SPECTRAL OCCUPANCY MEASUREMENTS IN URBAN AREAS AND THEIR APPLICABILITY TO THE BLIND STANDARD RECOGNITION SENSOR CONCEPT

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ABSTRACT

Cognitive Radio (CR) has been paid much attention in both academic and industrial domains during the last years for its potential capability to solve to the so-called spectrum scarcity problem. The CR concept arose as a result of the current spectrum underutilization, which was demonstrated in a number of spectrum measurement campaigns. The main objective of such measurements was to evaluate spectrum occupancy, and hence empirical data were employed mainly to determine whether spectral bands were occupied or not. Empirical spectrum measurements can find however further practical applications. In this context, this paper presents some spectrum measurements that have been performed in the framework of a broadband spectrum measurement campaign and presents the Blind Standard Recognition Sensor (BSRS) concept, which can be validated with such measurements. The BSRS is a sensor embedded in a CR equipment to permit the identification of many commercial wireless standards without the need to connect to any network.

1. INTRODUCTION

Cognitive Radio (CR) has been identified as a promising solution to the existing conflicts between spectrum demand growth and spectrum underutilization [1]. The basic idea of this paradigm is to allow unlicensed users to access in an opportunistic and non-interfering manner some licensed bands temporarily unoccupied by licensed users.

The CR concept relies on the premise that spectrum is currently underutilized, which has been demonstrated in several spectrum measurement campaigns covering both wide frequency ranges [2]–[4] as well as some specific licensed bands [5]–[9] in diverse locations and scenarios. The main objective of such measurement campaigns was to quantitatively evaluate spectral occupancy in order to determine the degree to which allocated spectrum bands were occupied in real wireless communication systems. Hence, the data digitized during these studies were employed mainly to determine whether certain spectrum bands were occupied or not during a given measurement period.

Nevertheless, besides evaluating actual spectrum usage, empirical spectrum measurements can find further practical applications such as evaluation of CR techniques (e.g., [9][10]) or modeling of spectral activity (e.g., [11]). Furthermore, empirical data may be useful to extract some signal information that can be used not only to determine whether a spectrum band is occupied or not, but also to infer the system and standard being detected. This information may be exploited by a CR network to properly adapt to the operating environment and hence to improve the overall spectrum utilization and system performance.

In this context, this paper presents some spectrum measurements that have been performed in the framework of a broadband spectrum measurement campaign [12] and presents the Blind Standard Recognition Sensor (BSRS) concept [13], whose feasibility can be demonstrated and validated with empirical measurements. The BSRS is a sensor embedded in a CR equipment to permit the identification of many commercial wireless standards without the need to connect to any network. It combines (by a fusion process) information provided by several other sensors using signal processing algorithms such as radial basis neural network, Wigner-Ville transform, cyclostationarity detection, etc.

The rest of this paper is organized as follows. First, Section 2 describes the equipment employed to perform the measurements reported in this paper, its configuration and the considered measurement methodology. The obtained occupancy results are presented and discussed in Section 3. The BSRS is presented in section 4. Finally, Section 5 summarizes and concludes the paper.

2. MEASUREMENT SETUP AND METHODOLOGY

The measurement configuration used to conduct this study consisted of a broadband discone antenna AOR DN753 (vertically polarized with omni-directional receiving pattern in the horizontal plane) specified for the frequency range 75 MHz – 3 GHz, connected with a 10-meter low loss coaxial cable RG-58A/U to a high performance handheld spectrum analyzer Anritsu Spectrum Master MS2721B.

During the measurements the antenna was placed on a building roof in Barcelona (latitude: 41º 23' 20" north; longitude: 2º 6' 43" east; altitude: 175 meters). The selected place is a strategic location with direct line-of-sight to several transmitting stations located a few tens or hundreds of meters away from the antenna and without buildings blocking the radio propagation. This strategic location enabled us to accurately measure the spectral activity of, among others, a TV repeater, a FM broadcast station, several nearby base stations for cellular mobile communications and a military headquarter as well as some potential maritime and aeronautical transmitters due to the relative proximity to the Barcelona's harbor and the Barcelona's airport.

The main configuration parameters used for the spectrum analyzer are shown in TABLE I. The measured frequency range was divided into six consecutive 500 MHz blocks. Each block was measured during a continuous period of 48 hours and more than 10000 traces were obtained for each block. The measured traces were saved in an external storage device and post-processed off-line using MATLAB.

