DVB-T CANDIDATE POWER DETECTOR FOR COGNITIVE RADIO

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ABSTRACT

Dynamic detection of primary users is one of the main functions of spectrum sensing for Cognitive Radio (CR) communications aiming to increase the use of radio spectrum. In this work the performance of the so-called Candidate power detector is reported. The main objective of this detector is the proper spectrum labelling of primary users in cognitive radio scenarios. The Candidate detector is tuned in order to detect Digital Video Broadcasting Terrestrial (DVB-T) signals, providing accurate power level estimates and frequency location in presence of interference signals or secondary users transmissions. The advantages of the resulting candidate detector are shown with respect to the existing alternatives based on energy detection and cyclo-stationary based detectors.

1. INTRODUCTION

Currently it is well recognized that the radio spectrum is over-licensed but not over-used. In the literature there are available several field test and measurements revealing the low usage of radio spectrum of certain frequency bands becoming extremely unused on specific geographic locations. Along 2002 several studies of the Federal Communications Commission (FCC) reported that the variation in the use of licensed spectrum ranges from 15% up to 85% [1]. Solving the under utilized spectrum represents a window of opportunity for telecom operators, whenever they are able to deploy open spectrum scenarios where secondary users become opportunistic customers. Within a flexible telecom market regulation, Cognitive Radio (CR) has been recognized as the set of technologies which allow the deployment of open spectrum scenarios. Among the key technologies in CR, together with reconfigurable physical layers and cross-layer approaches, the spectrum labelling represents the major problem to be over-passed.

This contribution focuses on the case of TV broadcast bands where FCC is considering the use of CR technologies for un-licenced operation [2]. On the main concept is allowing secondary users to access, in an opportunistic manner, to the frequency bands belonging to a primary user. Free frequency bands refer to those bands belonging to a primary user that opens its spectrum for secondary users, provided these secondary users do not interfere with primary transmissions.

In this paper the so-called candidate spectral estimation is tuned in order to cope with the DVB-T scenario. Firstly reported in reference [3], the Candidate estimate is based on a generalization of the spectral subtraction principle, widely used in, let us say, traditional spectral estimation. The name of candidate reflects the ability of the procedure to scan the radio spectrum for the presence of a given spectral shape different from the un-modulated carrier which is the common root of many traditional procedures for spectral estimation. In fact, the candidate estimate reduces to traditional spectral estimates when the candidate is just an unmodulated carrier [3]. The resulting candidate estimate provides accurate power levels of the DVB-T signal present, together with its central frequency location, just in case it is not known by the spectrum sensing processor. This accuracy remains almost the same regardless the presence of in-band or out-band location of interferers, whenever they differ on the spectral signature with respect the candidate.

The remainder of this paper is as follows: Section 2 describes briefly the DVB-T primary user signal. Section 3 describes the existing alternatives for spectral sensing of primary users in CR scenarios. Based on reference [3], Section 4 summarizes the basics of candidate spectral estimation. Section 5 includes the candidate detector implementation and a brief description of the major competitor of the Candidate approach which is the cyclo stationary approach. Finally, Section 6 reports the results in terms of spectral estimation for high SNR scenarios of the candidate estimate, and the Receiver Operation Characteristics (ROC) curves of low SNR scenarios. Also, included in this section, there is a comparison of the candidate method versus the cyclo-stationary approach proving the superiority of the Candidate method.

2. DVB-T SIGNAL CHARACTERISTICS

The DVB-T system has two modes of operation, namely 2K and 8K modes, allowing different levels of QAM modulation. We assume that the primary user is a DVB-T signal us-

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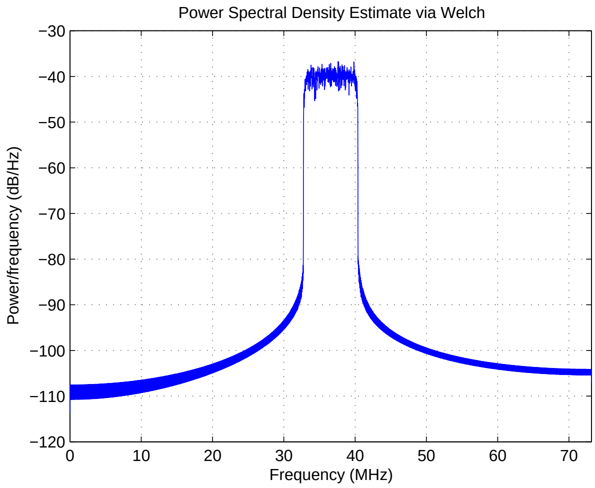

