This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE Globecom 2010 proceedings.

OFDM Signal Type Recognition and Adaptability Effects in Cognitive Radio Networks

Anna Vizziello*†, Ian F. Akyildiz‡, Ramon Agusti‡, Lorenzo Favalli†, Pietro Savazzi†
* Broadband Wireless Networking Laboratory, School of Electrical and Computer Engineering,
Georgia Institute of Technology, Atlanta, Georgia 30332, USA
Email: anna.vizziello@ece.gatech.edu
‡ Telecommunication Engineering School (ETSETB) - Department of Signal Theory and Communications (TSC),
Technical University of Catalonia (UPC), Barcelona, 08034 Spain
Email: ian@ac.upc.edu, ramon@tsc.upc.edu
† Department of Electronics, University of Pavia, Pavia, 27100 Italy
Email: {name.surname}@unipv.it

***Abstract*—The ability of adapting to the environment in the most efficient way is a crucial issue in Cognitive Radio (CR) networks. For this purpose, an accurate estimation of the characteristics and activity of the Primary Users (PUs) is required. A system that takes into account heterogeneous PUs with several features is developed. A new scheme is integrated in the system to exploit these motleys and to improve the adaptability in CR networks. Through the proposed PU signal type recognition, the PU signal is detected and classified. The features of each PU type: the allowed interference levels, the bandwidth and the idle time, are extracted and exploited for CR adaptability effects. For this, a new CR throughput/interference adapter is proposed. The CR throughput is efficiently increased depending on the specific characteristics of PU types. Simulation results show that the proposed PU type recognition detects, distinguishes and classifies PU signals in Additive White Gaussian Noise (AWGN). It is shown that CR throughput varies with PU features for the improvement of CR adaptability.**

I. Introduction

The recent deployment of wireless technologies requires an efficient radio spectrum utilization to resolve the scarcity of the spectrum resource. As one of enabling technologies, Cognitive Radio (CR) technology is proposed for opportunistic spectrum access. Specifically, a CR is capable of changing its transmitter parameters and interacting with the environment [1]. In particular, a CR can utilize the band on the condition that it has to vacate the spectrum as soon as the Primary User (PU) is detected [1]. However, CRs can utilize the same spectrum bands as long as CRs limit the interference with PUs to tolerable levels. To realize the spectrum awareness, the fundamental requirement is spectrum sensing.

Among all sensing techniques, cyclostationarity-based feature [7] sensing has recently gained attention due to better immunity to noise uncertainty and the ability to distinguish signal types. For example, OFDM signals exhibit periodicities embedded in equally spaced sinusoidal carriers, cyclic prefix and pilot patterns [2]. These periodicities are exploited to detect PU through the *Cyclostationary Autocorrelation Function* (CAF) [7] or the *Spectral Correlation Function* (SCF) [2], the Fourier transform of CAF.

Feature detection provides necessary information for signal classification. In [2], the cyclic features that arise from the periodic insertion of pilot tones are considered for the detection and the classification of OFDM signals. The authors propose a single spectral correlation function detector and a multi-class support vector machine classifier to recognize two signal types.

In general, the ability to classify signals enables the CR users a better awareness of the environment. Motivated by this issue, we develop a system that takes into account heterogeneous PUs, instead of the simple ON-OFF PU model. Moreover, we propose how to exploit these motleys to improve the adaptability in CR networks. To recognize heterogeneous PUs, we propose a novel *Detector/Classifier*. Besides PU detection/classification, we show how to exploit signals classification in CR networks. The latter is not addressed in existing classification methods, such as [2].

In the following, the feature Detection/Classification process is termed PU signal type recognition.

The main contributions of this paper are:

- A CAF feature *Detector/Classifier* for OFDM signals. A novel test statistic is proposed to detect and classify PU signals. A new PU activity model [3] is integrated in the scheme. The PU features, useful to adapt the CR parameters, are extracted for each PU type: the *Allowed Interference level*, the *Idle time* and the *Bandwidth*.
- A *Throughput/Interference Adapter* to exploit the PU motleys and improve the CR adaptability. We consider that each PU type allows a different interference level. Thus, depending on the recognized PU type, CRs achieve an adaptive interference protection towards PUs by changing the CR transmission power. The CR throughput is adapted by considering several PU characteristics in different scenarios.

