

Utilizing OFDM Guard Interval for Spectrum Sensing

Nilesh Khambekar
Department of Computer Science
Wayne State University
Detroit, Michigan 48202
Email: nilesh@wayne.edu

Liang Dong
Department of Electrical and
Computer Engineering
Western Michigan University
Kalamazoo, Michigan 49008

Vipin Chaudhary
Department of Computer
Science and Engineering
University at Buffalo, SUNY
Buffalo, New York 14260-2000

Abstract—Spectrum sensing is crucial for dynamic spectrum management systems. In this paper, we propose a scheme that utilizes the guard interval of OFDM symbol at the transmitter for spectrum sensing. The cyclic prefix is not inserted in the guard interval at the transmitter, whereas the circulant convolution is secured at the OFDM receiver through the proposed mechanism. Simulation results show that the scheme can be implemented with no impact on the BER under various channel conditions, and detection of incumbent DTV signal is possible in the OFDM guard interval. In addition, we develop enhancements to the circulant convolution preserving mechanism for handling the transceiver imperfections in practice.

I. INTRODUCTION

IEEE 802.22 workgroup is currently investigating the secondary usage of UHF TV channels to provide broadband access in rural and remote areas. Spectrum sensing is the vital task for secondary spectrum usage and future dynamic spectrum management systems [1]. With spectrum sensing, idle spectral ranges can be identified and efficiently used. This approach has motivated opportunistic, secondary and open type of spectrum access based on the cognitive radio [2].

Spectrum sensing techniques [3] include matched filtering, energy detection, cyclostationary feature detection and signal specific feature detection schemes. Secondary users need to ensure higher probability of detection (90%) and lower probability of false detection (10%) [4]. Sensing method needs to be chosen depending on SNR, spectral bandwidth to scan, computational complexity and minimal scanning time to meet the specified sensing accuracy. Sensing frequency is also an important design parameter and is dependent on the maximum allowable interference duration.

This paper focuses on inband channel sensing by integrating the spectrum sensing functionality within OFDM transmission. OFDM PHY is preferred in the development of broadband wireless access technologies. It offers low complexity transceiver design, higher spectrum efficiency, and robustness in the presence of multipath radio propagation.

We have developed a sensing strategy wherein sensing duration is comparable with OFDM guard interval. Broadband channels have delay spread typically in the range of 0-20 microseconds [5]. Secondary user in 802.22 system could utilize this period for the detection of primary users namely DTV and Part 74 microphone devices.

Cordeiro *et al.* [6] outlined the challenges in the design of PHY and MAC layer for 802.22 air interface. Han *et al.* [7] have applied spectral correlation to detect 802.22 primary users exploiting second order cyclostationarity. IEEE 802.22 group is working on allocating quiet period for spectrum sensing. One of the proposals [8] suggests using quiet bursts for spectrum sensing. During the quiet burst, some OFDM symbols in the sub-frames can be replaced by the sensing period. Another suggestion from the same source [8] utilizes the proposed downlink-uplink switching time for spectrum sensing. This sensing interval is however asynchronous and the length of the sensing interval varies with distance from WRAN base-station. We propose a scheme to use the guard interval of OFDM symbol for spectrum sensing. This scheme is generic and does not depend on distance from the base-station. This scheme can detect primary users much quicker due to very high frequency of spectrum sensing. Most importantly, explicit sensing interval need not be allocated and thus it does not affect spectrum utilization.

In this scheme, an idle OFDM guard interval is achieved by not inserting the cyclic prefix in the guard interval. We provide a way of securing the circulant convolution in the received OFDM symbol for avoiding the intercarrier interference (ICI) at the receiver.

This paper is organized as follows. OFDM and air interface model are described in Section II. Section III describes the scheme to utilize OFDM guard interval for spectrum sensing and explains the receiver side algorithm for preserving circulant convolution. In Section IV, we present evaluations of the proposed mechanism under various channel conditions. Transmitter spectrum sensing using cyclostationarity is described in Section V. In Section VI, we address practical imperfections and measures to reduce transceiver complexity. Finally, Conclusions are given in Section VII.