Figure 1: Power Spectral Density of DVB-T primary user using OFDM/16QAM modulation and located at 36 Mhz central frequency

ing an OFDM/16QAM modulation and 1705 carriers which corresponds to mode 2K [4]. The DVB-T primary signal is transmitted in frames, each frame is formed by 68 OFDM symbols. Each OFDM symbol contains a set of 1705 carriers and it is transmitted with a symbol duration (T_s) of $280\mu s$.

The transmitted signal in one frame is given by equation (1)

$$s(t) = Re\left\{ e^{j2\pi f_c t} \sum_{l=0}^{67} \sum_{k=K_{min}}^{K_{max}} c_{l,k} \psi_{l,k}(t) \right\} \quad (1)$$

where

$$\psi_{l,k}(t) = \begin{cases} e^{j2\pi k'(t-\Delta-lT_s)/Tu} & lT_s \le t \le (l+1)T_s, \\ 0 & \text{else.} \end{cases} \quad (2)$$

where k' is the carrier index relative to the centre frequency $k' = k - (K_{max} - K_{min})/2$, T_u is the inverse of the carrier spacing and Δ is the duration of the guard interval. The spectrum of the DVB-T signal, with a 8 MHz channel bandwidth and a central frequency of 36 MHz, is shown in Figure 1.

Note that the corresponding autocorrelation function or matrix will be similar to a $sinc(x)$ function corresponding to the inverse Fourier transform of the spectral density depicted in this figure. In fact, the baseband form of the above spectrum can be used to provide an estimate of the autocorrelation signal of the primary user. The alternative is to use the forward backward autocorrelation estimate directly from $s(t)$, the resulting autocorrelation matrix will be referred to hereafter as $\underline{\underline{R}}_c$, i.e. the candidate autocorrelation. At the same time, the autocorrelation matrix of the band pass signal with central frequency f_o can be formulated as $\left(\underline{S}.\underline{S}^H\right) \otimes \underline{\underline{R}}_c$, where $\otimes$ denotes the Kronecker product, and vector $\underline{S}$, for an order Q matrix is defined as $\underline{S} = [\ 1 \quad exp(j2\pi f_o) \quad \ldots \quad exp(j2\pi f_o(Q-1))\ ]^H$.

3. SPECTRUM SENSING METHODS

Spectrum sensing has been identified as an important functionality of CR with the objective of periodically and dynamically sensing the radio spectrum, in order to detect the presence of primary users in a reliable manner. In general, spectrum sensing methods can be divided in three categories namely transmitter detection, cooperative detection and interference-based energy methods [5]. This work focuses its contribution on the category of transmitter detection. Within this category, there are three different approaches which can be encompassed under: energy detection, matched filter detection and cyclo-stationary feature detection. The Candidate detector is included as the fourth alternative within this category. Each of these techniques differs from the others in the a priori knowledge available of the primary user signal. We describe next a summary of the major differences among these four methods.

The simplest method is energy detection, which is basically measuring directly the incoming energy in a given bandwidth of analysis. Energy detection is the baseline for the so-called filter bank analysis for spectral estimation The major drawback of energy detection is that it is unable to differentiate among primary user energy and secondary or interference energy. The main advantage, together with the mentioned low complexity is that it does not requires specific a priori knowledge of the transport waveform. Based on a full knowledge of the primary user signal structure , including time and carrier synchronization, one can be use the so-called matched filter detector. Nevertheless, this full coherent method becomes unpractical in actual CR scenarios. A technique that is in between the energy detection and matched filter detection is the so-called cyclo-stationary methods. In the letter the information required is the carrier frequency and the cycle frequency of the primary user, that most of the cases coincides with the modulation rate or baud rate. Nevertheless, only a non-parametric version of cyclic spectral estimation is reported. This non parametric character implies low resolution together with a low quality performance versus complexity trade-off. Since the sample size needed to obtain a reliable detection in spectrum sensing has to be low, the low resolution and the need of long data records constitute the major drawback of cyclo-stationary based methods.

