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COOPERATIVE SPECTRUM SENSING APPLICATION USING RTL-DONGLE TECHNOLOGY

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ABSTRACT

Cognitive Radio (CR) systems have become a key paradigm for future wireless communications. Spectrum management efficiency is improved by CR strategies, which allows to Secondary Users (SUs) get opportunistic access to idle bands licensed to Primary Users (PUs). Opportunistic access is usually achieved through spectrum sensing (SS) techniques to identify spectrum holes. Detection performance of spectrum holes, given by probability of detection (P_d) and probability of false alarm (P_{fa}), is improved when cooperative scheme is implemented. Cooperative Spectrum Sensing (CSS) schemes require a Fusion Center (FC) to collect and merge SS results from SUs, then to have enhance performance. In this paper, we propose a C/C++ application based on Client/Server architecture for Cooperative Spectrum Sensing (CSS). RTL-Dongle device with Software Defined Radio (SDR) capabilities is used to implement SUs nodes. Local sensing is implemented on each node by using Energy Detector (ED) method provided its lower computational costs. Then, each individual SS results are transmitted to the FC according to centralized model of data report. FC data fusion is implemented by applying AND and OR parallel fusion rules. Finally, detection report is stored into .txt file for further processing. Application performance is evaluated by detecting a transmitted reference pilot tone using ICOM-IC7100 equipment. Obtained results confirm the improvement of P_d and P_{fa} values.

KEYWORDS: Cooperative Spectrum Sensing, Data Fusion, Cognitive Radio, Energy Detector, Software Defined Radio.

RESUMEN

Los sistemas de Radio Cognitiva (CR) se han convertido en un paradigma clave para las futuras comunicaciones inalámbricas. La eficiencia de la gestión del espectro se mejora por las estrategias de CR, que permiten a los Usuarios Secundarios (SU) obtener acceso oportunista a las bandas inactivas licenciadas a los Usuarios Primarios (PU). El acceso oportunista se logra generalmente utilizando las técnicas de sensado de espectro (SS) para identificar los huecos espectrales. El rendimiento de la detección de huecos espectrales, dado por la probabilidad de detección P_d y la probabilidad de falsa alarma P_{fa}, mejora cuando se implementa el esquema cooperativo. Los esquemas de Sensado Cooperativo de Espectro (CSS) requieren que un Centro de Fusión (FC) recoja y fusione los resultados del SS de cada SU, para luego mejorar el rendimiento. En este trabajo, proponemos una aplicación C/C++ basada en la arquitectura Cliente/Servidor para el Sensado Cooperativo del Espectro (CSS). El dispositivo RTL-Dongle con capacidades de Radio Definida por Software (SDR) se utiliza para implementar los nodos de SUs. El sensado local se implementa en cada nodo utilizando el método de Detector de Energía (ED), dado que tiene bajos costos computacionales. A continuación, cada uno de los resultados del SS se transmite al FC de acuerdo con el modelo centralizado de informe de datos. La fusión de datos FC se implementa aplicando las reglas de fusión paralelas AND y OR. Finalmente, el informe de detección se almacena en un archivo.txt para su posterior procesamiento. El rendimiento de la aplicación se evalúa detectando

TELEMÁTICA
REVISTA DIGITAL de las Tecnologías de la Información y las Telecomunicaciones

un tono piloto de referencia transmitido utilizando el equipo ICOM-IC7100. Los resultados obtenidos confirman la mejora de los valores de P_d y P_{fa}.

PALABRAS CLAVES: Sensado Cooperativo del Espectro, Fusión de Datos, Radio Cognitiva, Detector de Energía, Radio Definido por Software.

1. INTRODUCTION

Currently, radio frequency spectrum is one of the most valuable natural resource to transmmit information. Wireless communications demand higher spectral resources to increase quality of service (QoS). However, different studies show that spectral resources are underutilized as a consequence of fixed allocation and access policies. According to the Federal Communications Commission, only 6% of spectrum is properly employed [1]. Therefore, Cognitive Radio (CR) paradigm emerge as a solution to increase the efficiency of spectrum use [2]. CR systems employs overlay and underlay dynamic spectrum access strategies. In overlay mode, secondary users (SUs) get opportunistic access to idle segments of licensed bands to transmit information. On the other hand, underlay mode proposes that SUs and PUs transmissions may coexist on the same frequency band with a fixed interference threshold [1].