The remainder of the paper is organized as follows: in Sec. II the System Architecture and the Modules of the proposed framework are presented. In particular, the *PU Type Characterization* Blocks are described in Sec. III, while the Module concerning *Adaptability Effects on CR* is shown in Sec. IV. In Sec. V the performance of the system is evaluated by the behavior of the CAF Detector/Classifier and CR adaptive throughput; finally the conclusions are presented in Sec. VI.

II. System Architecture and Modules

In this section, we present the system modules and the network architecture. We assume that the primary systems utilize the Orthogonal Frequency Division Multiplexing (OFDM). Furthermore, we consider an infrastructure-based CR network with a centralized entity, such as a CR base station. The CRs send sensing information to the CR base station, which

The work of Ian F. Akyidiz and Ramon Agusti was supported by the European Commission in the framework of the FP7 FARAMIR Project (Ref. ICT- 248351).

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE Globecom 2010 proceedings.

broadcasts the features of different PUs to all CR users. We consider PU signals specified in distinct standards, which are characterized by different values of OFDM parameters, such as guard interval length, symbol duration, and subcarrier spacing. A channel noise is modeled by Additive White Gaussian Noise (AWGN) $n(i)$ with zero mean and variance ${\sigma_n}^2$. Thus, at the receiver, the relationship between input and output of each OFDM symbol in the time domain is

$$y^j(i) = \begin{cases} x^j(i) & H_0 \\ x^j(i) + n(i) & H_1 \end{cases} \tag{1}$$

with $0 \leq i \leq N^j - 1$. N^j is the number of subcarriers in an OFDM block for the j^{th} PU type. The time instant t^j is equal to $i \times T_s^j$, where T_s^j the sampling period equal to $T^j/(N^j + G^j)$. T^j is the time duration of each OFDM symbol after adding the guard interval, which lasts G^j sampling periods. The hypothesis H_0 and H_1 indicate the absence or presence of the PU signal $x^j(i)$, which is an independent and identically distributed random process with mean μ_x^j and variance ${\sigma_x^j}^2$.

Fig. 1 illustrates the modules of the proposed model along with the input/output of the modules. The monitored vector $y^j(i)$ in time domain is the input of the proposed scheme. The model is composed of two parts: *PU Type Characterization* and *Adaptability Effects on CR*. The first group of *PU Type Characterization* consists of three blocks: the *PU Activity Model*, the *Cyclostationary Feature Detector/Classifier*, and the *PU Characteristics Module*; the second block *Adaptability Effects on CR* contains the *CR Throughput/Interference Adapter*.

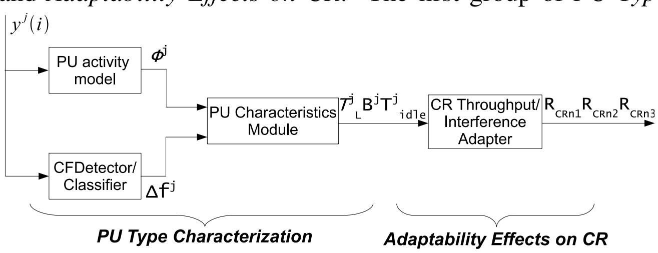


Fig. 1. Modules of the System

III. Primary Users Type Characterization

A. Primary Users Activity Model

The performance of a CR network is related to PU Activity, therefore a precise model of PU Activity is useful to characterize the availability of the spectrum. The model proposed in [3] follows the spiky fluctuations of PU activities over time and models the PU traffic accurately overcoming the drawbacks of the usual Poisson modeling [3]. In [3] a new activity index, called *Primary User Activity Index* $\phi^j(i)$, is derived:

$$\begin{aligned} \phi^j(i) = {} & [r(i) - r(i-1)] \times \\ & \left[\left| \tfrac{1}{2} \textstyle\sum_{q=1}^{3} \left(\tfrac{d(q) - E(d^{[3]})}{\sigma_{d^{[3]}}} \right) \left(\tfrac{r(i+1-q) - E(r^{[3]})}{\sigma_{r^{[3]}}} \right) \right| \right], \\ & \forall \;\; i \in [1, 2, \ldots, p] \end{aligned} \tag{2}$$