TABLE I. SPECTRUM ANALYZER CONFIGURATION.

Parameter	Value
Center frequency	Block 1: 250 MHz Block 4: 1750 MHz Block 2: 750 MHz Block 5: 2250 MHz Block 3: 1250 MHz Block 6: 2750 MHz
Frequency span	500 MHz
Resolution/video bandwidth (RBW/VBW)	10 kHz / 10 kHz
Sweep time	Automatically selected
Reference level	– 20 dBm
Scale	10 dB/div
Detection type	RMS detector

TABLE II. AVERAGE DUTY CYCLE STATISTICS.

Block	Frequency range (MHz)	Average duty cycle		
1	75 – 500	60.98 %	58.65 %	22.57 %
2	500 – 1000	56.67 %		
3	1000 – 1500	2.07 %	5.89 %	
4	1500 – 2000	12.08 %		
5	2000 – 2500	7.57 %		
6	2500 – 3000	1.85 %		

3. MEASUREMENT RESULTS AND ANALYSIS

3.1 Occupancy Metrics

The obtained measurement results are shown in Figures 1 and 2. Each figure is composed of three graphs, each one corresponding to a specific occupancy metric. The upper graph shows the minimum, maximum and average Power Spectral Density (PSD) measured for each 500 MHz spectrum block. The middle graph shows the temporal evolution of the spectrum occupancy during the whole 48 hour measurement period. A black dot indicates that the corresponding frequency point was measured as occupied at that time instant, while the white color means that the frequency point was measured as idle. To determine whether a given frequency is occupied or not, energy detection is assumed. Different sensing methods have been proposed in the literature to detect whether a frequency band is being used by a licensed user [14]. They provide different trade-off between required sensing time, complexity and detection capabilities. Depending on how much information is available about the signal used by the licensed network different performances can be reached. However, in the most generic case no prior information is available about the licensed signal. In such a case, the energy detection method is the only possibility left. Energy detection compares the received signal energy in a certain frequency band to a predefined threshold. If the signal is above the threshold, the band is determined to be occupied by the licensed network. Otherwise the band is supposed to be idle and could be used by a CR network. Following this principle, the measured PSD is compared to a threshold. Measured samples above the threshold are assumed to be occupied; the rest of frequencies are assumed to be idle. To compute the decision threshold, the antenna was replaced by a matched load of 50 Ω in order to measure the system's noise. At each frequency point the decision threshold was fixed such that only 1% of the measured noise samples lied above the threshold, which implies a false alarm probability of about 1%. It is worth noting that the decision threshold obtained with this method is not constant since the system noise floor slightly increases with the frequency. Finally, the lower graph in each figure shows the duty cycle or percentage of time that each frequency point is measured as occupied by a licensed signal. The average duty cycle over each 500 MHz spectrum block is also shown.

3.2 Overview of Spectrum Occupancy

The occupancy results shown in Figures 1 and 2 indicate that spectrum experiences a relatively high use below 1 GHz while remains mostly underutilized between 1 and 3 GHz, with some exceptions such as the DCS 1800 system (1710-1785 MHz and 1805-1880 MHz) and the UMTS system (1920-1980 MHz and 2110-2170 MHz). The obtained numerical occupancy results are summarized in TABLE II. As it can be appreciated, while the average duty cycle between 75 and 1000 MHz is 58.65%, the value for this parameter between 1000 and 3000 MHz is only 5.89%. The overall average duty cycle over the whole frequency range considered in this study is 22.57%, which indicates the existence of a significant amount of unused spectrum that could potentially be exploited by future CR networks.

Although these results indicate low spectrum utilization, they do not provide an idea of how spectrum is used in different bands allocated to different specific services. Looking into Figures 1 and 2 in more detail, it can be observed that spectrum bands below 235 MHz, assigned to FM broadcasting (87.5-108 MHz), maritime and aeronautical radionavigation (108-174 MHz), audio broadcasting (174-223 MHz) and Private/Professional Mobile Radio (PMR) systems (223-235 MHz), show an intensive usage with average duty cycles between 90% and 100%.