II. SYSTEM MODEL

In OFDM systems, blocks of samples are transmitted as OFDM symbols. Assume that the block size equals to N , the i th block can be written as

$$\mathbf{s}_i = [s_i(0), s_i(1), \dots, s_i(N-1)]^T \quad (1)$$

Each block of samples is passed through the inverse discrete Fourier transform (IDFT) operation before transmission

$$\mathbf{x}_i = \mathbf{F}\mathbf{s}_i \quad (2)$$

where \mathbf{F} is the unitary discrete Fourier transform (DFT) matrix. An FIR model with L taps is assumed for the channel, i.e.

$$\mathbf{h} = [h_0, h_1, \dots, h_{L-1}]^T \quad (3)$$

At the receiver, the received samples corresponding to the transmitted block \mathbf{x}_i , are collected into a vector \mathbf{r}_i . The received $N + L - 1$ samples are connected to transmitted symbols by following equation

$$\mathbf{r}_i = \underbrace{\begin{bmatrix} h_0 & 0 & \cdots & 0 \\ h_1 & h_0 & \cdots & 0 \\ \vdots & h_1 & \ddots & \vdots \\ h_{L-2} & \vdots & & \\ h_{L-1} & h_{L-2} & & \vdots \\ 0 & h_{L-1} & & \\ 0 & 0 & & \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & h_{L-2} \\ 0 & 0 & \cdots & h_{L-1} \end{bmatrix}}_{\mathbf{C}} \mathbf{x}_i + \mathbf{w} \quad (4)$$

The size of channel matrix \mathbf{C} is $(N + L - 1) \times N$ and \mathbf{w} is an additive white noise Gaussian noise (AWGN) vector. A cyclic prefix of length P is added to each transformed block of data and then transmitted through the channel. $L \leq P$, in order to preserve the orthogonality between tones. The the received samples at the P cyclic prefix positions are removed at the receiver.

Since the symbol is cyclically prefixed, the resulting convolution appears as circulant convolution. Circulant convolution guarantees orthogonality of sub-carriers. Therefore no ICI is presented after FFT and equalization is a scalar multiplication in the frequency domain.

III. SECURING CYCLIC CONVOLUTION IN RECEPTION

If cyclic prefix is not inserted in the guard interval, received symbol represents linear convolution and ICI is seen after FFT operation by the receiver.

We partition the channel matrix \mathbf{C} into two matrices with dimensions $N \times N$ and $(L - 1) \times N$, respectively. The first matrix represents the channel seen by the i^{th} OFDM symbol.

$$\mathbf{C}_S = \begin{bmatrix} h_0 & 0 & \cdots & \cdots & \cdots & 0 \\ \vdots & \ddots & \ddots & & & \vdots \\ h_{L-1} & \cdots & h_0 & & & \vdots \\ 0 & h_{L-1} & \cdots & h_0 & \ddots & \vdots \\ \vdots & \ddots & \ddots & & \ddots & 0 \\ 0 & \cdots & 0 & h_{L-1} & \cdots & h_0 \end{bmatrix} \quad (5)$$

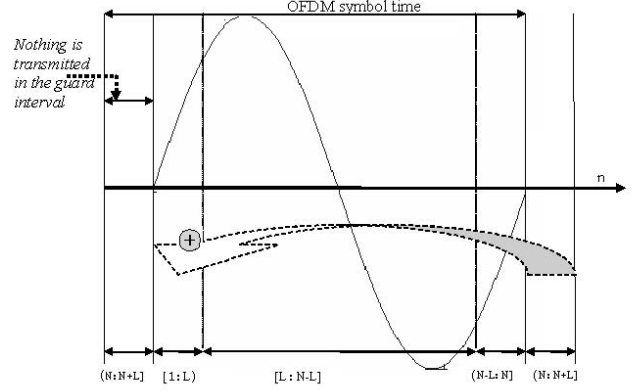


Fig. 1. Scheme for preserving circulant convolution.