Several spectrum sensing (SS) techniques are developed to detect spectrum holes, which is the first task to execute overlay strategies [3, 4]. SS reported techniques can be classified as follows: energy detector [3], matched filters [5] and cyclostationary methods [6]. These techniques computes a metric which is then processed as a binary hypothesis test to decide whether PU signals are present (hypothesis $\mathcal{H}_1$) or absent (hypothesis $\mathcal{H}_0$) [7]. Desired detection performance, computed by false alarm (P_{fa}) and detection (P_d) probabilities, is obtained when P_d is closer to one and P_{fa} is near to zero value. According to IEEE 802.22 standard, proper performance for cognitive wireless regional area networks (WRANs) states a value of P_d superior to 0.9 and P_{fa} lower than 0.1 [8].

Main advantage of CSS is to improve sensing performance by exploiting cooperation in spatially located SUs. Local sensing information is merged to have more accurate combined decision than local decision results [9]. CSS scheme implementation is based on three main stages: local sensing performed by SUs, data report sent on a given control channel and data fusion performed by FC. Local sensing is implemented on each SU by using SS techniques described above. Data report stage analyzes how local sensing results can be efficiently and reliably reported to the Fusion Center (FC) or shared to other SUs [10]. It can be implemented in centralized [11], distributed [12] and assisted mode [13]. Centralized scheme is easy to implement provided that FC controls CSS operations. FC receives local sensing information from each SU and formulates a final decision. Unlike centralized cooperative sensing, distributed scheme does not rely on a FC to have the cooperative decision. In this case, SUs communicate among themselves to have a final decision. Distributed mode requires a higher bandwidth and security policies than centralized. Assisted mode is used on scenarios where report channels are imperfect. Therefore, SUs with strong report channel conditions are used as relay node to send local detection results to FC.

On the other hand, data fusion combines the reported local sensing results to have the cooperative decision. Data fusion stage can be implemented according to two-cooperation models: parallel fusion [14] and models based on games theory. Parallel fusion is classified in hard [15], soft combination [16] or quantized combination [17]. In hard combination SUs make a local sensing and transmit the one bit decision. In soft combination SUs transmit the entire local sensing samples or local test statistics. By this scheme, higher detection performance is obtained but also higher bandwidth is required. Quantized combination emerges as solution to have proper balance on bandwidth-performance tradeoff. In this case, SUs quantize local sensing results and send only the quantized data to reduce report channel communication overhead.

TELEMÁTICA
REVISTA DIGITAL de las Tecnologías de la Información y las Telecomunicaciones
Revista Telemática. Vol.18 , No.2, mayo-agosto, 2019, p.139-150 ISSN 1729-3804

On real scenarios, CSS introduces some important pragmatic advantages in comparison to local SS. For instance, lower P_d values are obtained when hidden PU problem arises, as illustrated in Fig.1. In this case, cognitive radio device 1 (CR1) is out of the range of PU transmitter and may produce interference on licensed spectrum bands. Therefore, CR1 is no capable to detect presence of PU signals. In this scenario, Cooperative Spectrum Sensing (CSS) brings a solution to solve hidden PU problem provided CR2 may detect to the PU transmission, then P_d value is increased in a cooperative fashion. In addition, CSS strategies are proposed to solve noise uncertainty, fading, and shadowing problems in spectrum sensing operations [10]. Currently, CSS is a developing line of research to improve wireless communication applications.

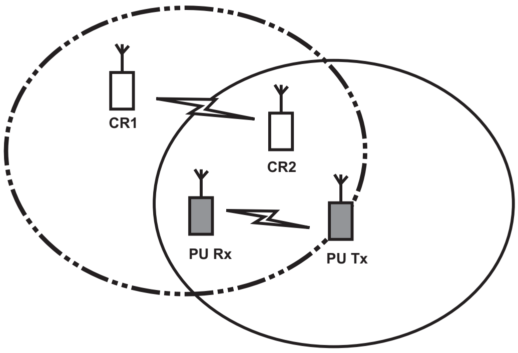

Figure 1: Hidden PU problem.

A variety of papers are reported to develop CSS strategies on different platforms. In [18], a comparison between Hard and Soft fusion methods for AWGN and Rayleigh channels is proposed by simulations on Matlab software. Obtained results state that Soft combination is the best fusion method on lower SNR conditions. Report in [6] exhibits the implementation of cyclostationary detector in Simulink with Xilinx System Generator blocks for FPGA technology by using Fast Fourier Transform Accumulation Method (FAM). On the other hand, Raspberry Pi is another widely used platform due to its lower costs and higher computational performance. An implementation of CSS in Raspberry Pi is developed in [19] by using Nokia cell phone as a spectrum sensing device while Raspberry Pi functions as a FC to collect local sensing results.