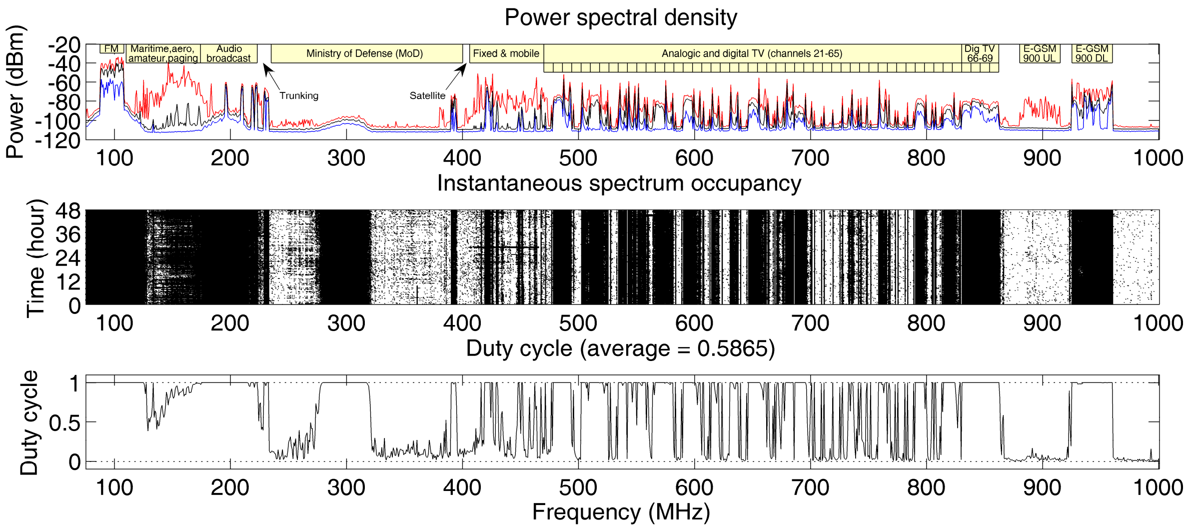

Figure 1. Occupancy results between 75 and 1000 MHz.

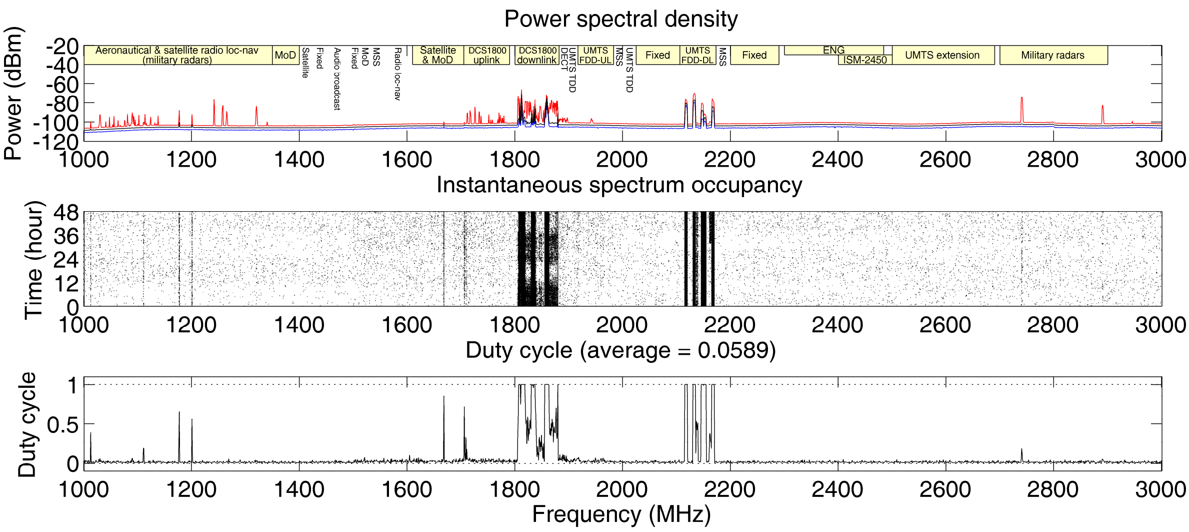

Figure 2. Occupancy results between 1000 and 3000 MHz.

