Implementation of an Energy Detection Based Cooperative Spectrum Sensing on USRP Platforms for a Cognitive Radio Networks

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***Abstract*— The paper describes a centralized cooperative spectrum sensing system, implemented on Universal Software Radio Peripheral (USRP) hardware platforms driven by the Genuinely Not Unix (GNU) Radio software. Spectrum sensing is realized by energy detection and a new block of energy detector with uncertainty is developed using GNU Radio out-of-tree implementation. A centralized scheme for cooperative spectrum sensing is applied and a hard global decision is taken in a fusion center which collects the local decisions from secondary users, selects those of them which will be taken for global decision estimation and performs classical decision fusion logic, such as AND, OR, MAJORITY rules. Based on measured data, the probabilities of detection for different Signal-to-noise ratios (SNRs) are built for each secondary user and for different scenarios of cooperative sensing.**

Keywords — Cooperative Spectrum Sensing;, Energy Detector; Fusion center; USRP; GNU Radio.

I. INTRODUCTION

In cooperative spectrum sensing, multiple secondary users (SUs) cooperate to overcome the unpredictable wireless environment which includes multipath fading, shadowing, and noise power uncertainty. By exploiting the spatial diversity, it has been proven that cooperative spectrum sensing outperforms single-user sensing [1].

In centralized cooperative sensing each local decision from SUs is collected in a central unit called fusion center (FC), which merges sensing data or local decisions and makes selection of the secondary users which will contribute to the global decision [13]. Then it takes a global decision through an algorithm often based on counting (voting), obtained by the classic logic rules such as AND, OR, MAJORITY applied on local decisions of SUs. The global decision is transmitted back by the FC to the SUs through a control channel. Different schemes of cooperative sensing, as well as issues, are considered in [7]. Two stage cooperative sensing with coarse and accurate stages in perspective to reduce power consumption and sensing time is proposed in [8]. Hard and soft information combined algorithms for cooperative sensing are described in [9], whereas [10] focuses on hard decision solutions. A widely used technique for spectrum sensing is energy detection [2] [3] [12]. The impact of noise uncertainty on the energy detector performances is considered in [6]. Recent papers are proposing some hardware implementations of energy detector and cooperative spectrum sensing schemes. An implementation of energy detector on USRP is presented in [4]. An implementation of centralized cooperative spectrum sensing with two SUs, realized on USRPs is described in [5] and its functionality is illustrated through a video transmission. In [15], probabilities of detection in cooperative sensing system implemented with 3 USRPs with 3 scenarios are compared – individual sensing, hard (OR) and soft decision. In [16], a validation of the advantages of cooperative sensing over individual sensing is proposed, through a hardware set-up with 2 SUs on USRPs and applying Roy's Largest Root Test algorithm for sensing decision. Joint energy-and-bandwidth spectrum sensing with GNU radio and USRP is proposed in [11]. Kullback-Leibler distance-based optimization to determine the decision thresholds for cooperative sensing and its scalability with the number of SUs is implemented in [14]. These implementations have quite limited applications and a more profound study is needed.

The paper describes a centralized cooperative spectrum sensing system, implemented on USRPs hardware platforms using GNU Radio software. Spectrum sensing is realized by energy detection and a new block of energy detector with uncertainty is developed in GNU radio. A centralized scheme for cooperative spectrum sensing is applied and a hard global decision is taken in FC which collects the local decisions from SUs, selects those of them which will be taken for global decision estimation and performs AND, OR, MAJORITY estimates of the global decision. Based on measured data, the probabilities of detection for different SNRs are built for each SU and for cooperative sensing with different scenarios.

The rest of the paper is organized as follows. Section 2 describes the Energy detector used for spectrum sensing and the GNU radio block built. Section 3 describes the Cooperative spectrum sensing scheme applied, the experimental setup, based on USRPs, as well as GNU radio flowgraphs constructed for the FC global decision making. Section 4 presents simulation results based on measurements and processing in GNU radio. Section 5 contains conclusion remarks.

II. ENERGY DETECTOR BLOCK WITH GHU RADIO

A. Theoretical aspects of energy detector

The energy detector (ED) is based on the idea that if a signal is present in the channel, there will be significantly more energy than if signal is absent. The block diagram of ED is shown on Fig. 1. Detection technique is available for every primary user (PU), without knowledge about any PU's signal, and it includes a threshold on the collected energy from the channel. The threshold is used by the ED to make the decision.