However, solutions above are based on proprietary software, which in turn increase costs of implementation. To the best of our knowledge any free licensed and open source application is available for CSS. Therefore, in this paper we propose the design of a C/C++ application for CSS operations based on Client/Server architecture. This is developed on Qt platform free of payed license. Main functionalities of proposed application are detailed as follows. Operating nodes are given by RTL-Dongle as a receiver device. By using this technology, SDR applications may be implemented based on offered adjusting parameters such as: central frequency (52 MHz-2000 MHz), gain (0-40 dB), total number of acquired samples (N) and sample rate (maximum value 2.8 MHz). Local sensing is developed on each SS node by applying ED technique. Nodes are connected by TCP/IP network to the FC. Data fusion is developed according to AND and OR parallel fusion rules. Finally, detection report is stored in .txt file for further processing.

The rest of the paper is organized as follows. The system model is presented in Section 2 to illustrate receiver configuration (Section 2.1), local sensing (Section 2.2) and data fusion (Section 2.3). Then, in Section 3 proposed application is described in detail. Detection results are obtained in Section 4 to validate application performance. Finally, Section 5 contains the conclusions.

2. SYSTEM MODEL

We assume a scenario with several SS nodes that sense in a cooperative manner PU transmissions as illustrated in Fig.2. We consider that data report is in accordance to centralized architecture. Therefore, each SS node senses locally the signal of interest (SoI) from PU channels. Then detection results are transmitted through a TCP/IP network to a FC. Finally, FC fuses received information from every SS node and a final decision regarding the presence or absence of the PU is conformed.

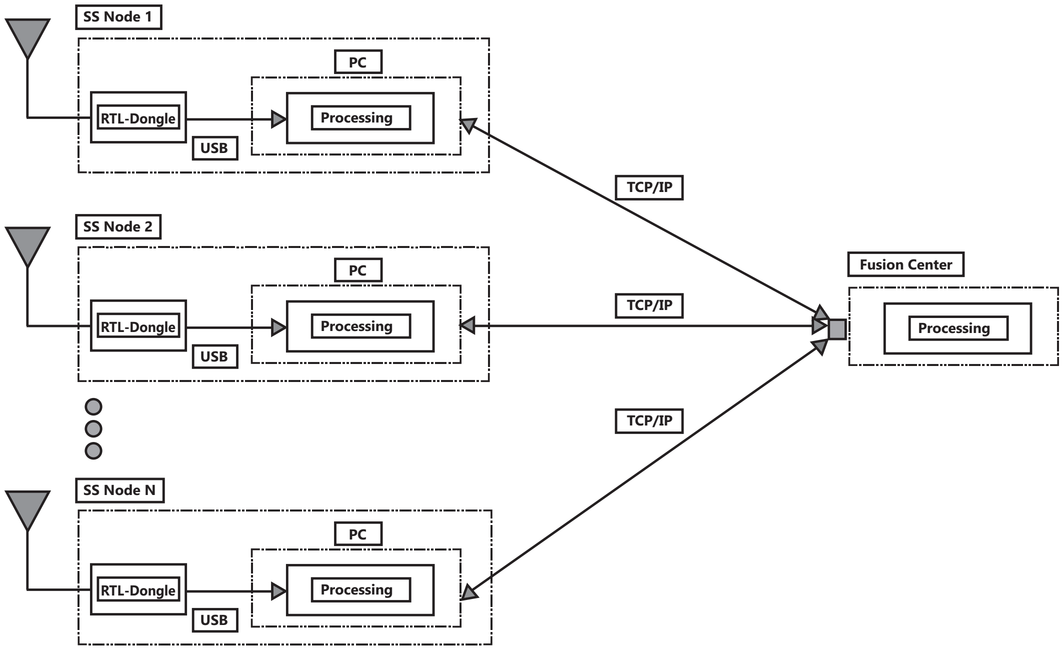

Figure 2: Scheme of the proposed system.

