

A Real-Time Spectrum Sensing Platform Using Software-Defined Radio for TV White Spaces

João Victor Fernandes Borges, Rausley Adriano Amaral de Souza, Luciano Leonel Mendes, Arismar Cerqueira Sodr  Junior, and Andr  Ant nio dos Anjos

Abstract—This paper presents a real-time spectrum sensing platform for TV white space (TVWS) applications based on software-defined radio (SDR) and experimentally validated under realistic propagation conditions. The proposed system employs the Ettus USRP N210 and MATLAB to perform energy-detection-based sensing over ultra high frequency (UHF) television channels compliant with the ISDB-T_B standard. Experimental evaluations were conducted in wired and wireless environments, including line-of-sight (LoS) and non-line-of-sight (nLoS) scenarios, considering different signal-to-noise ratio (SNR) levels and sample sizes. The results demonstrate close agreement between theoretical and experimental performance trends, validating the reliability of the implemented sensing system in practical environments. In addition, the analyses show the impact of multipath propagation and fading conditions on sensing performance, revealing the limitations of idealized theoretical channel models in real wireless scenarios. The developed SDR platform demonstrates the feasibility of low-cost, real-time spectrum sensing for future TVWS-based cognitive radio, 5G, and 6G systems.

Keywords—TV white spaces, spectrum sensing, energy detection, ISDB-T_B, wireless communication.

I. INTRODUCTION

The growing demand for ubiquitous connectivity and advanced wireless services is accelerating the evolution toward next-generation communication networks [1]. However, the deployment of these advanced systems is constrained by spectrum scarcity of the electromagnetic spectrum [2]. Several studies indicate that the current spectrum scarcity is not solely a result of the physical limitations of the electromagnetic spectrum but also stems from its underutilization [3]. This underutilization is particularly pronounced in the very high frequency (VHF) and ultra high frequency (UHF) bands designated for TV channel allocation. It is worth mentioning that radio waves in the TV frequency range exhibit characteristics that enable effective coverage over extensive areas. These waves can penetrate physical obstacles, such as buildings and vegetation, enabling broader and more efficient coverage in long-range scenarios.

Known internationally as TV white spaces (TVWS), the unutilized portions of the TV spectrum are emerging as a solution to the scarcity problem, aligning with the principles of Dynamic Spectrum Access. The National Telecommunications Agency (ANATEL) in Brazil has recently approved

a resolution to regulate the dynamic use of idle TVWS spectrum by secondary users, initially designating bands such as 54-72 MHz, 174-216 MHz, 470-608 MHz, and 614-698 MHz for this purpose [4]. Although the regulation of usage conditions is still ongoing, it is anticipated that it will open avenues for employing idle TV bands in mobile cellular and broadband services. Despite the interest from regional providers in utilizing TVWS, suitable equipment remains limited for opportunistic spectrum use. In this context, there is an urgent demand for the development of intelligent radios, commonly referred to as cognitive radios (CRs), equipped with advanced spectrum-sensing capabilities. This holds the promise of mitigating the challenge posed by the scarcity of the electromagnetic spectrum.

In spectrum sensing, numerous studies explore diverse scenarios and utilize various implementation techniques. For example, the authors of [5] provide an overview of cognitive radio architectures and spectrum sensing techniques, such as matched filtering, energy detection, and cyclostationary detection. Another study in [6] investigates spectrum sensing with multiple antennas, employing likelihood ratio detection and power spectral density division cancellation. Additionally, [7] presents research on spectrum detection based on a composite neural network, aiming to enhance the intelligence of CRs and, consequently, improve sensing technique performance. Despite the extensive body of scientific work, a noticeable gap still exists in practical implementations of spectrum sensing techniques and in experimental studies comparing theoretical models with real-world wireless measurements.

In recent work, the authors of [8] have conducted a practical evaluation of spectrum sensing using eigenvalues, employing the software-defined radio (SDR) USRP N310 for data acquisition. However, the scenarios considered are overly optimistic, assuming line-of-sight (LoS) conditions that may not always be present in real-world environments. Furthermore, the noise accounted for in their simulation setup was artificially introduced via software, which does not accurately represent the actual noise encountered in receiver systems. Thus, more realistic experimental evaluations are necessary for practical validation of cognitive radio systems.