The spectrum band between 235 and 400 MHz shows some potential opportunities for CR networks in the intervals 235-273 MHz (duty cycle of 18.14%) and 322-390 MHz (duty cycle of 12.89%). However, the whole band from 235 to 400 MHz is exclusively reserved for security services and systems, which in principle precludes the use of such spectrum bands for CR networks. Other bands below 1 GHz with low or moderate levels of activity but narrower available free bandwidths are those assigned to wireless microphones and RFID (862-870 MHz), CT1 cordless phones (870-871 and 915-916 MHz), cellular access rural telephony (874-876 and 919-921 MHz), R-GSM 900 (876-880 and 921-925 MHz) and several fixed and mobile services (400-470 MHz).

The frequency band 470-862 MHz, which is allocated to analogical and digital terrestrial TV, exhibits a notable usage. The average duty cycle in this band (66.58%) however indicates that one third of the band (approximately 130 MHz) can be considered as unoccupied due to the weak reception of signals from faraway TV broadcasting stations. Therefore, although this band is considerably populated it provides some interesting opportunities for CR networks.

Spectrum bands allocated to mobile cellular communication systems show a moderate to high usage, as it can be inferred from the average duty cycles of 96.20%, 59.75% and 48.38% observed in the downlink directions of E-GSM 900 (925-960 MHz), DCS 1800 (1805-1880 MHz) and UMTS (2110-2170 MHz) respectively. While E-GSM 900 is subject to an intensive usage, lower duty cycles are observed for DCS 1800 (due to a well defined periodic usage pattern, with higher occupancy between 0-12 and 24-36 hours in the middle graph of Figure 2) and also for UMTS (due to the presence of several 5 MHz unoccupied channels).

The usually overcrowded ISM-2450 band (2400-2500 MHz) appears as unused in our measurement location, which could be explained by the fact that is is usually occupied in indoor environments and signals at such frequencies are severely attenuated by walls. The rest of spectrum between 1-3 GHz not discussed in the lines above remains mostly unused, with the exception of some very low duty cycle signals from aeronautical and satellite radio-location/navigation systems (960-1350 and 1610-1710 MHz), DECT cordless phones (1880-1900 MHz) and military radars (2700-2900 MHz).

4. BLIND STANDARD RECOGNITION SENSOR

4.1 General Description

As it is described in Figure 3, this sensor analyzes the received signal in three steps. The first step is an iterative process that decreases the signal bandwidth to be analyzed further, so that the band of analysis is reduced to the only non-zero regions. During the second step an analysis is performed thanks to several sensors. Then during the third step, a fusion of all the information given by the analysis phase is performed in order to decide which standard is present.

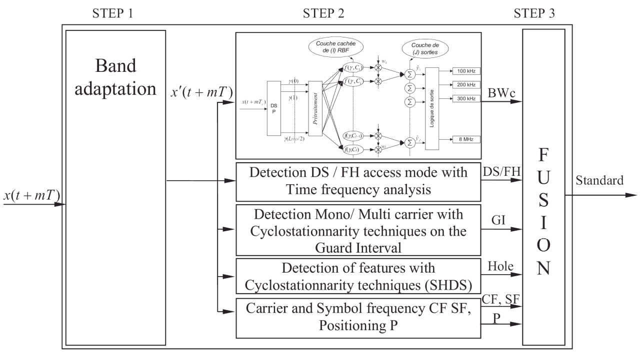

Figure 3. The new standard recognition sensor.

During the second step, different sensors analyze the bands selected in step one. Many sub-sensors could be used for the recognition of the standard in use as: positioning of the equipment, presence of the telecom signal, detection of the carrier frequency, recognition of the bandwidth of telecom signal, recognition of the Frequency Hopping / Direct Sequence (FH/DS) signal, recognition of single/multi-carrier, etc. In our implementation only three sub-sensors are used for the recognition of the standards in the table of the section.

4.2 Step 1: Bandwidth Adaptation

The difficulty here relies in the fact that the ratio between the global bandwidth to be analyzed and the smallest bandwidth parameter to be recognized may be very high. Therefore an iterative adaptation of the bandwidth to be analyzed is performed to solve it. Each iteration the process analyzes energy in the band with a conventional periodogram, then filters and decimates the samples around the detected peak of energy.

4.3 Step 2: Analysis with Sensors

We chose three sub-sensors to analyze and identify the received signal according with a list of predetermined standards: the bandwidth recognition, single/multi-carrier detection and FH/DS signal detection. Other sensors could be used to identify other parameters.