in which the index j refers to the j^{th} band, $r(i)$ is the modeled PU activity vector at the i^{th} time sample, $r^{[3]}$ is the vector r with three elements, $d^{[3]}$ is an index vector d with three elements, $E(.)$ is the mean, σ is the standard deviation, p is the total number of PU activity time samples. The first term $[r(i) - r(i-1)]$ in (2) captures the fluctuations of PU activity while the second term accounts for the correlation effects. P_{busy} and P_{idle} of PU activity depend on the PU model used and are expressed as in [3]:

$$P_{busy} = \sum_{i=1}^{p} \frac{2(r(i) - 2\Omega\Psi)}{2} \tag{3}$$

and

$$P_{idle} = \sum_{i=1}^{p} \frac{r(i) - 2\Omega\Psi}{2} \tag{4}$$

where $r(i)$ is the modeled PU activity vector. Ω and Ψ are binary variables employed to express the temporal correlation and the correlation slope, respectively.

B. Cyclostationary Feature Detector/Classifier

The *Cyclostationary Feature Detector/Classifier* Module consists of a feature detector and a signal classifier:

1) Feature Detector: In general, spectrum sensing should be more accurate than simple spectral power analyzer that only recovers the presence of the signal. The feature detection shows robustness to the uncertainty of noise power, unlike the energy detector, especially at low SNR. It also distinguishes signals from different networks. This feature can be exploited in several applications.

The *Cyclostationary Autocorrelation Function* (CAF) $R_x^\alpha(\tau_s)$ of a signal x is defined as:

$$R_x^\alpha(\tau_s) = \frac{1}{N} \sum_{n=0}^{N-1} x(n) x(n+\tau_s)^* e^{-j2\pi\alpha T_s} \tag{5}$$

where α is the cyclic frequency, A is equal to c/T with an integer c, τ_s is the delay time τ normalized by the sampling period T_s and N is the number of samples.

We utilize the CAF to detect PU signal. In particular, we focus on the features of OFDM signals because it is employed by several modern PU standards. The CAF of an OFDM signal exhibits peaks at $\alpha = c/T$ and $\tau = T_u$, where $T_u = T - T_g$ is the data duration time, normalized by the sampling period T_s. In an OFDM signal, these peaks are introduced by built-in periodicity due to equally spaced sinusoidal carriers, cyclic prefix and pilot patterns. In fact in a non-cyclostationary signal, such as AWGN, the CAF does not show any peak for $\alpha \neq 0$. The AWGN has a peak only for $\alpha = 0$ and $\tau = 0$ and we use this feature to distinguish between the presence or absence of PU signals.

For $\alpha = 0$ and $\tau = 0$, the feature detector is reduced to an energy detector. Choosing $\alpha = 0$ and $\tau \neq 0$, the feature detector become simpler, similar to an energy detector, but it has the ability of distinguishing different signals.

Given the received signal y, we define the test statistic as follows:

$$Z_y = max[R_y^0(\Delta t_s(i))] \quad \forall \Delta t_s(i) \neq 0 \tag{6}$$

in which R_y^0 is the CAF of received signal y and $\Delta t_s(i) = 1/i \times T_s$ for $1 < i < N_s$. Some considerations about the value of N_s are discussed in Sec. III-B2.

The decision threshold λ is defined as the mean value of the CAF of noise R_n^0:

$$\lambda = E[R_n^0(\Delta t_s(i))] \quad \forall \Delta t_s(i) \neq 0 \tag{7}$$

After having calculated Z_y, the detector makes the decision

$$\begin{cases} Z_y > \lambda & decide \;\; H_1 \\ otherwise & decide \;\; H_0 \end{cases} \tag{8}$$

In the following, the detection probability P_d and the false alarm probability P_f of the proposed detector are given:

$$P_d = Pr[Z_y > \lambda | H_1] \tag{9}$$

and

$$P_f = Pr[Z_y > \lambda | H_0] \tag{10}$$

P_d and P_f are related to Z_y. Specifically, under H_0, Z_y follows χ_{2K}^2, where χ_q^2 is the central chi-squared distribution with q degrees of freedom. Thus, the threshold for attaining a given $\bar{P}_f$ can also be calculated through the table of χ^2_{2K}.