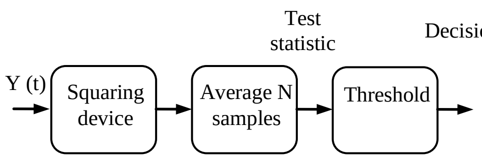

Figure1. Energy detector's block diagram

The PU signal is modeled by a random signal ***s*** with additive white Gaussian noise (AWGN) ***w***. The received signal ***y*** is sampled and it can be presented as a zero mean stationary Gaussian process with variance $\sigma_w^2 + \sigma_s^2$. The noise samples are assumed as a random variable with mean zero and variance σ_w^2. The received signal detection at the SU can be specified as binary hypothesis:

$$H_0 : y[n] = w[n] \Rightarrow signal\ is \quad absent \tag{1}$$

$$H_1 : y[n] = s[n] + w[n] \Rightarrow signal\ is \quad present$$

$$n = 1, \ldots, N.$$

where $y[n]$ is the received signal, $w[n]$ is the additive noise, $s[n]$ is the PU signal, and N is the number of received samples corresponding to the length of the interval of interest. The signal received is only noise when H_0 is true or signal plus noise when H_1 is true. The test statistic Λ, is a sum of squared input samples and it is compared with the detection threshold λ:

$$\Lambda = \sum |y(n)|^2 = \begin{cases} > \lambda & \text{under } H_1 \\ < \lambda & \text{under } H_0 \end{cases} \tag{2}$$

The ED threshold λ depends on the probability of detection P_d or the probability of misdetection P_{md} or the probability of false alarm P_{fa}, which are defined and interconnected, as follows.

$$P_d = P_r[\Lambda > \lambda \mid H_1] \tag{3}$$

$$P_{fa} = P_r[\Lambda > \lambda \mid H_0] \tag{4}$$

$$P_{md} = P_r[\Lambda < \lambda \mid H_1] = 1 - P_d \tag{5}$$

The choice of a suitable threshold is particularly important for good performance of the ED. If the threshold is too high, the SU can decide that there is free space in the spectrum when the PU signal is present, and its transmission will interfere with the PU transmission. If the value is too low, the detector will not react to the absence of a signal in the channel and the SU will then miss the opportunity to use the spectrum.

When the number of samples and the noise variance are known, the threshold is calculated with a constant false alarm probability P_{fa}. The IEEE 802.22 wireless regional area network (WRAN) limits P_{fa} down to 10% [2]. In practice, the exact value of the noise variance is not always available and first the noise in the channel must be evaluated.

Using the Central Limit Theorem (CLT) when $N \to \infty$, the test statistic Λ could be approximated by Gaussian distribution and evaluated, as follows:

$$P_{fa} \approx Q\left(\frac{\lambda - \sigma_w^2}{\sqrt{\frac{2}{N}}\sigma_w^2}\right) \tag{6}$$

$$P_d \approx Q\left(\frac{\lambda - (\sigma_w^2 + \sigma_s^2)}{\sqrt{\frac{2}{N}}(\sigma_w^2 + \sigma_s^2)}\right) \tag{7}$$

When it has included uncertainty in the noise model [5], the P_d and P_{fa} are calculate by:

$$P_{fa} \approx Q\left(\frac{(\lambda - (1+\rho)\sigma_w^2)}{\sqrt{\frac{2}{N}}(1+\rho)\sigma_w^2}\right) \tag{8}$$

$$P_d \approx Q\left(\frac{\lambda - ((1+\rho)^{-1}\sigma_w^2 + \sigma_s^2)}{\sqrt{\frac{2}{N}}((1+\rho)^{-1}\sigma_w^2 + \sigma_s^2)}\right) \tag{9}$$

where

$$Q(x) = \frac{1}{2} erfc\left(\frac{x}{\sqrt{2}}\right) \tag{10}$$

is the tail probability of the normal Probability density function. The parameter ρ defines the level of the noise uncertainty. The threshold can be calculated as follows:

$$\lambda_a = (1 - \sqrt{2}.erf^{-1}(2(1-\alpha)\frac{\sqrt{2}}{\sqrt{N}}))\sigma_w^2 \tag{11}$$

$$\lambda_\beta = (1 - \sqrt{2}.erf^{-1}(2(1-\beta)\frac{\sqrt{2}}{\sqrt{N}}))\sigma_w^2 \tag{12}$$

$$Q^{-1}(P_{fa}) = \sqrt{2}.erf^{-1}(1 - 2P_{fa}) \tag{13}$$

where: erf^{-1} is the inverse error function and α (resp. β) is the upper (resp. lower) false alarm probability. Then, if the test statistic Λ is greater than λ_α (resp. lower than λ_β), the detector decide H_1 (resp. H_0).