4.3.1 The Bandwidth Recognition

In [15] it was claimed that, in the frequency domain, the channel bandwidth (BWc) was a fully discriminating parameter. To find the bandwidth shape on the received signal a choice has been made to perform a PSD on this signal in order to obtain its BWc shape. The empirical spectrum shape is compared with a reference shape as shown in Figure 4.

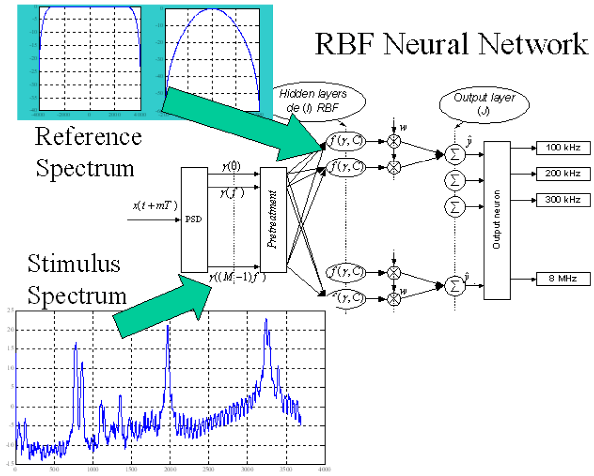

Figure 4. The radial basis functional neural network (RBF NN).

This comparison is performed using Radial Basis Functional Neural Networks (RBF NN). Using the RBF NN, this PSD is compared with the reference signals PSD. Then a neuron will be active. To each neuron number i corresponds the bandwidth of the standard number i.

4.3.2 Single/Multi-Carrier Detection

The overall results presented in [15] shown that the recognition rate between DVB-T and LMDS on the one hand, DAB and DECT on the other hand, was not good enough. Therefore we propose to improve this recognition adding a new sensor that discriminates between single and multi-carrier systems based on Guard Interval (GI) detection.

It is well known that a GI is inserted in multi-carrier systems in order to avoid Inter-Symbol Interference (ISI). There are several possibilities for creating this GI. The simplest and the most usual way is to copy the end of the symbol in the GI. After the computation of the autocorrelation function, the cyclic frequency corresponding to the GI is derived.

4.3.3 FH/DS Signal Detection

The results previously presented with the fusion of the two previous sensors are not sufficient yet. It fails in the discrimination of Bluetooth and IEEE 802.11b at 2.4 GHz in FHSS mode. In this situation, the two standards coexist at the same time in the same frequency band, so the resulting spectrum is the product of the original spectrums and consequently the previous sensor does not run correctly.

Therefore, we need to find another parameter. The detection between FH and DS modes should solve this difficulty. Recently, [16] addresses this particular problem and proposes to use Wigner-Ville Transform (WVT) in order to discriminate between Bluetooth and IEEE802.11b. The results are well adapted to our needs, because the system can discriminate between FH and DS signals. Figure 5 presents the result of the WVT of a FH signal with noise.

4.4 Step 3: Fusion

During the third step, a fusion of all the information given by the analysis phase is performed in order to decide which standard is present. At the end of the analysis step, three indicators are obtained. The simplest way to make the fusion is to

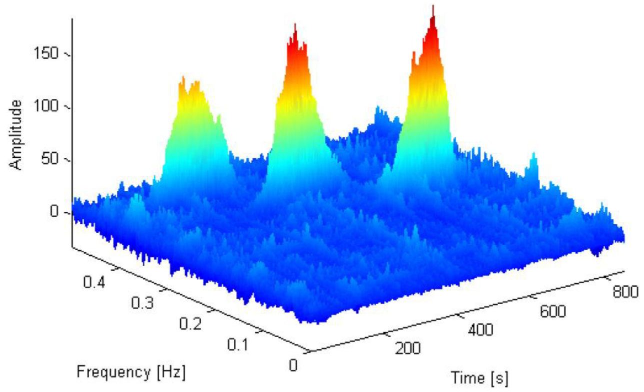

Figure 5. WVT of a FHSS signal with SNR = 5 dB.

apply some logical rules on these indicators. This method could be improved by the use of a NN (like a multilayer perceptron). Moreover, as these indicators give information that could be weighted by a reliability factor, a future work will further explore solutions based on Bayesian networks.