2.1. Receiver configuration

RTL-Dongle implements the SS node receiver, which tune signals from 52 MHz to 2000 MHz and have a maximum bandwidth of 2.8 MHz. RTL-Dongle captures SoI by using an omnidirectional antenna. Then, received signal is digitized by 8 bit Analogue to Digital Converter (ADC). Phase and quadrature (I/Q) samples are transmitted to a personal computer (PC) through USB port. According to Software Defined Radio (SDR) technology, RTL-Dongle is capable to modify several operational parameters as central frequency (52 MHz-2000 MHz), gain (0-40 dB), total number of acquired samples (N) and sample rate (maximum value 2.8 MHz) [20].

2.2. Local sensing

I/Q samples are processed to conform the test statistic by using an ED scheme provided its low computational complexity. In addition, ED is rather useful on blind detection application as long as it operates without any specific knowledge related to SoI parameters. ED computes test statistic Z by estimating the energy of received signals. Then, Z is compared with a fixed threshold λ. If $Z > \lambda$, PU channels is busy, while $Z < \lambda$ implies that PU channel is idle. Test statistic Z is computed as [21]:

TELEMÁTICA
REVISTA DIGITAL de las Tecnologías de la Información y las Telecomunicaciones
Revista Telemática. Vol.18 , No.2, mayo-agosto, 2019, p.139-150 ISSN 1729-3804

$$Z = \frac{1}{\sigma_\omega^2} \sum_{n=0}^{N-1} |s[n]|^2, \tag{1}$$

where $s[n]$ represents received signal samples. We assume that noise signal introduced by PU channel is an Additive White Gaussian Noise (AWGN) with zero mean and variance σ_ω^2 .

Thresholds λ is obtained by Newman-Pearson theorem as [22]:

$$\lambda = \sqrt{N}\mathcal{Q}^{-1}(P_{fa}) + N, \tag{2}$$

where N is total processed samples and $\mathcal{Q}(x) = \frac{1}{2\pi}\int_x^\infty e^{-\frac{t^2}{2}} dt$ is the complementary distribution of a standard Gaussian random variable. Performance parameters given by P_{fa} and P_d are computed as [21]:

$$P_{fa} = \mathcal{Q}\left(\frac{\lambda - N}{\sqrt{N}}\right), \tag{3}$$

$$P_d = \mathcal{Q}\left(\frac{\lambda - N(1+\gamma)}{\sqrt{N(1+\gamma)}}\right), \tag{4}$$

where γ is signal to noise ratio (SNR). Then, substituting equation (2) into (4), P_d can be expressed in terms of P_{fa}, γ, and N as:

$$P_d = \mathcal{Q}\left(\frac{\sqrt{N}\mathcal{Q}^{-1}(P_{fa}) - N\gamma}{\sqrt{N(1+\gamma)}}\right). \tag{5}$$

2.3. Data fusion

Data fusion is implemented according to parallel fusion model by using hard combination. Each SS node transmits local results to the FC, the result is expressed in a single bit indicating the presence ("1") or absence ("0") of PU on the given frequency band. Then, FC fuses received data according to AND and OR rules which work similar to AND and OR digital gates. Therefore, in case of AND rule, FC determines that PU channel is idle if at least one SS node do not detect SoI. On the other hand, by using OR rule, FC determines that PU channel is busy if at least one SS node detects SoI. We implement hard combination provided it is easier to implement than other decision rules and requires smaller bandwidth to share results.

Cooperative final decision by applying OR rule has P_d and P_{fa} global values given by [9]:

$$P_d = 1 - \prod_{i=1}^{k}(1 - P_{d,i}), \tag{6}$$

$$P_{fa} = 1 - \prod_{i=1}^{k}(1 - P_{fa,i}), \tag{7}$$

where $P_{d,i}$ and $P_{fa,i}$ are respectively, the probability of detection and false alarm for the ith SS node and k is the total number of SS nodes. In case of AND rule, global values of P_d and P_{fa} after final decision are given as [9]:

$$P_d = \prod_{i=1}^{k} P_{d,i}, \tag{8}$$

$$P_{fa} = \prod_{i=1}^{k} P_{fa,i}. \tag{9}$$

3. DESCRIPTION OF PROPOSED APPLICATION

Proposed application is based on Client/Server architecture to perform CSS. This application is developed in C/C++ language by using Qt v5.054. Client interface is designed to perform local sensing on each SS node by using ED scheme. Then, sensing results are transmitted to a FC by using TCP/IP communication protocol. FC Server interface is implemented to capture local sensing results and to obtain a final decision.