2) Signal Classifier: The periodicities of the OFDM signals, due to equally spaced sinusoidal carriers, cyclic prefix and pilot patterns, are useful not only to detect PU signal, but also to characterize different PU signals specified in standards.

We use the test statistic in (6) to classify the signals. As explained previously in Sec. III-B1, the CAF of an OFDM signal exhibits a peak at $\alpha = c/T$ and $\tau = T_u$. The useful duration time T_u is equal to $1/\Delta f$, where Δf is the subcarrier spacing. This parameter depends on the PU type. Thus, we use the interval time in which the CAF R^0_y exhibits the maximum to distinguish different PU signals. Specifically, we know that

$$R^0_y(T^j_u) = max[R^0_y(\Delta t_s(i))] \quad (11)$$

in which $T^j_u = T_s \times N^j$ and N^j is the FFT size of the j^{th} PU signal type. $R^0_y(\Delta t_s(i))$ varies for $1 < i < N_s$ where N_s is set to the maximum value of N^j. Without loss of generality, we fix a unique value of the sampling period T_s and vary the FFT size depending on the standard.

After having calculated $R^0_y(\Delta t_s(i))$ for $1 < i < N_s$, the value of $\Delta t^*_s(i)$ in which R^0_y has the maximum is extracted:

$$\Delta t^*_s(i) \ : \ R^0_y(\Delta t^*_s(i)) = max[R^0_y] \quad (12)$$

From (11), we know that $\Delta t^*_s(i)$ corresponds to T^j_u. Thus, $T^j_u = 1/\Delta f^j$ is obtained. Δf^j is different for each PU type specified in a standard. The value of Δf^j is the input of the *PU Characteristics Module*, which extracts the PU features.

C. PU Characteristics Module

In this module, we describe the characteristics of different PUs, useful to adapt more efficiently the CR transmitter parameters. As shown in Fig. 1, the PU activity index $\phi^j(i)$ and the subcarrier spacing Δf^j are the input of this module. $\phi^j(i)$ is useful for the definition of the PU idle time, while Δf^j is used for the extraction of PU bandwidth and the allowed interference levels. In fact, the value of Δf^j, calculated in Sec. III-B2, is compared with the known subcarriers spacing of PU standards. Thus, the type of the detected PU signal is extracted along with the allowed interference level and bandwidth for each standard. The PU features are analyzed in the following:

1) PU Allowed Interference Temperature level: Besides CR transmissions when the PU is absent, we consider the simultaneous transmission when a PU is present, provided that tolerable interference level is satisfied.

Following the FCC model in [5], we adopt the interference temperature model. As in [4], we use the ideal temperature model with several temperatures limits. However, we do not consider the average CR transmission power as in [4]. We overcome the challenge of knowing the PU types by means of the *Cyclostationary Feature Detector/Classifier* module. After having recognized different PU signals, we define various interference limits $\mathcal{T}_L(f^j)$, related to the robustness of the j^{th} PU standard. Therefore, similar to [4] but varying the CR transmission power, the tolerable interference $\mathcal{T}_I(f^j, B^j)$ is expressed as:

$$\mathcal{T}_I(f^j, B^j) = \frac{M^j P_{s_n}}{kB^j} \leq \mathcal{T}_L(f^j) \quad \forall\, 1 \leq j \leq J \quad (13)$$

where f^j and B^j are the j^{th} central frequency and j^{th} bandwidth of the j^{th} PU standard, respectively. M^j is a constant taking into account the attenuation between CR transmitter and PU receiver and k is the Boltzmanns constant equal to 1.38×10^{-23} Joules per Kelvin degree. P_{s_n} is the power of the n^{th} CR user that experiences the j^{th} PU in the band B^j.