5. SUMMARY

Several spectrum measurements campaigns have been performed with the aim of evaluating the degree to which allocated spectrum bands are occupied in real wireless communication systems. However, empirical spectrum measurements can find further practical applications such as evaluation of CR techniques, modeling of spectral activity and validation of new concepts. In this context, this paper presented some spectrum measurements that were performed in the framework of a broadband spectrum measurement campaign and described the Blind Standard Recognition Sensor (BSRS) concept, whose feasibility is demonstrable and verifiable with empirical measurements. In future work we plan to further explore the applicability of such empirical data to the demonstration and validation of the BSRS concept.

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REFERENCES

[1] F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, "A survey on spectrum management in cognitive radio networks," *IEEE Communications Magazine*, vol. 46, no. 4, pp. 40 – 48, Apr. 2008.

[2] F. H. Sanders, "Broadband spectrum surveys in Denver, CO, San Diego, CA, and Los Angeles, CA: methodology, analysis, and comparative results," in *Proc. IEEE International Symposium on Electromagnetic Compatibility* (EMC 1998), Aug. 1998, vol. 2, pp. 988–993.

[3] Shared Spectrum Company (SSC), "Spectrum occupancy measurements," *SSC reports* (Jan. 2004 – Aug. 2005). Available at: http://www.sharedspectrum.com/measurements.

[4] A. Petrin, P. G. Steffes, "Analysis and comparison of spectrum measurements performed in urban and rural areas to determine the total amount of spectrum usage," in *Proc. International Symposium on Advanced Radio Technologies* (ISART 2005), Mar. 2005, pp. 9–12.

[5] P. G. Steffes, A. J. Petrin, "Study of spectrum usage and potential interference to passive remote sensing activities in the 4.5 cm and 21 cm bands," in *Proc. IEEE International Geoscience and Remote Sensing Symposium* (IGARSS 2004), Sep. 2004, vol. 3, pp. 1679–1682.

[6] J. Do, D. M. Akos, P. K. Enge, "L and S bands spectrum survey in the San Francisco bay area," in *Proc. Position Location and Navigation Symposium* (PLANS 2004), Apr. 2004, pp. 566–572.

[7] M. Biggs, A. Henley, T. Clarkson, "Occupancy analysis of the 2.4 GHz ISM band," *IEE Proc. on Comms*, vol. 151, nº 5, pp. 481–488, Oct. 2004.

[8] S. W. Ellingson, "Spectral occupancy at VHF: implications for frequency-agile cognitive radios," in *Proc. IEEE 62nd Vehicular Technology Conference* (VTC 2005 Fall), Sep. 2008, vol. 2, pp. 1379–1382.

[9] S. D. Jones, E. Jung, X. Liu, N. Merheb, I.-J. Wang, "Characterization of spectrum activities in the U.S. public safety band for opportunistic spectrum access," in *Proc. 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks* (DySPAN 2007), Apr. 2007, pp. 137–146.

[10] M. Wellens, J. Riihijärvi, M. Gordziel, P. Mähönen, "Evaluation of cooperative spectrum sensing based on large scale measurements," in *Proc. 3rd IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks* (DySPAN 2008), Oct. 2008, 12 pp.

[11] S. Geirhofer, Lang Tong, B. M. Sadler, "A measurement-based model for dynamic spectrum access in WLAN channels," in *Proc. Military Communications Conference* (MILCOM 2006), Oct. 2006, 7 pp.

[12] M. López-Benítez, A. Umbert, F. Casadevall, "Evaluation of spectrum occupancy in Spain for cognitive radio applications," to appear in *Proc. IEEE 69th Vehicular Technology Conference* (VTC 2009 Spring), Apr. 2009 (accepted).

[13] R. Hachemani, J. Palicot, C. Moy, "A new standard recognition sensor for cognitive terminals," in *Proc. 15th European Signal Processing Conference* (EUSIPCO 2007).

[14] A. Sahai, N. Hoven, R. Tandra, "Some fundamental limits on cognitive radio," in *Proc. Forty-second Allerton Conference on Communications, Control, and Computing* (Allerton Conference 2004), Sep. 2004, 10 pp.

[15] J. Palicot, C. Roland, "A new concept for wireless reconfigurable receivers," *IEEE Communications Magazine*, vol. 41, no. 7, pp. 124 – 132, Jul. 2003.

[16] M. Gandetto, A. F. Cattoni, M. Musso, C. S. Regazzoni, "Distributed cooperative mode identification for cognitive radio applications," *General Assembly of International Union of Radio Science* (URSIGA 2005), Oct. 2005.