To overcome the above mentioned drawbacks in [3], [6], the authors proposed a new procedure for spectral estimation that is able to detect the presence of a given spectral shape, which is defined by its autocorrelation matrix $\underline{\underline{R}}_c$ at baseband, in a given data signal record. Next section describes briefly this procedure.

4. CANDIDATE POWER ESTIMATE

Most of the important procedures for spectral estimation can be formulated as a problem of spectral subtraction. Given a data autocorrelation matrix estimate, the spectral subtraction framework states the problem as how much power can be subtracted at a given frequency, defined by vector $\underline{S}$ as defined previously, from the data autocorrelation matrix, as indicated in (3)

$$\left(\underline{\underline{R}} - \lambda(f).\left(\underline{S}.\underline{S}^H\right)\right). \tag{3}$$

First, note that the baseband model for the spectral subtraction is the contribution of a dc signal, i.e. zero frequency, which is described by $\underline{\underline{R}}_c = \underline{1}.\underline{1}^H$ where $\underline{1}$ denotes the vector with one in all its components. This $\underline{\underline{R}}_c$ dc baseband candidate is modulated at any frequency f as (4) indicates

$$\left(\underline{S}.\underline{S}^H\right) \otimes \left(\underline{1}\underline{1}^H\right) = \underline{S}.\underline{S}^H. \tag{4}$$

The purpose is to do a frequency scanning when solving the spectral subtraction problem in (3). For example, looking for the power level that minimizes the Frobenious norm of (3) the result is the well known WOSA method or average of periodograms. On the other hand, looking for the maximum power level that preserves the definite character of the difference matrix, the Capon's method arises (see reference [6] for further details).

The basic idea of the Candidate estimate is to replace the baseband single carrier form by the primary user baseband autocorrelation matrix. Thus, the candidate formulation of the spectral subtraction problem becomes (5)

$$\left(\underline{\underline{R}} - \lambda(f).\lfloor\left(\underline{S}.\underline{S}^H\right) \otimes \underline{\underline{R}}_c\rfloor\right). \tag{5}$$

The power level $\lambda(f)$ is estimated as the maximum that preserves the positive definite character of the difference matrix. The solution to this problem is the minimum eigenvalue shown in (6) [3][6]

$$\lambda(f) = \lambda_{min}\left(\underline{\underline{R}}^{-1}\left(\underline{S}.\underline{S}^H\right) \otimes \underline{\underline{R}}_c\right). \tag{6}$$

In summary, the autocorrelation matrix for the DVB-T is estimated from a baseband data record with enough samples to obtain a reliable estimate. Once the matrix is available, for every scanned frequency, the power level of a potential primary user present in the signal under processing is obtained from (6). Note that (6) reduces to the well-known Capon's power level estimate when the candidate is a single carrier at zero frequency.

5. DVB-T PRIMARY USER DETECTORS

This section describes briefly the two procedures to be evaluated in the simulations section, i.e. the candidate detector described in the previous section and the cyclo detector as it is reported in reference [7].

The wireless scenario used in the simulations section will contain a DVB-T primary user centered at 36 MHz, and 1705 subcarriers using 16 QAM modulation. A narrowband interference (an unmodulated carrier) is present with 10 dB SNR and located at 60 Mhz. The cyclic prefix of the OFDM signal represents the 25% of the duration of the information symbol.

The filter order of the candidate estimate is denoted as Q and it will be set equal to 40 in the simulations section. The number of samples of the signal used for detection M, will be set to 200.