This paper addresses this gap by presenting a practical real-time spectrum sensing platform based on energy detection for TVWS applications, implemented using the Ettus USRP N210 SDR and MATLAB. The proposed system performs real-time scanning of UHF television channels to identify transmission opportunities in practical wireless environments. Initially, the sensing performance is evaluated in a controlled wired sce-

Jo o V. F. Borges and Andr  A. dos Anjos are with Universidade Federal de Uberl ndia (UFU), Pat s de Minas, MG, Brazil (e-mails: joao.borges04@ufu.br, andre.anjos@ufu.br). Rausley, A. A. Souza, Luciano L. Mendes, and Arismar C. Sodre, Jr. are with Instituto Nacional de Telecomunica  es (INATEL), Santa Rita do Sapuca , MG, Brazil (e-mails: rausley@inatel.br, luciano1@inatel.br, arismar@inatel.br).

nario, enabling validation of the theoretical formulation under stable channel conditions. Subsequently, the system is experimentally assessed in realistic wireless environments, including LoS and non-line-of-sight (nLoS) conditions. The obtained experimental results are compared with theoretical predictions, considering both additive white Gaussian noise (AWGN) and Rayleigh fading channels. The presented analyses provide important insights into the impact of practical propagation effects, multipath, and fading on real-time spectrum sensing systems for future cognitive radio, 5G, and 6G applications.

II. SPECTRUM SENSING IN COGNITIVE RADIOS

A. Mathematical Modeling of a Spectrum Sensing System

The system model considers two hypotheses used for decision-making: $\mathcal{H}_0$, corresponding to the absence of a primary user (PU) signal, and $\mathcal{H}_1$, corresponding to its presence. The two hypotheses can be mathematically described as

$$y(t) = \begin{cases} n(t), & \text{if } \mathcal{H}_0 \\ h(t)x(t) + n(t), & \text{if } \mathcal{H}_1 \end{cases} \quad (1)$$

where $y(t)$ is the signal captured and analyzed by the CR, $n(t)$ corresponds to the thermal AWGN in the receiver (RX), $h(t)$ represents the gain or attenuation caused by the communication channel, and $x(t)$ is the PU transmitted signal. To perform the decision-making process regarding spectral occupancy, it is necessary to define a decision variable, T , generated by processing $y(t)$, which will depend on the sensing technique used, and a decision threshold, λ . Thus, if $T > \lambda$, the spectrum is declared occupied; otherwise, it is considered idle.

B. Energy Detection Technique

In energy detection (ED), the presence or absence of a signal is determined by comparing the measured channel energy with a predefined decision threshold. Despite being a well-established spectrum sensing technique, energy detection still attracts considerable attention from researchers due to its low computational complexity and practical implementation simplicity [9], [10].

The decision statistic, T , in ED is calculated according to

$$T = \sum_{i=1}^N |y(i)|^2, \quad (2)$$

where N is the total number of collected samples and $y(i)$ represents the i -th digitized sample acquired by the CR. The computed value of T is then compared with the decision threshold λ to determine whether $\mathcal{H}_0$ or $\mathcal{H}_1$ is satisfied. Under the hypotheses of absence and presence of the PU signal, the decision statistic follows a chi-square distribution with N degrees of freedom [11]. For a sufficiently large number of samples, N , the central limit theorem allows the decision statistic to be approximated by a Gaussian random variable. Under hypothesis $\mathcal{H}_0$, the statistic follows $T \sim \mathcal{N}(N\sigma_w^2, N\sigma_w^4)$, whereas under hypothesis $\mathcal{H}_1$, it follows $T \sim \mathcal{N}(N(\sigma_s^2 + \sigma_w^2), N(\sigma_s^2 + \sigma_w^2)^2)$. Thus, the probabilities

of false alarm and detection are respectively given by

$$P_{fa} = Q\left(\frac{\lambda - N\sigma_w^2}{\sqrt{N\sigma_w^4}}\right), \quad (3)$$

$$P_d = Q\left(\frac{\lambda - N(\sigma_s^2 + \sigma_w^2)}{\sqrt{N(\sigma_s^2 + \sigma_w^2)^2}}\right), \quad (4)$$

where σ_w^2 and σ_s^2 denote the noise and PU signal variances, respectively, and $Q(\cdot)$ represents the Gaussian Q-function associated with the tail probability of the standard normal distribution.