The second matrix represents the tail end of the channel's impulse response that generates ISI in the succeeding symbol.

$$\mathbf{C}'_T = \begin{bmatrix} 0 & 0 & \cdots & h_{L-1} & \cdots & h_1 \\ \vdots & & & \ddots & \ddots & \vdots \\ 0 & 0 & \cdots & \cdots & 0 & h_{L-1} \end{bmatrix} \quad (6)$$

Padding an $(N - L + 1) \times N$ zero matrix to \mathbf{C}'_T to make it an $N \times N$ matrix

$$\mathbf{C}_T = \begin{bmatrix} \mathbf{C}'_T \\ \mathbf{0} \end{bmatrix} \quad (7)$$

Matrices \mathbf{C}_S and \mathbf{C}_T have the property that

$$\mathbf{C}_S + \mathbf{C}_T = \mathbf{C}_{\text{cyclic}} \quad (8)$$

where $\mathbf{C}_{\text{cyclic}}$ is the channel matrix desired for avoiding ICI.

We exploit this property to preserve circulant convolution even when cyclic prefix is not inserted in the guard interval. The scheme is shown in Fig. 1.

The data received with length N , starting from the beginning of the received OFDM symbol block, is given by

$$\mathbf{r}_{st} = \mathbf{C}_S \mathbf{x} + \mathbf{w}_{st} \quad (9)$$

The data received in the guard interval (with length P), padding $N - L + 1$ zeros, is given by

$$\mathbf{r}_g = \mathbf{C}_T \mathbf{x} + \mathbf{w}_g \quad (10)$$

If \mathbf{r}_g is added to \mathbf{r}_{st} , circulant convolution of OFDM symbol is preserved.

To implement this scheme, the transmitter should be modified not to insert cyclic prefixes in the guard intervals of OFDM symbols. In this interval, transmitter performs spectrum sensing. Algorithm on the receiver consists of the following steps

- 1) Do not discard the guard interval portion of the received signal. That is, keep $r(N + 1), r(N + 2), \dots, r(N + L)$.
- 2) Add $r(N + 1), r(N + 2), \dots, r(N + L)$ to $r(1), r(2), \dots, r(L)$ to preserve the circulant convolution.

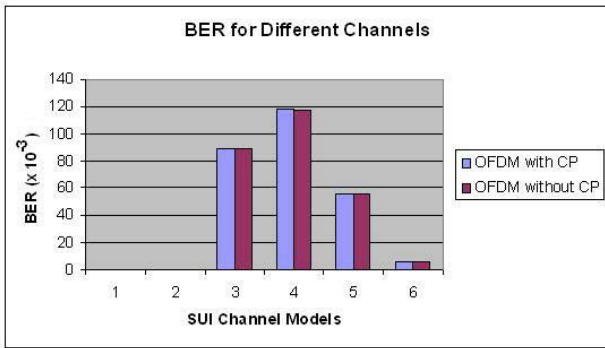


Fig. 2. BER under various SUI channel conditions. [Subcarrier modulation QPSK, CP=1/4, $E_b/N_0=20\text{dB}$]

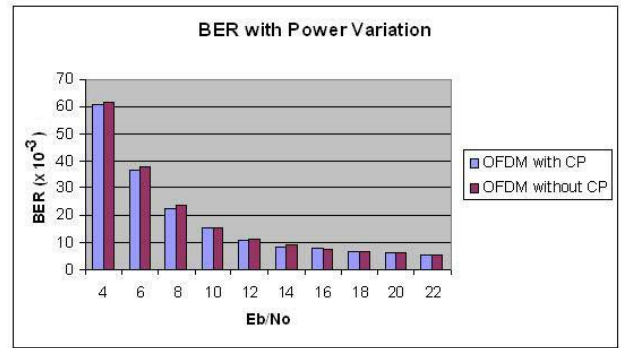


Fig. 4. BER with variation in the signal power (dB) [Subcarrier modulation QPSK, CP=1/4, SUI-6 channel]

