kth* sweep. The output of the FFT for frequency f in *kth* sweep is:

$$Y(f,k) = \underline{a}^T(k)\underline{X}(f) + w(f,k) \tag{3}$$

where X is the wideband input, and w is the wideband noise.

After receiving K different directions, vector of received signals corresponding to a primary user at frequency f is:

$$\overline{Y}(f) = A\underline{X}(f) + \overline{w}(f) \tag{4}$$

By applying the Least Squares estimation, directions of primary users signals can be computed as:

$$\hat{\underline{X}}(f) \text{ s.t. } \min \left\| \overline{Y}(f) - A\underline{X}(f) \right\|^2 \tag{5}$$

$$\hat{\underline{X}}(f) = (A^* A)^{-1} A^* \overline{Y}(f) \tag{6}$$

In order to solve for optimal coefficients that provide dynamic range reduction, the algorithm selects M strongest signals in the frequency domain and then solves the equation:

$$\underline{a}_{opt}{}^T [\hat{\underline{X}}(f_1) \ \hat{\underline{X}}(f_2) \ldots \hat{\underline{X}}(f_M)] = \underline{C} \tag{7}$$

where $\underline{C}$ is a vector of constraints on the received power set by the desired dynamic range reduction quantity.

Figure 4 shows the outlined algorithm performance for the case of two strong primary users whose power is 30-40 dB larger than average power in other frequency bands. After the optimal coefficients are applied, the dynamic range reduces by approximately 22 dB (saving 3-4 bits in A/D converter resolution) using a 4-element antenna array. This preliminary analysis shows that spatial filtering techniques could relax requirements for the implementation of RF wideband sensing front-end.

B. Primary User Signal Detectors

After reliable reception and sampling of a wideband signal, digital signal processing techniques should be utilized to further increase radio sensitivity by processing gain, and for primary user identification based on knowledge of the signal characteristics. Three detection techniques are considered in this paper: a matched filter, an energy detector [2], and a cyclostationary feature detector [9]. In order to identify the most suitable candidate, we compare and contrast them using the following metrics: processing gain required for a given probability of detection, sensitivity to unknown noise and interference, and implementation complexity.

A matched filter is the optimal detector in a sense that it can also demodulate signals due to coherent signal processing. The processing gain is linearly proportional to the number of samples N: $SNR_{out}=N{\cdot}SNR_{in}$. However, its implementation complexity is prohibitively large since the cognitive radio would have to have a separate matched filter based receiver for every primary user system.

An energy detector is the sub-optimal detector due to non-coherent signal processing, which only integrates squared samples. The processing gain is $SNR_{out}=N{\cdot}SNR_{in}^2$ which in case of a very small SNR_{in} becomes significantly inferior to the matched filter due to quadratic scaling. The signal is detected by comparing the output of the energy detector with a

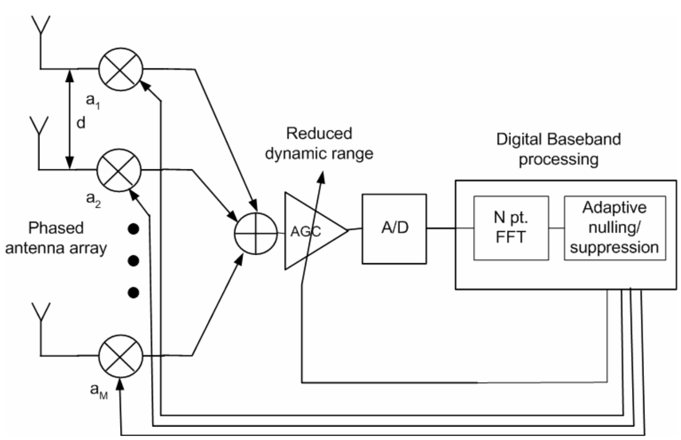
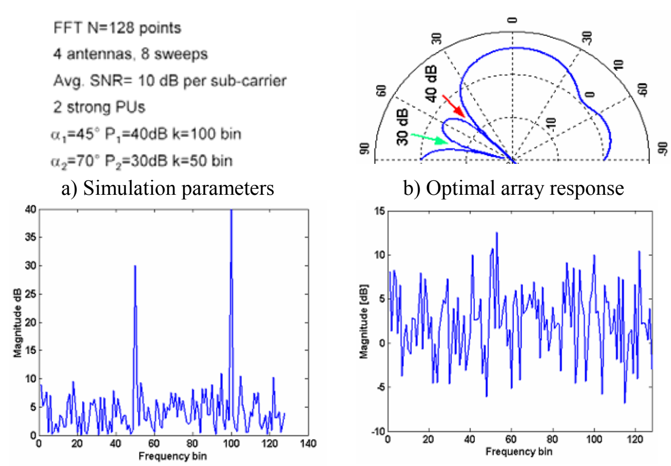