Considering a Rayleigh slow-fading channel, which models a mobile radio environment under nLoS conditions, the instantaneous signal-to-noise ratio (SNR) varies randomly at each sensing interval according to the exponential probability density function $f_\gamma(\gamma) = \frac{1}{\bar{\gamma}}e^{-\frac{\gamma}{\bar{\gamma}}}$, where γ and $\bar{\gamma}$ denote the instantaneous and average SNRs, respectively. In this case, the average detection probability is given in its integral form by

$$P_d = \int_0^\infty \frac{1}{\bar{\gamma}}e^{-\frac{\gamma}{\bar{\gamma}}} Q\left(\frac{\lambda - N(\gamma + 1)}{\sqrt{N(\gamma + 1)^2}}\right) d\gamma. \quad (5)$$

To define the threshold to be used, a constant false alarm rate value is normally used, which can be calculated by isolating λ in (3), and then $\lambda = \sigma_w^2(Q^{-1}(P_{fa})\sqrt{N} + N)$.

III. SDR IMPLEMENTATION

A. Implementation Hardware

The SDR used in the practical implementation is the USRP N210 manufactured by Ettus Research. The platform architecture includes a Xilinx® Spartan® 3A-DSP 3400 FPGA, 100 MS/s dual ADCs, 400 MS/s dual DACs, and Gigabit Ethernet connectivity for streaming data to and from host processors. A modular design enables the USRP N210 to operate from DC to 6 GHz and stream up to 50 MS/s to host applications [12]. The device operates with a daughterboard responsible for the RF analog front-end, and the specific daughterboard employed in this work is the WBX. The WBX operates as a transceiver, providing up to 100 mW of output power with a 5 dB noise figure. In addition, it offers a reception sensitivity of approximately -130 dBm and a bandwidth of up to 40 MHz over the frequency range from 50 MHz to 2.2 GHz.

B. TVWS Primary User

An important step in the laboratory evaluation of the spectrum sensing system is the generation of the PU signal. In this work, the investigated scenario considers the use of TVWS. Therefore, the PU signal was implemented according to the ABNT 15601 standard of the ISDB-T/T_B protocol, which corresponds to the digital TV standard adopted in Brazil, Japan, and several Latin American and African countries¹. The signal generation was performed using GNU Radio 3.7

¹It is important to note that ISDB-T employs an OFDM-based waveform, similarly to other worldwide digital TV (DTV) standards such as DVB and ATSC 3.0. Therefore, the conclusions presented in this work can also be extended to other OFDM-based DTV systems.

TABLE I
OFDM ISDB-T_B SYSTEM TRANSMISSION PARAMETERS.

Parameter	Value
Total number of carriers	8192 (Mode 3)
Number of active carriers	5617
Guard Interval	1/32
Number of segments Layer A	13
Data carriers modulation Layer A	64-QAM
Encoding rate of layer A	7/8
Pilot carriers and TMCC modulation	BPSK/DBPSK
OFDM symbol duration	1.26 ms
Subcarrier spacing	0.992 kHz
Pilot spacing	11.9 kHz
IFFT clock	512/63 MHz
BW	5.572 MHz

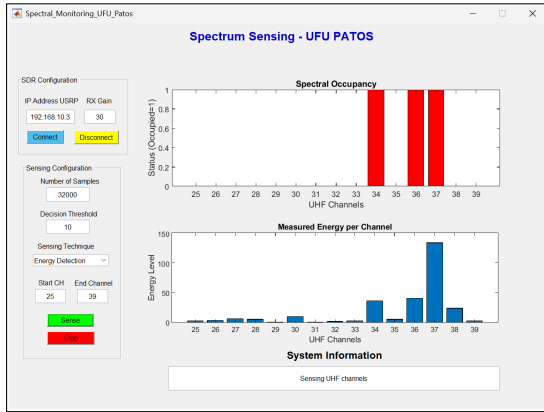


Fig. 1. Spectrum sensing system graphical interface.

to transmit digital TV signals over UHF channels 14 to 51. Table I summarizes the transmission parameters adopted for the implemented ISDB-T_B PU signal.