3.1. Client module

Client graphical interface is configured by adjusting parameters in regard to three main blocks: Estimation, Detection and Transmission, as described in Fig.3. Estimation block is designed to compute noise variance (σ_ω^2) and detection threshold (λ). Based on constant power spectral density of AWGN, we compute σ_ω^2 in an idle frequency band given by *noise_frequency* parameter as follows:

$$\sigma_\omega^2 = \frac{1}{N} \sum_{n=0}^{N-1} |w[n]|^2 \tag{10}$$

where $w[n]$ represents noise samples and N is total number of collected samples adjusted by *window_length* parameter in Detection Block. This procedure is repeated several times according to *iterations* variable. Obtained σ_ω^2 values are averaged to improve accuracy in estimation. A fixed P_{fa} value is another input parameter required to compute λ according to equation (2).

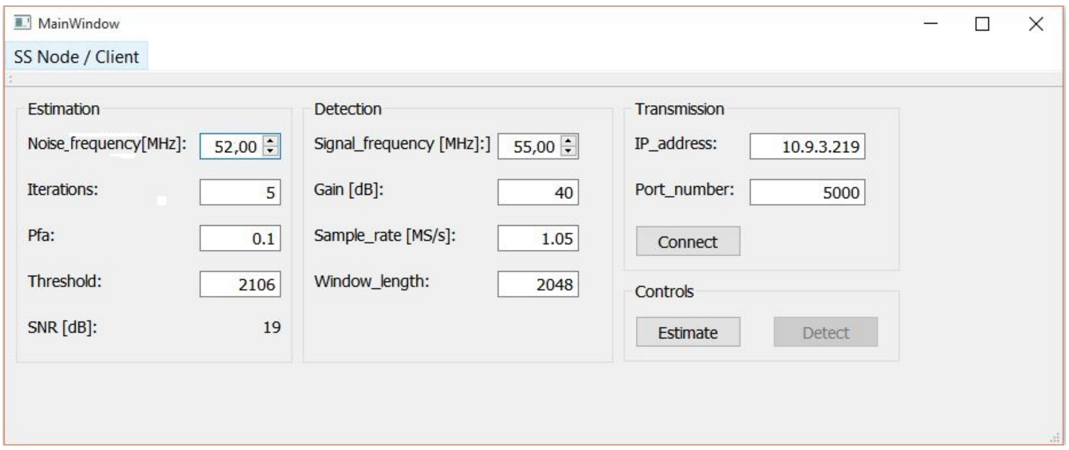

Figure 3: Client interface.

Detection block adjusts RTL-Dongle parameters to capture SoI. RTL-Dongle is controlled by using RTL-SDR library [23]. Then, collected samples are processed by ED according to equation (1). Finally,

TELEMÁTICA
REVISTA DIGITAL de las Tecnologías de la Información y las Telecomunicaciones
Revista Telemática. Vol.18 , No.2, mayo-agosto, 2019, p.139-150 ISSN 1729-3804

detection result expressed as a boolean variable is transmitted to the FC, which is identified by an $IP\_address$ and a fixed $port\_number$. Communication is established by using TCP/IP protocol, which allows a reliable information transport layer between applications.

3.2. Server module

Server interface is compounded by three main blocks: Data Fusion, Network Configuration and Detection Report as depicted in Fig.4. Data fusion is configured by selecting $fusion\_rule$ (AND and OR) to be used and the total number of SS_nodes that server will attend. Network configuration is given by server $IP\_address$ and $port\_number$ to receive data from SS nodes.