Figure 3.Wideband RF front-end with antenna array for spatial filtering



a) Simulation parameters b) Optimal array response

c) Large dynamic range signal d) Spatially filtered signal

Figure 4. An example of dynamic range reduction using antenna arrays

threshold dependent on the estimated noise power. As a result, a small estimation error in the noise power causes significant performance loss of the energy detector [10]. At low SNRs of interest, the energy detector completely fails in the detection of weak signals. Even though the implementation simplicity of the energy detector makes it a favorable candidate, the requirement to estimate the noise power of the actual RF transceiver within a fraction of a dB would be difficult to achieve. In practice, it would require a calibration of noise figure and gains of a wideband RF front-end across whole frequency range.

Cyclostationary feature detectors have the ability to extract distinct features of modulated signals such as sine wave carrier, symbol rate, and modulation type. These features are detected by analyzing a spectral correlation function that is a two-dimensional transform, in contrast with power spectrum density being one dimensional transform. The main advantage of the spectral correlation function is that it discriminates the noise energy from modulated signal energy. This property is a result of the fact that noise is a wide-sense stationary signal with no correlation, while modulated signals are cyclostationary with spectral correlation due to embedded redundancy of signal periodicities. Therefore, a cyclostationary feature detector is a better than energy detector in discriminating against noise due to its robustness to unknown noise variance. Its implementation complexity increases by N^2 complex multiplications due to the needed to compute the cross-correlation of the N point FFT outputs. On the other hand, the energy detector has complexity of N point FFT [2].

IV. WIDEBAND TRANSMISSION

After reliable detection, a cognitive radio should use transmission schemes that provide the best spectrum utilization and capacity. There are several unique requirements that a modulation scheme should provide. First, spectrum bands available for transmission could be spread over a wide frequency range, with variable bandwidths and band separations, as illustrated in Figure 5. The unoccupied spectrum distribution is a function of geographic location and time of usage, and it is updated after every spectrum sensing period. Secondly, for optimal spectrum and power efficiency every cognitive radio estimates the quality of unoccupied frequencies in order to provide higher layers with signal-to-noise measurements to be used for power and bit allocation. Lastly, different applications might require selection of

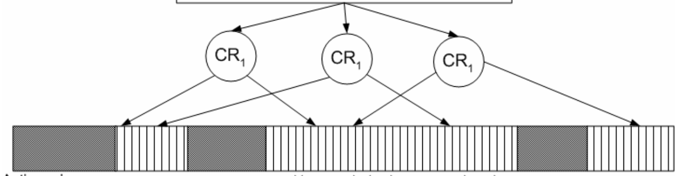


Figure 5. Cognitive radio wideband spectrum access

frequency bands based on propagation characteristics or interference measurements. Therefore, the transmission scheme should allow assignments of any frequency band to any cognitive user, and should be scalable with the number of users and bands. In order to keep the cognitive receiver demodulator fairly simple, it is desirable to restrict a single user transmission in a single frequency band. This constraint could be further justified by reduced transmission power of a single user rather than additive transmission power of many users, which would potentially cause interference to the active primary user in the vicinity.

The modulation scheme based on orthogonal frequency division multiplexing (OFDM) is a natural approach that might satisfy desired properties. OFDM has become the modulation of choice in many broadband systems due to its inherent multiple access mechanism and simplicity in channel equalization, plus benefits of frequency diversity and coding [11]. The transmitted OFDM waveform is generated by applying an inverse fast Fourier transform (IFFT) on a vector of data, where number of points N determines the number of sub-carriers for independent channel use, and minimum resolution channel bandwidth is determined by W/N, where W is the entire frequency band accessible by any cognitive user. The frequency domain characteristics of the transmitted signal are determined by the assignment of non-zero data to IFFT inputs corresponding to sub-carriers to be used by a particular cognitive user. Similarly, the assignment of zeros corresponds to channels not permitted to use due to primary user presence or channels used by other cognitive users. The output of the IFFT processor contains N samples that are passed through a digital-to-analog converter producing the wideband waveform of bandwidth W. A great advantage of this approach is that the entire wideband signal generation is performed in the digital domain, instead of multiple filters and synthesizers required for the signal processing in analog domain.