B. Energy detector block in GNU radio

A new block of ED is developed and implemented in the GNU Radio Companion's libraries [17]. The input parameters of the ED block are the number of samples, the noise variance and the parameters α and β that specify the level of uncertainty.

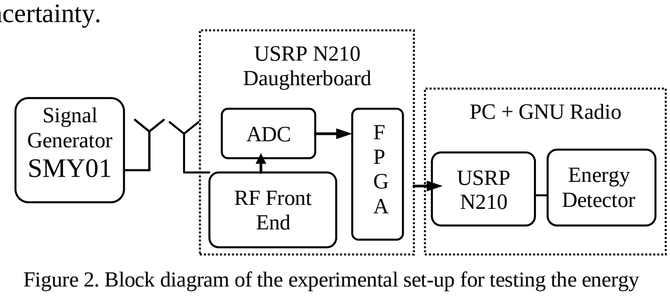

Figure 2. Block diagram of the experimental set-up for testing the energy detector

The ED developed is tested, as shown on the block diagram of the experimental set-up from Fig. 2. A signal generator SMY01 9 kHz – 1.040 GHz Rohde & Schwarz is used for transmitter. It is connected with broadcast antenna by Bayonet Neill–Concelman (BNC) coaxial cable. The generator is set to a frequency of 433MHz, with FM modulation with a deviation of 200 kHz. The generator provides different values of the transmitted signal in the range -30 dBm to 10 dBm with step of 2 dBm. The receiver is implemented with USRP N210 of Ettus Research, connected to a PC via Gigabit Ethernet, installed with a GNU Radio.

III. COOPERATIVE SPECTRUM SENSING SCHEME AND EXPERIMENTAL SET-UP USING USRPS AND GNU RADIO

The system considered consists in a single PU and four SUs, all located in a laboratory. One of the SUs - SU1 is put behind a screen. During the experience no change in noise conditions is considered. The SUs detect the spectrum for the presence of the PU signal and a FC takes the global decision after a preliminary selection of the PUs to be involved in the decision process. Hard decision combining rules are applied in the FC, for making decision about the presence of PU signal. The SUs make local decision and send 1 bit decision to the data FC. The FC combines sensing results and makes the global decision by AND, OR and MAJORITY rule. The function OR decides that the PU signal is present when any SU has reported "1". The function AND decides that the PU signal is present when all SUs have reported decision "1". In MAJORITY rule, if half or more SUs have reported a local decision "1", FC decides that PU signal is present. The block diagram of the experimental set-up is shown on Fig. 3. Here, also a signal generator SMY01 9 kHz – 1.040 GHz Rohde & Schwarz is used as a transmitter. It is connected with broadcast antenna by BNC coaxial cable. The generator is set to a frequency of 433MHz, with FM modulation with a deviation of 200 kHz. The generator provides values with different of the transmitted signal in the range – from 30 dBm to 10 dBm with a step of 2 dBm/5 dBm.

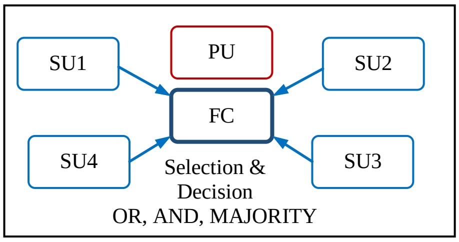

Figure 3. Block diagram of the model of cooperative sensing system

The receivers are implemented with 4 USRP N210 of Ettus Research, connected to a host personal computer (PC) via Gigabit Ethernet installed with a GNU Radio.

Photos of the experimental set-up are shown and the flowgraph in GNU Radio for saving measurement data files at Fig. 4. Data are saved for 2 minutes at each emitted power. Fourteen files are created for each one of the 4 SUs. The first group of 4 measured files is obtained when signal is missing and only noise is received. The EDs in the SUs calculate in that case the noise variance σ_w^2 estimations. These estimations are used later as input data for each one of the EDs in the SUs. The values obtained are presented in Table I.

TABLE I. NOISE VARIANCE ESTIMATIONS σ_w^2 IN SUS

SU	SU1	SU2	SU3	SU4
σ_w^2	14.7nW	46.5nW	43.6nW	46.1nW

Combining rule block diagrams for functions OR/AND applied for decision making in the FC are built in GNU Radio companion. On Fig. 5 is shown the flowgraph for global decision taking in FC, using the function OR. The sequences emerging at the output of the detector are collected by the block File Sink and they are saved in files. The files are binary type, and they can be opened in MATLAB. The FC decisions for MAJORITY function are calculated in MATLAB.