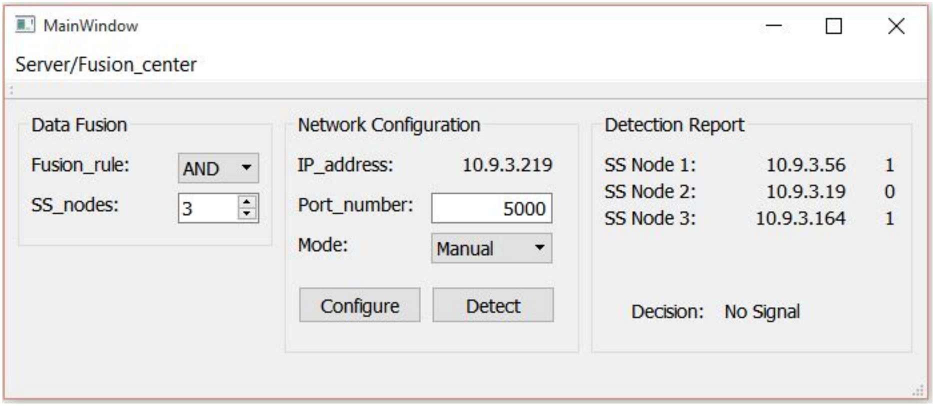

Figure 4: Server interface

Communication protocols between Clients (SS nodes) and Server (FC) would be established according to operation mode: automatic or manual. Automatic mode allows continuous CSS operations, while manual mode performs only one detection. Commands “sense” and “stop” are defined to control operations of each SS node. These commands are sent from FC to each SS node to start and stop local SS operations. Communication procedure is stated as follows: first, connection between Clients and Server are established by properly configuring IP address and port number. Then, each SS node starts detection process only when FC broadcasts the “sense” command. Local detection results are sent back automatically to FC. Finally, SS nodes sleep until new “sense” a command is established in case of manual mode. On the other hand, if automatic mode is selected, SS nodes perform continuous CSS operations until “stop” command is transmitted by the FC.

Detection report block depicted in Fig.4, illustrates each SS node connected and individual detection results. In addition, final decision about occupancy of PU channel is shown by using “Decision” label. These results are stored in .txt file for further processing.

4. RESULTS

Application performance is evaluated by detecting prior known signals. To that end, we generate, by using Matlab, a single tone with unitary amplitude and zero phase $s[n] = cos(2\pi f_0 n)$, where $f_0 =$ 2 kHz represents the analogue frequency. Then, we use Upper Side Band (USB) modulation centered on 55 MHz by using an ICOM radio “IC-7100”, this modulated radio frequency signal is used as PU SoI. ICOM-7100 is a Software Controlled Radio equipment capable of receiving and transmitting signals in several analogue modulation waveforms from 1.8 MHz to 430 MHz. An omnidirectional 50 Ω antenna is

(a) (b)

Figure 5: Utilized devices:(a) Transmitter; (b) Receiver.

connected to the ICOM-7100 with a PL-259 plug connector. A coaxial cable is used as transmission line [24]. Fig.5(a) illustrates the transmitter device, while Fig.5(b) depicts the receiver RTL-Dongle device.

We set a scenario with three SS nodes, where two nodes are located inside the coverage area (SS1 and SS3) of the transmitter and the third one (SS2) is located at the edge of the coverage area, simulating hidden PU problem as depicted in Fig.6. Each SS node senses the frequency band of the PU transmission by using Elonic E4000 device. RTL-Dongle parameters are configured in Client interface as illustrated in Fig.3. Estimated SNR values in SS1, SS2 and SS3 are $\gamma_1 = 19$ dB,$\gamma_2 = 0$ dB and $\gamma_3 = 15$ dB, respectively. Higher SNR values are obtained in SS1 and SS3 provided the transmitter and receiver antenna are inside the coverage area.

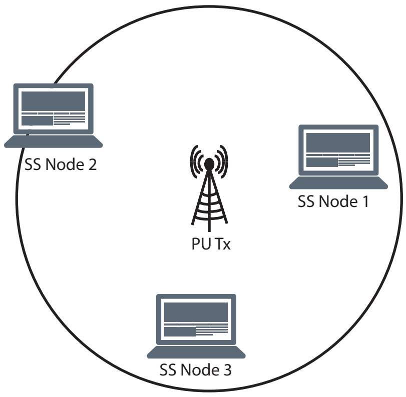

Figure 6: Distribution of SS nodes.

We generate 100 Monte Carlo simulations to determine application performance when PU channel is idle (hypothesis $\mathcal{H}_0$) and busy (hypothesis $\mathcal{H}_1$). Fig.7 shows detection results obtained by SS1, SS2 and SS3 when PU channel is idle. Detection performance of SS1 is expressed by fraction $\frac{6}{100}$ indicating that SoI is detected 6 times from 100 attemps. In the same way, SS2 and SS3 achieve $\frac{0}{100}$ and $\frac{10}{100}$, respectively. SS2 never detects SoI because it is located at the edge of the coverage area and energy value is always lower than computed threshold. Fig.8 shows results obtained by applying AND and OR fusion rules in FC. Based on these results if we apply AND rule we reduce to zero the total number of times that SoI is detected when PU channel is idle ($\frac{0}{100}$). However, by applying OR rule, detection performance decreases provided that the number of wrong detection is increased to 16 ($\frac{16}{100}$).