From the cognitive network perspective, OFDM spectrum access is scalable while keeping users orthogonal and non-interfering, provided the synchronized channel access. However, this conventional OFDM scheme does not provide truly band-limited signals due to spectral leakage caused by sinc-pulse shaped transmission resulted from the IFFT operation [12]. The slow decay of the sinc-pulse waveform, with first sidelobe attenuated by only 13.6dB, produces interference to the adjacent band primary users which is proportional to the power allocated to the cognitive user on the corresponding adjacent sub-carrier. Therefore, a conventional OFDM access scheme is not an acceptable candidate for wideband cognitive radio transmission.

In order to provide protection to adjacent primary user bands, it is necessary to understand the performance of primary user receivers. Due to the inevitable need for frequency reuse, every primary receiver is designed to tolerate a limited amount of co-channel interference as well as adjacent channel interference. There are so called desired-to-undesired ratios or reference interference ratios for co-channel and adjacent channel interferers, usually specified for the reference sensitivity levels [13][14]. Therefore, the spectral leakage of the OFDM waveform can be optimized to satisfy these interference constraints.

The interference optimization would require two stages. First, it is necessary to measure the received signal power of a primary receiver in the adjacent band since the interference constraints are referenced to it. This power measurement could be obtained from the spectrum sensing, and used to create transmit power mask for the cognitive radio transmitter. Then, the spectrum of the OFDM signal generator needs to be shaped to fit the spectrum mask.

There are several spectrum shaping techniques that could be used to improve OFDM spectral leakage:

- Introducing guard bands
- Windowing
- Power control per sub-carrier

Introducing guard bands would assign more sub-carriers to zero, thus resulting in significant power loss and inefficient spectrum use. Its only benefit would be preserved user/channel orthogonality. Windowing techniques [15] would pre-filter each sub-carrier to reduce the sidelobes, but would also introduce power loss. The main disadvantages of the windowing approach are the increased complexity due to additional filtering and potential loss of orthogonality. The third option is to assign independent power constraints for each sub-carrier and optimally fit the spectrum mask. This approach would preserve all benefits of OFDM transmission without sacrificing spectrum utilization.

In order to quantitatively compare these three approaches under constraints of number of sub-carriers N and sub-carrier spacing we define the following metrics:

Sum Capacity:

$$C = \sum_{i=1}^{N} A_i \log\left(1 + \frac{|h_i|^2 p_i}{N_0}\right) \quad \text{for} \quad p_i \le P_i \tag{8}$$

Spectrum utilization: $\frac{1}{N}\sum_{i=1}^{N} A_i$ (9)

Power efficiency: $\sum_{i=1}^{N} A_i p_i$ (10)

where $A_i=1$ if sub-carrier i is permitted to use and $A_i=0$ if sub-carrier i is not permitted to use. P_i is the power constraint, p_i is the power assignment, and h_i is the channel gain of the *i-th* sub-carrier. N_0 is the additive white noise power.

It is expected that understanding the trade-offs between these metrics for the approaches outlined above would provide the answer if the OFDM-like scheme is a good candidate for wideband cognitive radio transmission.

V. Conclusion

This paper presents some unique design issues encountered in a physical layer design of cognitive radios. First, we consider the implementation of the core functionality to reliably detect primary user signals through spectrum sensing. This function requires a wideband RF front-end and signal processing to meet stringent requirements on radio sensitivity. One of the most challenging circuits in its implementation is the A/D converter required to sample wideband signal with potentially large dynamic range. The specifications for both high speed and high resolution might be unachievable; therefore it is necessary to reduce the dynamic range of the signal before A/D conversion. We propose an algorithm and architecture that spatially filters strong signals and provides a reduced dynamic range signal at the input of the A/D converter.

For primary user signal detection, we compared three different signal processing techniques. Our comparison revealed that cyclostationary feature detectors have the best performance versus implementation complexity trade-off. However, performance characterization through experiments would provide better insight into detectors robustness to unknown noise and other RF front-end impairments.

For the cognitive radio transmission scheme, the approach of using orthogonal frequency division multiplexing (OFDM) is investigated. It was found that a conventional OFDM scheme is not acceptable due to out-of-band emission caused by spectral leakage that would cause interference in adjacent primary user bands. Power control and spectrum shaping techniques are proposed to augment the OFDM transmitter to create an interference free wideband modulated waveform.

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