The sample autocorrelation matrix will be computed using the forward and backward method formulated as (7)

$$\underline{\underline{R}} = \frac{1}{2(M-Q)}\sum_{n=Q}^{M-1}\{\underline{X}_n.\underline{X}_n^H + \underline{\underline{J}}.\underline{X}_n^*.\underline{X}_n^T.\underline{\underline{J}}\} \tag{7}$$

where upper indexes H, T and $*$ denote hermitic, transpose and complex conjugate respectively, $\underline{X}_n$ is a column vector arranging Q consecutive samples of the data signal from $x(n)$ down to $x(n-Q+1)$, finally matrix $\underline{\underline{J}}$ denotes the exchange matrix with main cross diagonal elements equal to one and the rest entries equal to zero.

The candidate estimate will exhibit the estimate power level at each frequency scanned through vector $\underline{S}$, and computed as the minimum eigenvalue formulated in (6). For detection purposes the estimate (6), at a pre-selected central frequency, will be compared with a threshold γ set to achieve a given point in the probability of detection versus false alarm graphic (ROC).

Since our aim is to prove the superiority of the candidate approach versus the cyclo-stationary approach, the second is summarized briefly herein.

A non-stationary cyclic random process, as it is the case for the most used linear modulation schemes, presents an autocorrelation function as given in (8)

$$r(t,\tau) = r(\tau) + \sum_{\alpha\in\Psi} R(\alpha,\tau)e^{j2\pi\alpha t} \tag{8}$$

where

$$R(\alpha,\tau) = \lim_{T\to\infty}\frac{1}{T}\int_{-T/2}^{T/2} r(t,\tau)e^{-j2\pi\alpha t}dt \tag{9}$$

which is named the cyclic autocorrelation function, α is the cyclic frequency and Ψ is the total set of cyclic frequencies. Applying the principle of synchronized averaging [7] to (8) and using the sampled version of the original signal $x(t)$, the autocorrelation function is (10)

$$\hat{r}^{(N)}(n,\tau) = \frac{1}{N}\sum_{k=0}^{N-1} x(n+kT_o)x(n+kT_o+\tau) \tag{10}$$

where T_o is any cyclic period and N is the number of symbols of the signal.

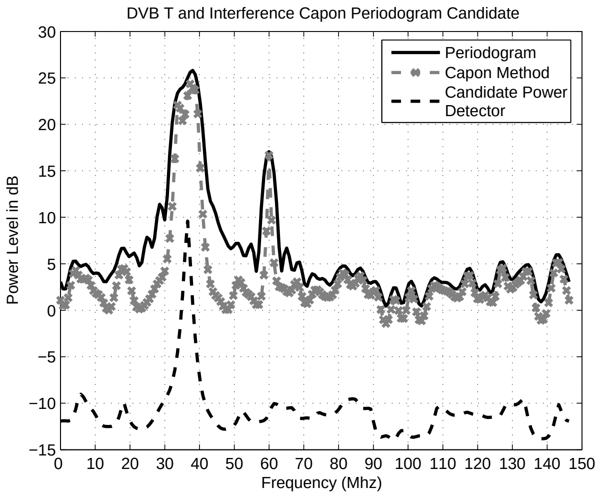

Figure 2: Power spectral estimation using Periodogram, Capon's Method and Candidate power detector. 36 Mhz DVB-T primary user signal with SNR=10 dB and the interference located at 60 Mhz and with SNR=10 dB. The record consists of 200 samples

Next, we formulate the hypothesis testing for this cyclo-stationary approach. Considering that this procedure is only based on the test of presence of cyclo-stationary signal. In others words the first term in (8) is present for any cyclic and non-cyclic autocorrelation in consequence the detection variable is formed as the difference between (8) and its first term [7], i.e. $\overline{r}(n,\tau) = r(t,\tau) - r(\tau)$. This variable will be theoretically zero for records when the cyclic component is absent, H_0 hypothesis, and different from zero under the presence of a cyclic component, H_1 hypothesis. Nevertheless, the finite number of data samples available induces and error term that depends on the symbols number (N). In summary the hypothesis testing is (11)

$$\begin{array}{lll} H_0 & : & \hat{\overline{r}}^{(N)}(n,\tau) = \varepsilon^{(N)}(n,\tau) \\ H_1 & : & \hat{\overline{r}}^{(N)}(n,\tau) = \overline{r}(n,\tau) + \varepsilon^{(N)}(n,\tau) \end{array} \quad (11)$$

where $\varepsilon^{(N)}(n,\tau)$ is the estimation error.