C. Spectrum Sensing System using SDR and MATLAB

The developed spectrum sensing platform is available at [13]; the main source file is named `Spectral_Monitoring_UFU_Patos.m`. Fig. 1 illustrates the graphical interface of the sensing system, which includes several configuration parameters. For real-time operation, the first step is to configure the IP address of the USRP employed as the CR. Subsequently, the reception front-end gain must be configured, with a default value of 30 dB adopted to improve the sensitivity when detecting signals in the sensed channels. After these settings are configured, the “Connect” button is used to establish communication with the SDR. If the connection is successful, the message “Radio connected” is displayed in the system information field. The connection can be terminated using the “Disconnect” button. The settings available in the “Sensing Configuration” tab must also be defined. These include the number of collected samples used for the computation of the decision statistic T (default value of 32000), the decision threshold (default value of 10), the adopted sensing technique (energy detection), and the range of channels to be monitored, with configurable values spanning UHF channels 14 to 51. Other parameters related to the USRP N210 hardware are also internally configured by the platform, such as the center frequency,



Fig. 2. Measurement and test environment.

given by $473.142857 \times 10^6 + (\text{Channel} - 14) \times 6 \times 10^6$ (depending on the sensed channel), a 100 MHz board clock, a decimation factor of 16, burst mode enabled, and Int8 sample type.

With the platform properly configured, the “Sense” button is used to initiate the spectrum sensing process. The system can scan all UHF channels from 14 to 51 in less than 350 ms.

The sensing result illustrated in Fig. 1 was obtained in an indoor environment at the Analog and Digital Communications Laboratory of UFU – Patos de Minas campus, where all empirical measurements considered in this work were conducted. The environment comprised workstations, computers, and various measurement equipment, as depicted in Fig. 2, creating conditions favorable to multipath propagation.

Analyzing the spectral occupancy and energy detection results presented in Fig. 1, three channels were detected (red bars) within the evaluated sensing range (channels 25 to 39). The experimental results obtained in the laboratory environment demonstrated satisfactory sensing performance, with the system successfully detecting the presence of the ISDB-T_B transmitter (TX) on channel 37 in all tests conducted under positive SNR conditions and with the transmitter located inside the same room. Nevertheless, real wireless propagation environments may impose significantly more challenging reception conditions, including multipath propagation and fading effects, which are investigated in the next section.

IV. PERFORMANCE EVALUATION

This section presents the performance results obtained in both wired and wireless scenarios. All experimental curves were derived from 10000 Monte Carlo realizations, with half performed under $\mathcal{H}_1$ (TX on) and half under $\mathcal{H}_0$ (TX off). Measurements were conducted on UHF channel 37. The noise variance was first measured in the absence of primary transmission. Then, the transmission power was adjusted to achieve the target SNR, calculated in dB as $\text{SNR}_{\text{dB}} = 10 \times \log_{10} \left(\frac{\sigma_s^2 + \sigma_w^2}{\sigma_w^2} - 1 \right)$, which is required for constructing the performance curves. The theoretical curves shown in this section were obtained from (3), (4), and (5), corresponding to P_{fa} , P_{d} over AWGN, and Rayleigh average P_{d} , respectively.

A. Wired Performance

To verify the agreement between the developed spectrum sensing system and the theoretical behavior described in



Fig. 3. Wired measurement environment.

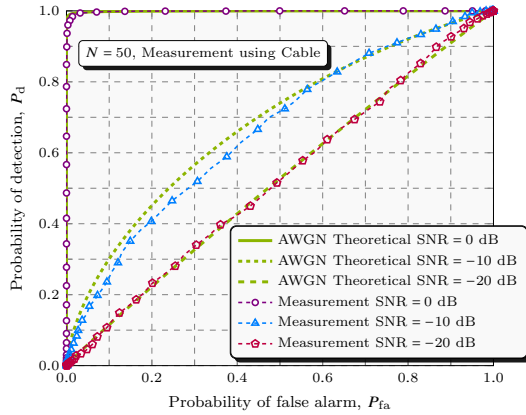


Fig. 4. ROC curves varying the SNR values in a wired measurement environment.