Besides the identification of PU signals, another challenge in the ideal model is connected to the measure of interference temperature floor $\mathcal{T}_I$, underneath the PU signal. We overcome this problem by calculating $\mathcal{T}_I$ as follows

$$\mathcal{T}_I(f_c, B) \approx \frac{P_{ric}}{kB} \quad (14)$$

where P_{ric} is obtained by the proposed *Feature Detector*. When the test statistic in (6) does not show any peak for $\Delta t_s(i) \neq 0$ it means that the PU signal is absent, thus we use the $R^0_y(\Delta t_s(i))$ value at $\Delta t_s(i) = 0$ to measure the received power:

$$P_{ric} = R^0_y(\Delta t_s(i)), \quad \Delta t_s(i) = 0 \quad (15)$$

Thus, we measure in real time the underneath interference temperature whenever the PU signal is not detected.

2) PU Bandwidth: Each PU transmission band has a given bandwidth depending on the standard. In Sec. IV-B the impact of the bandwidth on the CR throughput is described.

3) PU Idle time: The transmission time allowed to CR user is related to the idle time of PUs. For this, it is important an accurate model of the PU activity. In Sec. III-A, the PU Activity Index $\phi^j(i)$ represents the traffic patterns on the j^{th} band and time i. The mean value of the PU arrival rate is defined as the average value of the activity index $E[\phi^j(i)]$. Thus, the mean inter-arrival rate is equal to $1/E[\phi^j(i)]$, which is the value of the average idle time $E[T^j_{idle}]$.

IV. Adaptability Effects on Cognitive Radio

Through well characterized PU signals it is possible to exploit the PU features and better adapt the CR parameters. Thus, the CR interference and throughput is improved. Depending on the recognized PU type, the CR adaptive interference protection towards PUs is achieved by changing the CR transmission power. The CR throughput is adapted, depending on both the PU type and the scenario.

A. CR Adaptive Parameters

The CR parameters, related to the features of PU type and useful for CR adaptability improvement, are listed in the following:

1) CR Transmission Power: A CR user adapts more efficiently its transmission power, according to different allowed interference. In particular, if a CR does not detect any PU, the CR is allowed to transmit with its maximum power; if a PU is detected, CR changes its transmission power depending on the PU type. From (13) the CR transmission power is calculated:

$$P_{s_n} \leq \frac{kB^j}{M^j}\mathcal{T}_L(f^j) \quad \forall\, 1 \leq j \leq J \quad (16)$$

When CR does not detect PU, P_{s_n} is set to $P_{s_{max}}$.

2) CR Bandwidth: The CR throughput depends directly on the bandwidth in which it transmits at that moment. In particular, we consider a system where the bandwidth and the central frequency are assigned to a CR user after having detected the PU type. Thus, in our system, CR has to choose the transmission frequency only when a specific PU spectrum band is assigned because it better meets its throughput requirement.

3) CR Transmission Time: In a CR network, it is a reasonable assumption that the CR transmission time is shorter compared to average idle time [6]. Thus, we consider that the maximum achievable value of CR transmission time is:

$$T_{tx_n}^{max} = \frac{1}{E[\phi^j(i)]} \tag{17}$$

where $T_{tx_n}^{max}$ is the maximum transmission time of the n^{th} CR user, which transmits on the spectrum band of the j^{th} PU.

B. CR Throughput/Interference Adapter

We propose a throughput/interference adapter to exploit the PU signal type features and improve the CR adaptability. We consider that each PU type allows a different interference level. Thus, depending on the recognized PU type, CRs change their transmission power to achieve an adaptive interference protection towards PUs, as in (16).

The CR throughput is adapted by considering several PU characteristics and different scenario that CR user experiences. Let the period $T_{tot_n} = T_{tx_n} + T_{s_n}$ denote CR transmission plus sensing time. We express the mean achievable throughput in the period T_{tot_n} as follows:

$$\bar{R}_{CR_n} = R_{CR_{n1}} + R_{CR_{n2}} + R_{CR_{n3}} \tag{18}$$

It is composed of three contributions:

- The first term: it is referred to the situation in which PU is absent and the CR user correctly detects the idle state without false alarm.
- The second term: in this scenario the PU is present and the CR user detects the PU correctly; CR transmits and coexists with PU. Thus, CR parameters have different values than those in the first case.
- The third term: in this case the PU is present, but the CR detector fails and causes interference towards PU user.