On the other hand, Fig.9 depicts detection results obtained by SS1, SS2 and SS3 when PU channel is busy. In this case, SS1 and SS3 detect properly the presence of SoI on each attempt ($\frac{100}{100}$), while SS2

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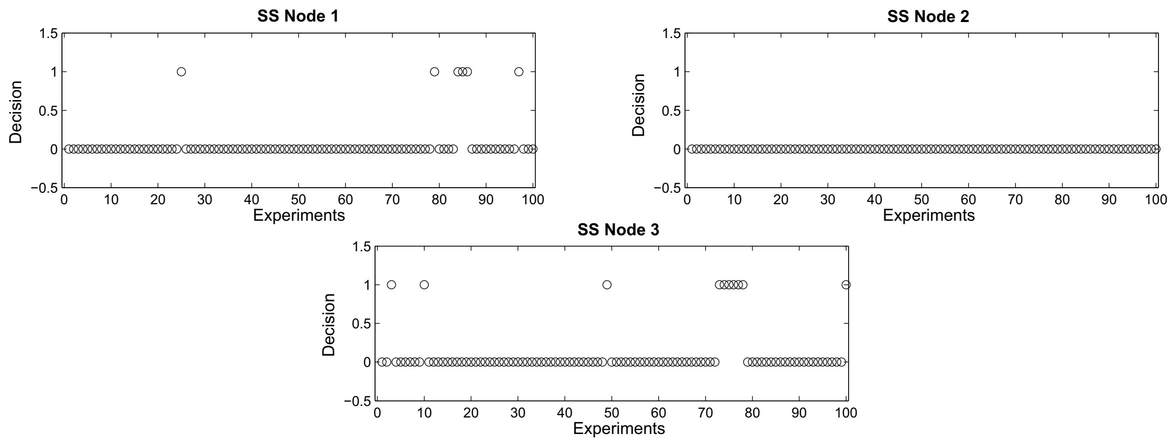

Figure 7: Local sensing results when PU channel is idle.

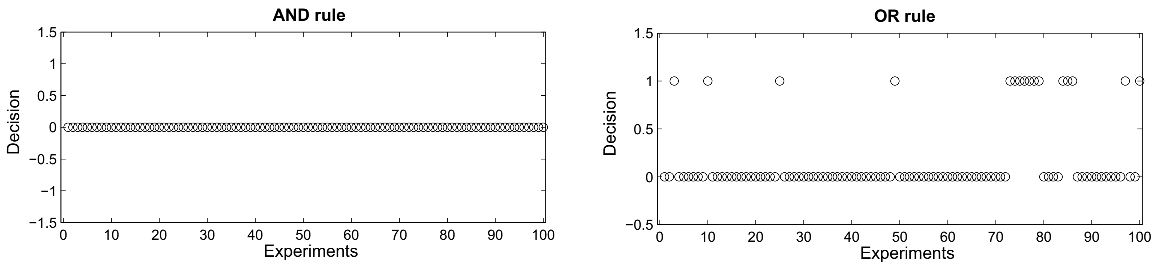

Figure 8: Cooperative sensing results when PU channel is idle.

achieves $\frac{79}{100}$ correct decisions. Fig.10 illustrates detection results in FC with AND ($\frac{79}{100}$) and OR ($\frac{100}{100}$) rule. We note that detection performance is improved by using OR rule.