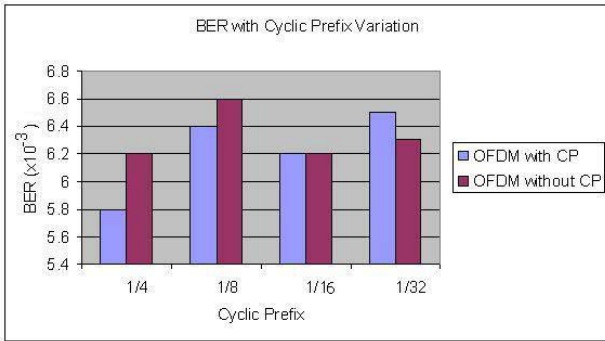


Fig. 3. BER for various cyclic prefix values [Subcarrier modulation QPSK, SUI-6 channel, $E_b/N_0=20\text{dB}$]

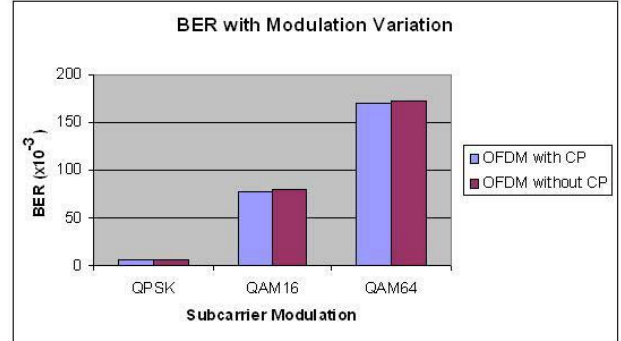


Fig. 5. BER for various subcarrier modulation [SUI-6channel, CP=1/4, $E_b/N_0=20\text{dB}$]

IV. EVALUATION OF RECEIVER PERFORMANCE

In our simulations, the transmitter is modified not to insert cyclic prefix in the guard interval of OFDM symbols. The receiver adds the signal received in the guard interval to the beginning portion of received OFDM symbol as explained in Section III. The bandwidth is set to 10 MHz, the total number of sub-carriers is 256, and no equalization techniques are used. For the fixed broadband wireless access channel, Stanford University Interim (SUI) model [5] is used. This model has a set of six typical channels that were selected for the three terrain types that are typical of the continental US. We have compared the performance of OFDM-without-CP with OFDM-with-CP. The above figures show the BER performance at the receiver for variations in the signal/channel parameters.

The performance of OFDM signal is tested under SUI 1-6 channel environments with $E_b/N_0 = 20\text{dB}$, QPSK and CP=1/4. As shown in Fig. 2, it is found that BER is almost the same in each of the six SUI channel models. Fig. 3 shows variation in BER when guard interval length is varied as 1/4, 1/8, 1/16 and 1/32 of the OFDM symbol period. BER variation with signal power is shown in the Fig. 4. Impact on BER with QPSK, QAM16 and QAM64 subcarrier modulation is shown in Fig. 5. From the above figures, it can be seen that the receiving performance for OFDM-without-CP is almost the

same as OFDM-with-CP.

V. TRANSMITTER SPECTRUM SENSING IN THE GUARD INTERVAL

In this section, we investigate how the guard interval in OFDM symbol could be utilized for spectrum sensing. Spectrum sensing can be done in guard interval if nothing is transmitted during this interval. The length of guard interval is dependent on delay spread of the channel. For broadband wireless systems like 802.22 the delay spread is between 0 to 20 microseconds. Table I lists the delay spread for various channels of the SUI model.