$R_{CR_{n1}}$ is given as

$$R_{CR_{n1}} = \frac{T_{tx_n}}{T_{tx_n} + T_{s_n}} C_{n1}(1 - P_f) P_{idle} \tag{19}$$

in which the term $\frac{T_{tx_n}}{T_{tx_n}+T_{s_n}}$ is the CR efficiency expressed as the ratio between the CR transmission time and the transmission plus sensing time. The maximum value of T_{tx_n} is given by (17). The term C_{n1} is the achievable capacity in the first case. $(1 - P_f)P_{idle}$ is the probability of the occurrence of the first scenario given by the probability P_{idle} that the PU is absent, multiplied by the probability $(1 - P_f)$ that CR detects the idle state without false alarm. P_{idle} is given in eq. (4).

The capacity C_{n1} is be expressed as

$$C_{n1} = B^j \log_2 \left(1 + \frac{P_{s_{max}}}{N_0}\right) \tag{20}$$

in which B^j is the transmission band of the j^{th} PU, assigned to the n^{th} CR user. $\frac{P_{s_{max}}}{N_0}$ is the signal to noise ratio, where $P_{s_{max}}$ is the transmission power of CR user and N_0 is the noise in the considered band.

The second term $R_{CR_{n2}}$ in (18) is defined as follows

$$R_{CR_{n2}} = \frac{T_{tx_n}}{T_{tx_n} + T_{s_n}} C_{n2} P_d P_{busy} \tag{21}$$

C_{n2} is the achievable capacity in the second case. $P_d P_{busy}$ is the probability that the second case happens: the probability P_{busy} that a PU is transmitting, multiplied by the probability P_d that CR correctly detects PU. P_{busy} is given in eq. (3).

C_{n2} is expressed as

$$C_{n2} = B^j \log_2 \left(1 + \frac{P_{s_n}}{P_{I_n} + N_0}\right) \tag{22}$$

where the CR transmission power P_{s_n} is calculated by (16). In this case, the noise is composed of channel noise power N_0 plus interference power of PU measured at CR. We have simultaneous PU and CR transmissions in the same band and P_{I_n} takes into account for the interference suffered by CR.

The third term in (18) is given as

$$R_{CR_{n3}} = \frac{T_{tx_n}}{T_{tx_n} + T_{s_n}} C_{n3}(1 - P_d) P_{busy} \tag{23}$$

where $(1 - P_d)P_{busy}$ is the probability that the third situation happens: the probability P_{busy} that the spectrum is occupied by a PU multiplied by the probability $(1 - P_d)$ that CR does not detect it. CR transmits causing interference towards PU.

The capacity C_{n3} is expressed as

$$C_{n3} = B^j \log_2 \left(1 + \frac{P_{s_{max}}}{P_{I_n} + N_0}\right) \tag{24}$$

We have $C_{n1} > C_{n3} > C_{n2}$. In (20) and (24), the CR transmission power is $P_{s_{max}}$, but in (24) there is P_{I_n}, which is inversely proportional to C_{n3}. In fact, eq. (24) is similar to (20) when there are simultaneous PU and CR transmissions. In (24) the CR user does not detect PU and transmits with the maximum power causing the interference towards PU. C_{n2} is lower than C_{n3} because CR transmission power in (22) is limited by allowed interference levels, as explained in (16).

Some considerations are discussed about the sensing time T_{s_n}. On one hand, for a given T_{tx_n}, a longer T_{s_n} gives a lower coefficient $\frac{T_{tx_n}}{T_{tx_n}+T_{s_n}}$. On the other hand, for a given probability of detection, a longer sensing time corresponds to a lower probability of false alarm. This is the case in which a CR has major possibilities to use the channel. In fact, T_{s_n} is related to P_d and P_f of the feature detector, proposed in Sec. III-B1.

V. Performance Evaluation

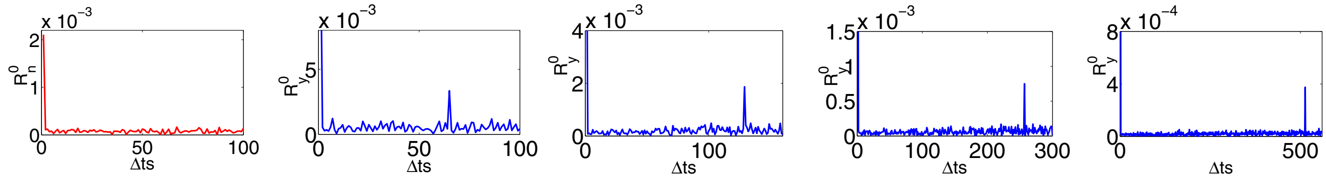
The performance of the proposed scheme is evaluated by the behavior of the CAF Detector/Classifier and CR adaptive throughput.