Figure 4. Experimental set-up for cooperative sensing and flowgraph in GNU Radio for saving measured data files

IV. RESULTS FROM COOPERATIVE SPECTRUM SENSING BASED ON MEASUREMENT DATA

The ED's performance characteristic of the probability of detection P_d as a function of SNR is built, based on subsets of the first 700000 data of each file from the experimental file set for the 4 SUs. Fig. 6 presents the P_d(SNR) curves for all 4 SUs.

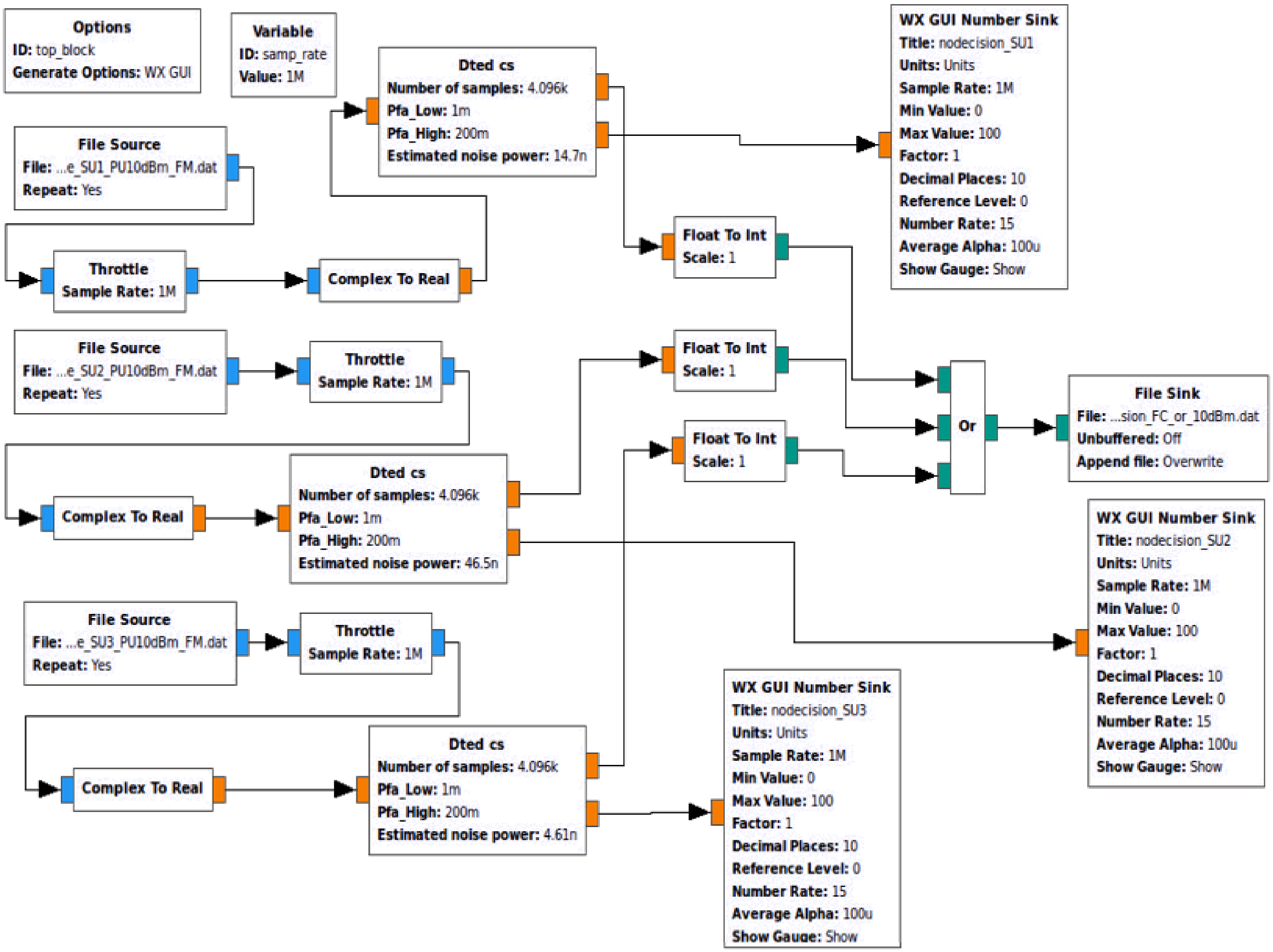

Figure 5. Flowgraph in GNU radio for global decision taking in a fusion center, using the function OR on the local decisions of SUs