TABLE I
DELAY VALUES (μSEC) FOR SUI CHANNELS 1-6

Channel	Tap1	Tap2	Tap3
SUI-1	0	0.4	0.8
SUI-2	0	0.5	1
SUI-3	0	0.5	1
SUI-4	0	2	4
SUI-5	0	5	10
SUI-6	0	14	20

We have utilized the proposed sensing interval for the detection of primary users in secondary spectrum usage systems. In 802.22 based secondary spectrum usage framework, a

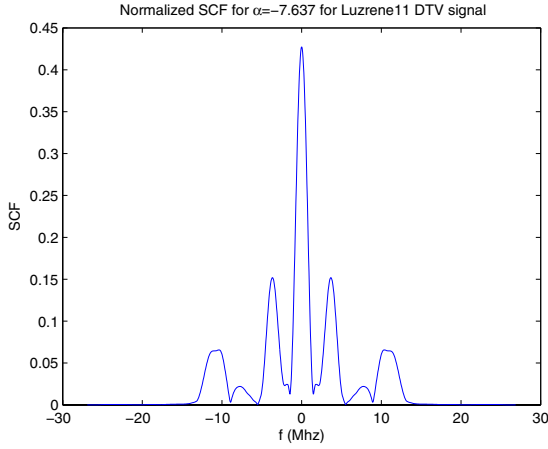


Fig. 6. Detection of DTV signal based on the SCF estimate for real DTV signal.

base-station communicates with Customer Premise Equipment (CPE) via a point to multi-point air interface operating in the VHF/UHF broadcast bands. The spectrum is used by cognitive radios if the licensed users such as DTV are not using the channel(s).

The DTV transmit signal consists of a symbol stream shaped by the transmit pulse-shaping filter plus the pilot tone. The DTV transmission uses 6 MHz bandwidth and employs Vestigial Side Band (VSB) modulation scheme, where the symbol rate of the DTV signal is 10.76M symbols per second. Various DTV signals [9] having weak to moderate pilot strength, shallow to deep spectrum nulls with noise floor range 35-40 dB were used for testing.

In the simulation, we kept the guard interval length equal to 25 μ sec. With sampling frequency of 50 MHz, spectrum data is acquired. This data is analyzed for the cyclic features of DTV and other spectrum exploiting second order cyclostationarity [10].

Spectral Correlation Function (SCF) measures the temporal correlation between frequency components separated from each other by cyclic frequency (α). SCF is calculated using the following formula [11]

$$S_x^\alpha(f) = \int_{-\infty}^{\infty} R_x^\alpha(\tau) e^{-i2\pi f\tau} d\tau \quad (11)$$

where, $R_x^\alpha(\tau)$ is calculated as

$$R_x^\alpha(\tau) = \lim_{T \rightarrow \infty} \frac{1}{T} \int_{-T/2}^{T/2} x(t + \tau/2) x^*(t - \tau/2) e^{-i2\pi\alpha t} dt \quad (12)$$

Fig. 6 denotes the cyclic feature exploited from the SCF in the DTV signal acquired in the OFDM guard interval.

Sensing in the OFDM guard interval thus provides in-band sensing of the channel. Since the spectrum sensing activity is very frequent, the cognitive radio can take appropriate action to avoid interference to primary users immediately. No dedicated period is allocated for sensing hence system can achieve high bandwidth utilization.

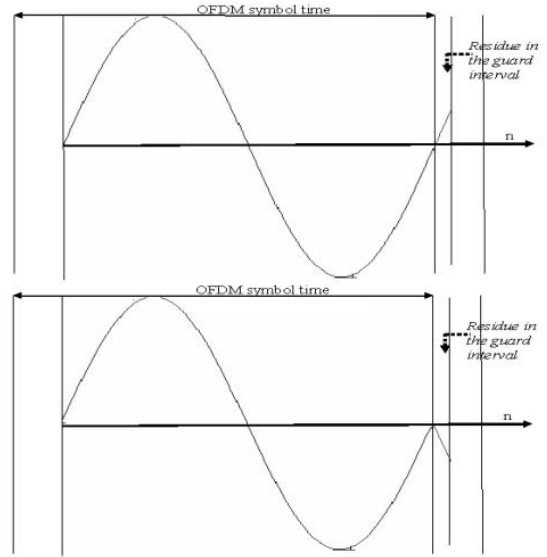


Fig. 7. Possible residue in the guard interval

VI. IMPLEMENTATION ISSUES

In this section, we identify several implementation issues in practice that would increase the transceiver complexity.