A. Simulation Environment

We implement the modules of the scheme in MATLAB. The considered system is composed of several PU types which use the OFDM transmission technique, and a CR centralized network. The CRs, after having detected PUs, send their information to a CR base station that broadcasts the presence of PU types and their characteristics to all CRs for throughput adaptation. We consider the following PU standards: 802.11, 802.16 and UHF TV signal. Moreover, we take into account different levels of interference temperature limit allowed by each PU standard. The PU activity index $\phi^j(i)$ defined in Sec. III-A is randomly distributed between 0.1 and 0.4. As explained in [3], the value within the range models the PU activity fluctuations better than the Poisson model.

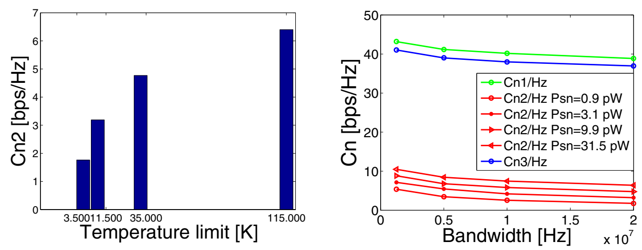
B. CAF Detector/Classifier

We evaluate the CAF by considering the built-in periodicity introduced by the cyclic prefix in an OFDM signal. (E_b/N_o) is set to 5 dB, where E_b is the energy per bit and N_o is the noise variance. As shown in Fig. 2(a), the CAF of AWGN at $\alpha = 0$, $R_n^0(\Delta t_s(i))$, does not exhibit any peak besides the one at $\Delta t_s(i) = 0$. Δt_s is the sampling period normalized to the sampling time T_s. Fig. 2(b)-2(e) show that the CAF of OFDM signal, $R_y^0(\Delta t_s(i))$, has another peak at $\Delta t_s(i) = T_u$. We use this feature to distinguish between the presence and absence of



(a) AWGN (b) PU1 signal (c) PU2 signal (d) PU3 signal (e) PU4 signal

Fig. 2. CAF Detection/Classification



(a) C_{n2} vs allowed Interf. Temp. (b) Capacity terms vs Bandwidth

Fig. 3. Normalized Capacity terms depending on the allowed Interference Temperature and Bandwidth

PU and to classify the PU types. In fact, the data duration time $T_u^j = 1/\Delta f^j$ varies depending on the PU standard. Without loss of generality, as explained in Sec. III-B2, we set T_s to a unique value and vary the FFT size N^j by setting its value to 64, 128, 256 and 512 in order to differentiate the PU types. As expected by (12), Fig. 2(b)-2(e) show that the CAF of the OFDM signals has the peak at $\Delta t_s(i) = T_s \times N^j$, where $T_s \times N^j$ is equal to T_u^j. Thus, it is possible to distinguish the PU type, depending on the value of $\Delta t_s(i)$ in which R_y^0 exhibits the peak.

C. CR Adaptive Throughput

In the following, we show that the CR throughput adaptation depends on each feature of heterogeneous PU signals.

1) Allowed interference levels: Fig. 3(a) shows the behavior of the term C_{n2} expressed in (22) normalized to the transmission band, depending on the various interference temperature levels allowed by different PU standards. We set these interference limits to 3500 K, 11500 K, 35000 K, 115000 K. The received PU power level is set to the typical value of 100 pW. We set a bandwidth of 20 MHz and the noise temperature $\mathcal{T}_n$ is the usual value of 290 K. Moreover, $\mathcal{T}_I$ equal to 1000 K is the interference that a PU transmission causes to the CR user. In this way, the CR power interferences, allowed by a PU device receiving CR interference, are 0.9 pW, 3.1 pW, 9.9 pW and 31.5 pW respectively. In our work, we do not consider the path loss in the signal strength. Thus, we suppose that these values are the same of the CR transmission power levels. When CR does not detect any PU signal, it uses the maximum transmission power set to 50 mW. Thus, C_{n1}, normalized to the band in (20), results equal to 39 while the normalized C_{n3} in (24) gets 37.