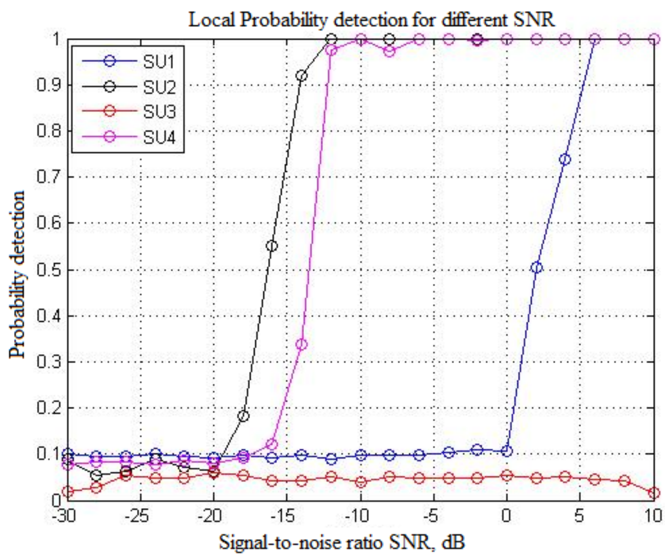

Figure 6. Pd(SNR) curves for all 4 SUs

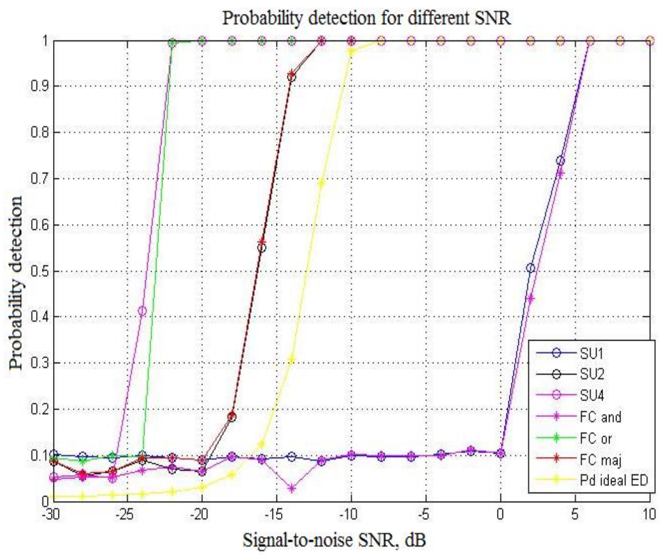

Figure 7. P_d(SNR) curves of 3 SUs selected by FC, P_d(SNR) curves of FC using functions OR, AND, MAJORITY and MATLAB curve as reference

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The observation of the 4 curves show that 3 of the Pd curves for SU1, 2, 4 are typical ED curves and the P_d curve for SU3 is almost invariant. It's a good illustration of the need of selection procedure in the FC for security and reliability reasons. Outliers and sharply differing curves have to be discarded to avoid skewed result for the global decision.

Here, the criterion proposed in [12], for discarding SUs with invariant curves by the FC, before decision making, is applied. So, the global decision, taken by the FC is based on results from SU1, 2, 4. Three SUs, often used in cooperative sensing experiments [7][15], are enough to give meaningful results for MAJORITY function, which is not possible with 2 SUs [5][16].

Three rules - OR, AND, MAJORITY combinations of the local decisions of the three SUs are experimented. Fig. 7 presents the P_d(SNR) curves of the 3 SUs, selected by FC and the P_d(SNR) curves of the FC when using functions OR, AND, MAJORITY on the local decisions of these 3 SUs. As it can be noticed, the OR function gives the best result in this particular experience. The yellow curve comes from simulation in MATLAB and it's given as reference. The results on Fig. 7 are obtained after 100 minutes long simulation on a notebook. The results on Fig.7 fully correspond to theory. Functions OR and MAJORITY in FC decision allow to overcome the late detection from SU1 which is behind the screen. The MAJORITY curve is the closest to the MATLAB simulation curve and it's the recommended function for the FC since the risk in the OR function is that in case of false alarm in only one SU, it will be transmitted to the FC decision.

V. Conclusion

The paper presents the results of a research on the implementation on USRP and GNU Radio of cooperative sensing system with EDs. The experimental setup realized permits to perform experiments using different scenarios as OR, AND, MAJORITY rules for decision making in FC on the basis of local decisions of SUs. More research on the performance of each function in cases of lower and higher thresholds in the EDs is foreseen. Special attention is given to selection function which is important to be included in the FC in order to discard outlying and misleading results, thus improving reliability and security of the system. Further work is foreseen focused on uncertainty influence and overcoming in cooperative sensing systems.

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