Section II, a controlled wired setup was assembled, in which the ISDB-T_B TX was directly connected to the CR through a coaxial cable and a 30 dB Mini-Circuits attenuator VAT-30A+, as shown in Fig. 3. The experimental performance was assessed for $N = 50$ and SNR levels of -20 dB, -10 dB, and 0 dB. The theoretical and experimental receiver operating characteristic (ROC) curves are shown in Fig. 4.

As observed in Fig. 4, the experimental ROC curves follow the expected SNR-dependent behavior. For $\text{SNR} = 0$ dB, the system approaches the optimal operating point ($P_d = 1$ and $P_{fa} = 0$), while for $\text{SNR} = -20$ dB the limited number of samples reduces the discrimination capability, making the ROC curve approach the diagonal. The close agreement between theoretical and experimental curves confirms the consistency of the implemented sensing platform in the controlled wired scenario. The small deviations between theoretical and experimental curves may be attributed to practical implementation factors not considered in the mathematical model, such as the limited resolution of the SDR ADC, residual filtering errors, sampling clock jitter, and other hardware impairments.

B. Performance in a Wireless Environment

To assess the sensing system's performance in a more realistic environment, the same setup presented in Fig. 2 was used. In this setup, both SDRs were connected to their respective transmission (VERT900 omnidirectional) and reception (LP0410 log-periodic) antennas, positioned 3 meters apart. Initially, the system was evaluated under LoS conditions between the transmit and receive antennas. Subsequently, the

transmission SDR, along with its antenna, was moved behind a notebook connected to the TX, while maintaining the same 3-meter distance, resulting in an nLoS condition.

The first wireless analysis considers $N = 100$ and $\text{SNR} = -5$ dB under LoS and nLoS conditions. The corresponding ROC curves are shown in Fig. 5(a). As expected, the LoS measurement exhibits better performance than the nLoS case and lies closer to the theoretical AWGN curve. However, its performance is still below the AWGN prediction, since even under LoS conditions the received signal is affected by practical wireless impairments, such as reflections, diffraction, and scattering caused by objects in the laboratory environment. These effects generate multipath components and instantaneous envelope fluctuations, degrading the sensing performance. In contrast, the nLoS measurement is closer to the theoretical Rayleigh curve, which represents a more severe multipath scenario without a dominant propagation path. Nevertheless, the measured nLoS performance is better than the Rayleigh prediction. This behavior suggests that, even without a direct physical line of sight, the indoor arrangement still produces residual dominant components, reducing the envelope fluctuations and improving the sensing performance compared with the ideal Rayleigh model.

The performance of the sensing system in the wireless LoS environment shown in Fig. 2 was also assessed under different average SNR conditions. For this analysis, the considered parameters were $N = 100$ and $\text{SNR} = -3$ dB, -5 dB, -7 dB, and -10 dB. The resulting ROC curves are presented in Fig. 5(b), along with the upper theoretical benchmark (AWGN model: $N = 100$ and $\text{SNR} = -3$ dB) and the lower theoretical benchmark (Rayleigh model: $N = 100$ and $\text{SNR} = -10$ dB). As expected, the empirical curves preserve the theoretical trend, with improved detection performance as the SNR increases. It is also observed that the measured curves remain between the AWGN and Rayleigh theoretical limits, indicating that the LoS wireless measurements are consistent with an intermediate propagation condition affected by practical multipath effects.

The final analysis in the wireless scenario focuses on assessing the impact of the number of collected samples on the system performance at a fixed SNR. The average SNR was set to -5 dB, and the spectrum sensing system performance was evaluated for $N = 100$ and 500 captured samples. The results are presented in Fig. 5(c), which also includes the theoretical performance curves for the best (AWGN model: $N = 500$ and $\text{SNR} = -5$ dB) and worst (Rayleigh model: $N = 100$ and $\text{SNR} = -5$ dB) evaluated configurations. The analysis of Fig. 5(c) shows that increasing the number of collected samples improves the channel occupancy decision, as expected. The empirical performance with 500 samples remains below the theoretical AWGN performance. In contrast, with 100 samples, it surpasses the theoretical Rayleigh performance, since the measurements were performed under LoS conditions.