6. SIMULATION RESULTS

First we show the claimed performance of the candidate power level estimation. For this purpose the high SNR scenario depicts clearly the behavior of the candidate estimate, the OFDM signal is set to 10 dB of SNR at 36 MHz, together with a narrowband interference located at 60 MHz, with the same SNR, in white gaussian noise. The sample size was 200 samples (M=200) and the estimates order is 40 (Q=40).

Figure 2 presents the periodogram estimate, i.e. the response of an energy detector, and the traditional Capon's estimate.

Note that the candidate is robust against interference or narrowband secondary users's transmissions. At the same time it provides a clear peak at the actual frequency location of the OFDM signal with 9.6 dB as power level estimate. Clearly the candidate only reacts to the presence of the candidate in the signal. Also note that even in-band narrowband interferences do not affect severely the accuracy of the OFDM power level estimate.

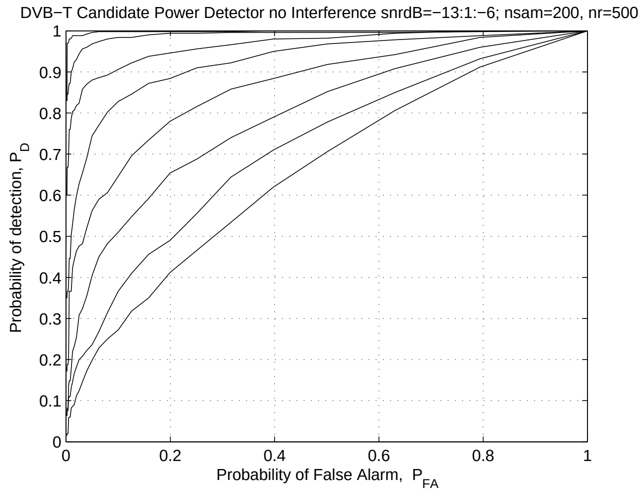

Figure 3: ROC performance of Candidate Power Detector, no interference. 36 Mhz DVB-T primary user signal with SNR ranges from -13 dB to -6 dB. Each record consist of 200 samples

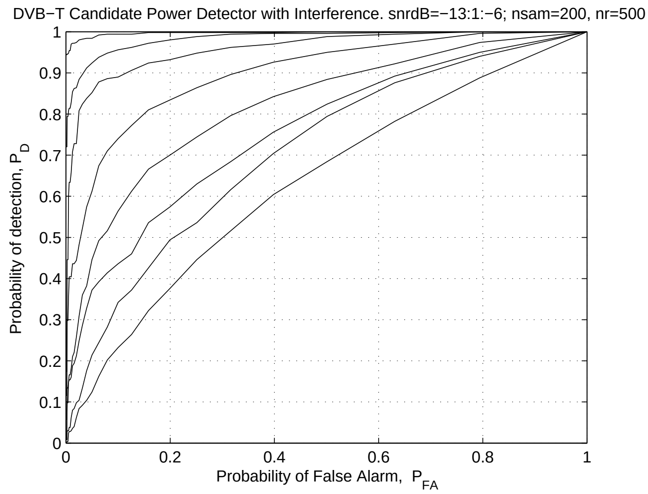

Figure 4: ROC performance of Candidate Power Detector. 36 Mhz DVB-T primary user signal with SNR ranges from -13 dB to -6 dB and 60 Mhz interference with SNR 10 dB. Each record consist of 200 samples

In order to test the candidate estimate in realistic CR scenarios, Figure 3 shows the ROC performance, i.e. probability of detection versus probability of false alarm, for SNR ranging from -13 dB up to -6 dB.