A. Residue in the guard interval

During OFDM symbol guard interval, the RF front-end of the transmitter switches to receive mode for spectrum sensing. The RF front-end switches to transmit mode within few microseconds depending upon the length of the guard interval. The turn-off action of the transmitter may not be time-accurate. That is, there may be a few residual samples in the guard interval due to the RF front end on-off transient. Fig. 7 shows the residue samples in the guard interval. The residue could be the extension of the current OFDM symbol as shown in the top figure, or part of the cyclic prefix of the next OFDM symbol, arbitrary to the current symbol, as shown in the bottom figure.

We performed simulations to find out effect of residue on the reception BER. It is shown in Fig. 8 that the BER increases with the amount of residue in the guard interval. The normalized residue varies from 0 to 1, indicating the portion of the residue in the guard interval. The increase in BER results from the loss of circulant convolution property.

Based on the estimation of the residue at the receiver, we propose a scheme to overcome the effect of residue. The scheme is an enhancement of the method to secure circulant convolution. It is assumed that receiver can ensure a residual case as in the top figure of Fig.7, and can estimate the length of residue in the guard interval. With residue compensation according to the estimated residual length, and, for the remaining of the guard interval, the scheme proposed in Section III applied, the circulant convolution property can be preserved at the receiver. We can subtract the transmission of residue in spectrum sensing, or use the remaining quiet portion of the

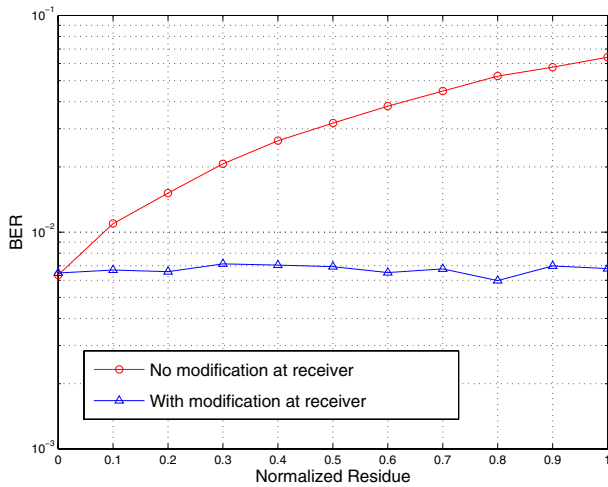


Fig. 8. Effect of residue in the guard interval on BER

guard interval for spectrum sensing. The overall scheme is depicted in Fig. 9. With the assumption of correct estimation of residue, we evaluated the performance of above scheme. It is shown in Fig. 8 that the effect of residue on BER is overcome with the modified scheme.

B. High switching rate

If the individual guard interval is small and occurs with high rate, the hardware may not be able to cope with the switch speed and do anything meaningful. Maybe we can argue there is a tradeoff, meaning that the block transmission time can be extended, say n samples. The quiet guard interval is k samples. Here, k is a fixed parameter because it is determined by the maximum path delay. After such block extension, the switching rate, the RF front end switching to do something else, is reduced. Also, the overhead is reduced, that is, $k/(k+n)$ reduces as n increases. The cost is that the receiver complexity increases.

The transmitter could reduce the switching rate by not performing sensing operation in every guard interval. Instead, sensing operation can be performed in an adaptive manner based on the SNR and the MAC layer control.

C. Synchronization

Cyclic prefix plays a vital role in OFDM synchronization. The proposed spectrum sensing scheme can be accomplished only after synchronization is complete. Therefore, the receiver complexity could be high since we need to separate the synchronization phase from the normal communication phase.