2) Bandwidth: Fig. 3(b) shows the behavior of the C_{n1}, C_{n2}, C_{n3} expressed in (20), (22), (24) varying the transmission band: 5 MHz bandwidth if a UHF TV PU signal has been detected, 1.25 Mhz and 10 MHz for 802.16 PU signals and 20 MHz for 802.11 PU signal.

3) Activity index: As explained in Sec. IV-A3, the maximum value of CR transmission time $T_{tx_n}^{max}$ is equal to PU idle time $E[T_{idle}^j]$. $E[T_{idle}^j]$ is in inverse proportion to $E[\phi^j(i)]$.

TABLE I
CR Throughput depending on PU Activity Index

$\phi^j(i)$	0.1	0.2	0.3	0.4
R_{CR_n}	18	17.7	17.4	17.1

Using (17), we set the maximum value of the CR transmission time in (19), (21) and (23) to calculate the CR throughput. Tab. I shows how the average value of the maximum CR throughput of (18) varies depending of the value of $\phi^j(i)$. The sensing time is set 10 OFDM symbol time that, for FFT size of 1024 and guard interval equal to $T_u/4$ with $Ts = 0.1$ μs, corresponds to 1.28 ms. We consider a bandwidth of 20 MHz and a $\mathcal{T}_L$ of 115000 K, so that C_{n1}, C_{n2} and C_{n3} are equal to 39, 6.4 and 39, as calculated in Sec. V-C1. P_f and P_d are set to reasonable values of 0.1 and 0.95 respectively, while P_{busy} is set to $[0.63\ \ 0.64\ \ 0.65\ \ 0.66]$ and P_{idle} is set to $[0.37\ \ 0.36\ \ 0.35\ \ 0.34]$, as in the simulation results in [3].

VI. Conclusion

A system with heterogeneous PUs and CRs is considered. We propose the PU type recognition to improve the environment awareness and the CR interference and throughput adaptability. Through the PU detector/classifier the PU type is distinguished. The PU type features, useful to adapt CR parameters, are extracted. An adaptive CR interference protection and improvement throughput method is proposed. The proposed PU type recognition detects and classifies PU signals, while CR throughput varies with PU features for the improvement of CR adaptability.

Acknowledgment

The authors would like to thank Brandon F. Lo for his constructive criticism which helped to improve the quality of the paper.

References

[1] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mhanty "Next generation/dynamic spectrum access/cognitive radio wireless networks: a survey," *Computer Networks, Elsevier*, Vol. 50, no. 13, pp. 2127-215, Sept. 2006.

[2] L. Bixio, G. Oliveri, M. Ottonello, C. S. Regazzoni, "OFDM recognition based on cyclostationary analysis in an Open Spectrum scenario," *IEEE 69th Vehicular Technology Conference*, Apr. 26-29 2009.

[3] B. Canberk, I. F. Akyildiz, and S. Oktug, "Primary User Activity Modeling Using First-Difference Filter Clustering and Correlation in Cognitive Radio Networks," *Submitted for journal publication*, Dec. 2008.

[4] T. C. Clancy, "Formalizing the Interference Temperature Model," *Wiley Journal on Wireless Communications and Mobile Computing*, Vol. 7, Issue 9, pp. 10771086, May 2007.

[5] FCC, "Establishment of interference temperature metric to quantify and manage interference and to expand available unlicensed operation in certain fixed mobile and satellite frequency bands," *ET Docket* 03-289, Notice of Inquiry and Proposed Rulemaking, 2003.

[6] W.-Y. Lee and I.F. Akyildiz "Optimal Spectrum Sensing Framework for Cognitive Radio Networks," *IEEE Transaction on Wireless Communications*, Vol. 7, pp. 3845-3857, Oct. 2008.

[7] K. Muraoka, M. Ariyoshi,and T. Fujii "A Novel Spectrum-Sensing Method Based on Maximum Cyclic Autocorrelation Selection for Cognitive Radio System," *IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks, DySPAN 2008*, Oct. 14-17 2008.