It is important to highlight the challenges in obtaining empirical curves in wireless scenarios with low SNR and few samples. The instantaneous SNR variation in such conditions can compromise the quality of the collected samples. Despite the differences between theoretical and empirical

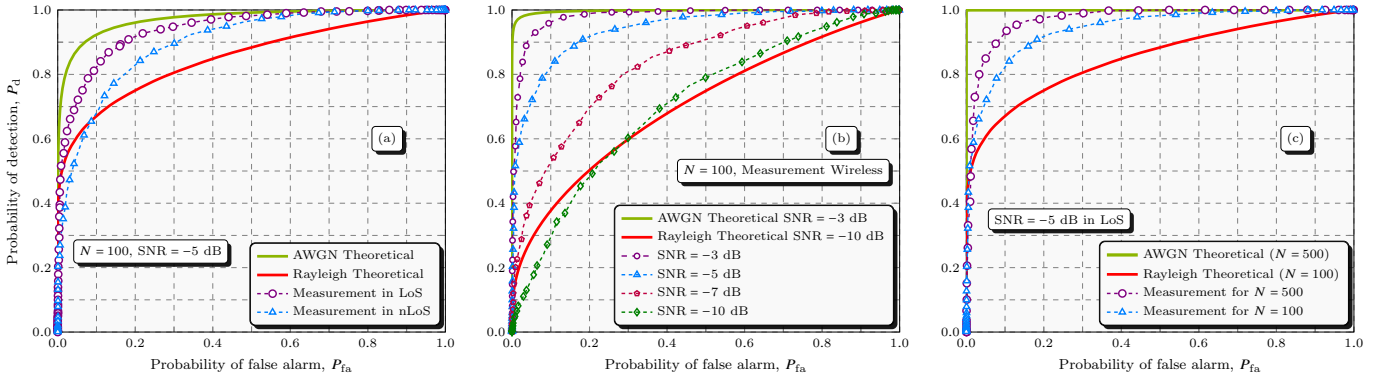


Fig. 5. ROC curves for wireless measurements: (a) LoS and nLoS conditions, (b) LoS condition with varying SNR, and (c) LoS condition with varying number of collected samples N .

results, the developed sensing system behaved consistently, with the observed discrepancies being attributed to practical implementation factors and the adopted theoretical channel models. For more accurate modeling of the real wireless environment, especially the indoor setting shown in Fig. 2, more advanced fading channel models, such as Rice or κ - μ fading models, should be considered, since they account for the presence of a dominant path in their physical formulations.

V. CONCLUSIONS

The proposed real-time spectrum sensing platform for TVWS applications was successfully implemented using the USRP N210 SDR and MATLAB. The developed system proved to be fully operational, enabling real-time scanning of VHF/UHF TV channels and experimental detection of an ISDB-T_B primary transmission. The platform was evaluated in controlled wired conditions and in indoor wireless scenarios under LoS and nLoS conditions. In the wired setup, the experimental ROC curves closely followed the theoretical AWGN predictions, validating the implementation and the adopted energy detection formulation. In wireless measurements, the results showed the expected degradation caused by multipath propagation and fading effects, with LoS measurements exhibiting performance closer to the AWGN model and nLoS measurements approaching the Rayleigh-based prediction. The analyses also confirmed the impact of the average SNR and the number of collected samples on the sensing performance. In the laboratory environment, under high-SNR conditions and when a sufficient number of samples was collected, the system achieved perfect detection in the evaluated experimental conditions. Therefore, the proposed platform represents a practical and low-cost solution for real-time spectrum sensing in TVWS scenarios. Future work will investigate the implementation of more robust sensing techniques, including phase-based methods and deep-learning-based approaches, aiming to improve detection performance under more challenging propagation conditions.

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