VII. CONCLUSION

We have addressed the problem of inband channel sensing by incorporating spectrum sensing functionality in the OFDM guard interval. Idle OFDM guard interval is achieved at the transmitter by not inserting the cyclic prefix. We have provided a scheme of securing circulant convolution at the receiver to avoid intercarrier interference. The idle guard interval

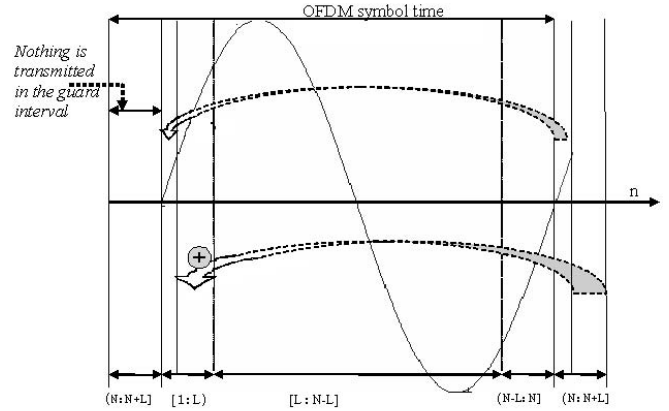


Fig. 9. Scheme to overcome effect of residue in the guard interval

can be utilized for spectrum sensing. High rate of spectrum sensing helps quicker detection of primary users thus avoiding interference. System bandwidth is saved because an explicit sensing interval need not be allocated. We have identified implementation issues like high switching rate and residue in the guard interval. An enhanced scheme based on the estimated value of the residue is developed for overcoming the effect of residue on BER. We will further explore MAC layer schemes for adaptive sensing and dynamic spectrum access based on the proposed approach of spectrum sensing.

ACKNOWLEDGMENT

The authors would like to thank Dr. Chad Spooner of NorthWest Research Associates, Inc. for discussions on the cyclostationary feature detection of DTV.

REFERENCES

- [1] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *IEEE J. Select. Areas Commun.*, vol. 23, no. 2, pp. 201–220, Feb. 2005.
- [2] J. Mitola, III and J. G. Q. Maguire, "Cognitive radio: making software radios more personal," *IEEE Personal Communications*, vol. 6, no. 4, pp. 13–18, Aug. 1999.
- [3] D. Cabric, S. M. Mishra, and R. W. Brodersen, "Implementation issues in spectrum sensing for cognitive radios," *38th Annual Asilomar Conference on Signals, Systems and Computers*, Nov. 2004.
- [4] IEEE 802.22 working group, "Functional requirements for the 802.22 WRAN standard," <http://www.ieee802.org/22/>, Jan. 2006.
- [5] IEEE 802.16.3c-0129r4, "Channel models for fixed wireless applications," <http://www.ieee802.org/16/>, June 2001.
- [6] C. Cardoero, K. Challapalli, D. Birru, and S. Shankar, "IEEE 802.22: the first worldwide wireless standard based on cognitive radios," *New Frontiers in Dynamic Spectrum Access Networks, DySPAN*, Nov. 2005.
- [7] N. Han, S. Shon, J. H. Chung, and J. M. Kim, "Spectral correlation based signal detection method for spectrum sensing in IEEE 802.22 WRAN systems," *The 8th International Conference on Advanced Communication Technology, ICACT*, Feb. 2006.
- [8] IEEE 802.22 working group, "IEEE 802.22-06/0082r0," <http://www.ieee802.org/22/>, June 2006.
- [9] Cornell University BARD Group, "DTV channel characterization," <http://bard.ece.cornell.edu/>, 2001.
- [10] W. Gardner, "Statistical spectrum analysis: A nonprobabilistic theory," *Englewood Cliffs, NJ: Prentice Hall*, 1987.
- [11] W. Gardner and C. M. Spooner, "Cyclic spectral analysis for signal detection and modulation recognition," *Military Communications Conference, MILCOM*, Oct. 1988.