Figure 4 shows the ROC curves for the same SNR range and OFDM signal than in previous figure, but in the presence of a narrowband interference of 10 dB, i.e. from 16 up to 23 dB above the primary user power level. This performance is

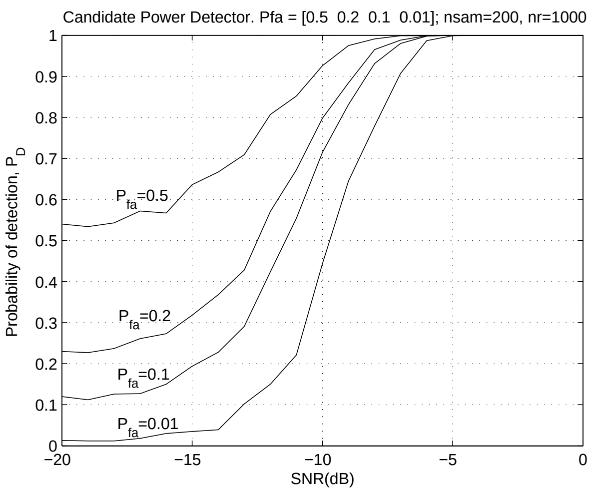

Figure 5: Performance of Candidate Power Detector as a function of SNR for several constant false alarm rate (0.5, 0.2, 0.1 and 0.01). The record length is 200 samples. The wireless scenario is free interference and 36 Mhz DVB-T primary user signal with SNR ranges from -20 dB to 0 dB.

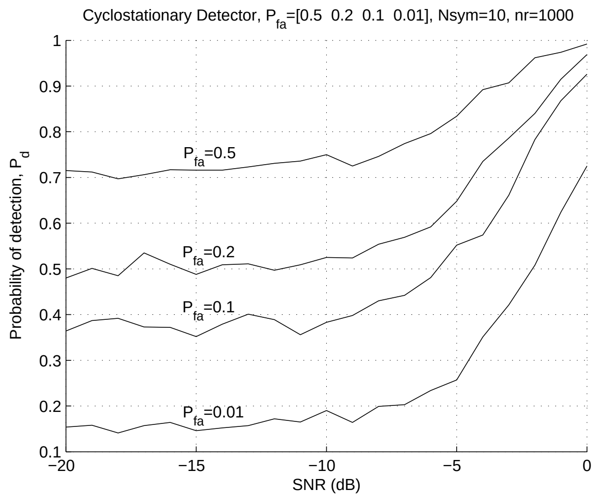

Figure 6: Performance of Cyclo-stationary Detector as a function of SNR for several constant false alarm rate (0.5, 0.2, 0.1 and 0.01). The wireless scenario is the same as in Figure 5 but the record length is of 800 samples (i.e. four times larger than in Figure 5)

in accordance with the low sensitivity of the candidate estimate shown in Figure 2.

Finally, figures 5 and 6 compare the performance of the candidate method versus the cyclo-stationary approach outlined in the previous section. These plots show the evolution of the probability of detection versus primary SNR for several constant false alarm rate (0.5, 0.2, 0.1 and 0.01). The scenario is the same but the number of samples used in the cyclo-stationary approach is four times greater than for the candidate. It can be observed in the Figure 5, If the SNR is -10 dB the candidate detector obtains a $P_d = 0.92$ for a $P_{fa} = 0.5$. Whereas, the cyclo-stationary detector to achieve the same probability of detection as candidate a SNR= -3 dB is needed (see Figure 6). Therefore, by using less number of samples, the candidate detector still obtains a gain of 7 dB gain with respect to the cyclo-stationary detector. Besides, this gain can be computed with good approximation as $10log10(\lambda_{max}(Rc))$=12.8 dB, which corresponds to how much dB's the candidate detector's performance is better than cyclo-stationary approach.

7. CONCLUSIONS

The performance of the so-called Candidate detector, based on generalized spectral subtraction, is reported for DVB-T signals. The DVB-T signal, considered as the primary user signature in a cognitive radio scenario, is detected in presence of narrowband interferers that may correspond to secondary users and in SNR regimes ranging from -13 up to -6 dB that correspond to realistic scenarios. Requiring only the spectral shape of the primary user, the Candidate detector stays always with superior quality than traditional energy detectors or the cyclo-stationary based methods. The candidate detector provides accurate power level estimates and central frequency location, even in the presence of severe narrow band interferences.

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