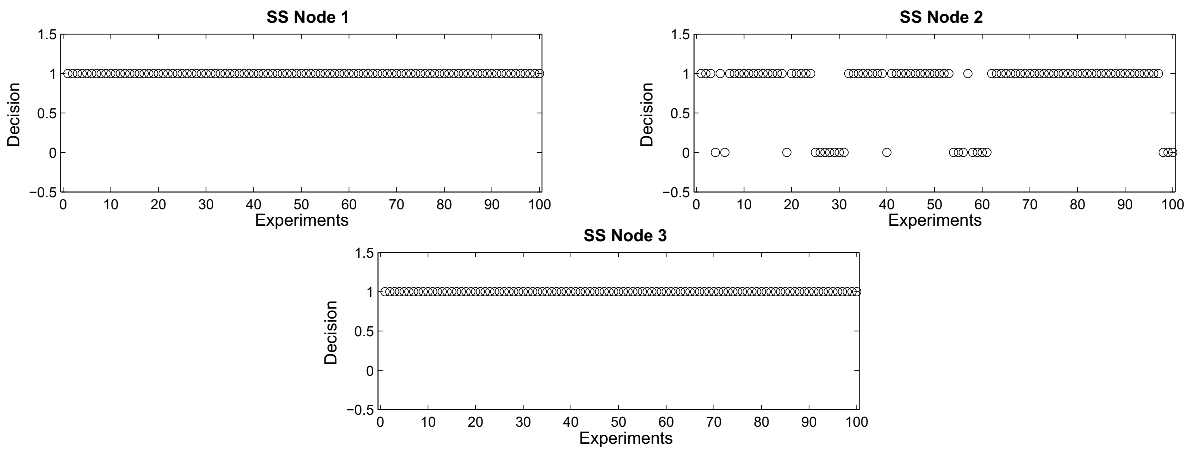

Figure 9: Local sensing results when PU channel is busy.

Table 1 show theoretical values of P_d and P_{fa} achieved in local and cooperative sensing, respectively. P_{fa} value for local sensing is fixed to 0.1 this setted at Client interface as illustrated in Fig.3. Then, P_d is

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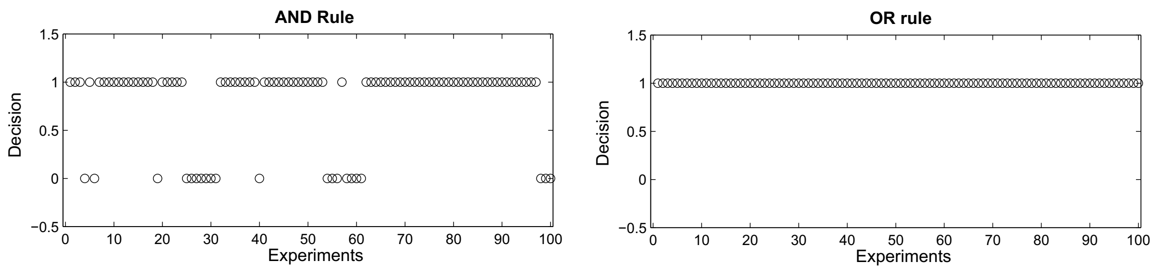

Figure 10: Cooperative sensing results when PU channel is busy.

Table 1: Theoretical values of P_d and P_{fa} achieved in local sensing

Local sensing	**SS1**	**SS2**	**SS3**	**AND rule**	**OR rule**
P_{fa}	0.1	0.1	0.1	1e-03	0.271
P_d	≈ 1	≈ 1	≈ 1	≈ 1	≈ 1

computed by using equation (5) for $N = 2048$ and the proper SNR value for each SS node. Cooperative sensing results are obtained by equations (6),(7),(8),(9) described in Section 2.3. Experimental results are quite similar to theoretical values validating the proper performance of the application. Based on results from Table 1, CSS implemented by AND mechanism illustrates to have better performance than local decision.

5. Conclusions

Cooperative Spectrum Sensing represents a major solution to improve detection performance in CR systems. In this paper a C/C++ application for CSS based on Client/Server architecture is described. Client interface is designed to configure RTL-Dongle as a receiver device. Software Defined Radio technology is proven to be a key component to develop a CR system provided the flexibility that offers to radio design. In addition, ED technique is applied at Client equipment to perform local sensing operations. This is one of the most employed SS techniques provided that demands low computational resources and achieves higher performance on blind detection applications. On the other hand, Server interface fuses individual sensing results by using AND and OR rules. These rules are commonly reported solutions provided simplicity in their implementation. Therefore, low computational costs and bandwidth for control channel will be required. Obtained detection results are quite similar to theoretical P_d and P_{fa} values for cooperative scenarios, which validate application performance. In addition, results show that by using AND fusion rule P_{fa} values is decreased, but also P_d. However, by using OR rule P_d and P_{fa} values are both increased. Proper selection of AND or OR fusion rule is regarded to CSS strategy. A maximum value of P_{fa} may be fixed indicating the usability of the PU channel while P_d is increased by using OR rule. On the other hand, a minimum values of P_d may be fixed defining a PU protecting level and in this case AND rule is selected to decrease P_{fa} value. Future line of research is orientated to incorporate to the application new fusion rules to obtain better detection performance.

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