Paper

Implementation of Selected Spectrum Sensing Systems for Cognitive Radio Networks using FPGA Platform

Hikmat N. Abdullah and Hadeel S. Abed

Al Nahrain University, College of Information Engineering, Baghdad, Iraq

https://doi.org/10.26636/jtit.2018.125018

Abstract—The energy efficient spectrum sensing method is very important in cognitive radio (CR), since high power drain may limit its implementation in mobile applications. The spectrum sensing feature consumes more energy than other functional blocks, as it depends on continuous detection of the presence or absence of the primary user (PU). In this paper, we proposed two methods to reduce energy consumption of the spectrum sensing feature. The first is of a single stage variety with a reduced number of sensed samples. The other uses two stages. The first stage performs coarse sensing for many subchannels, and the best subchannel is forwarded for fine sensing in the second stage. The performance of the proposed methods is evaluated in AWGN channel and compared with the existing approach. The proposed methods are simulated using Matlab and ModelSim and are then hardware implemented using the Altera Cyclone II FPGA board. Simulation results show that the proposed methods offer an improvement in energy consumption with an acceptable reduction in the probability of detection. At E_b/N_0 of 0 dB, the energy consumption is reduced by 50% and 72% in the first and second proposed method, respectively, compared to the traditional method (100% sensing).

Keywords—cognitive radio, energy consumption, energy detection, FPGA.

1. Introduction

Cognitive radio (CR) is defined as a wireless technology that changes its operating parameters (e.g., power, carrier frequency, bandwidth, modulation and coding) based on the environment conditions. CRs allow unlicensed (secondary) users (SUs) to access spectrum bands at the time they are not used by licensed (primary) users (PUs). The channels that remain unused, on a temporary basis, are called spectrum holes [1]. Cognitive radio networks suffer from many problems, i.e. the energy efficiency problem which has received a lot of research attention during recent years [2], [3].

CR networks consist of a number of units sensing PU activity by using a specific sensing technique. All CR units consume energy, but the sensing stage draws more energy than others, since the spectrum sensing techniques depend on detecting the activities of the PU. Many techniques are used to sense the spectrum (energy detector, cyclostationary, matched filter and others).

A lot of methods have been investigated to improve energy consumption. Sequential sensing is a method to decrease the average number of sensors required to make a decision [4]–[7]. The authors of [8] proposed a fixed size censoring scheme, where each sensor senses fixed size samples of the spectrum and employs a censoring policy to send the results of local decisions to the fusion center (FC). In this method, only energy consumption in the transmission stage is reduced and there is no improvement in the sensing stage, since it senses a fixed number of samples. The authors of [9] implemented an algorithm-based energy detection technique in the Xilinx Virtex2pro FPGA board, but the algorithm did not aim to reduce energy consumption. In [10], a method for improving energy consumption is proposed based on two stages: coarse and fine, but was implemented only in the course of a simulation. In this paper, we have proposed two energy detector-based techniques to reduce energy consumption of the sensing stage. In the first method, energy savings are achieved in a single stage, by reducing the number of sensed samples, while the other method consists of two stages: coarse and fine, with an algorithm that is modified compared to that from [10]. The main contribution of this paper is that the proposed methods are simulated using the ZigBee wireless standard as a case study for cognitive user (CU), and are then implemented using the Altera FPGA Cyclone II board.

2. Energy Detector

Energy detection is one of the most popular spectrum sensing techniques, because of its simplicity and because it does not need any knowledge about the PU signals. In CR networks, CU senses the spectrum and detects the absence of a PU signal. After finding a hole, CU begins to transmit data to CU receiver. The samples received at CU are [11]:

$$X(n) = h\theta S(n) + N_o(n) \ , \tag{1}$$

where h is channel gain, $S(n)$ is the samples transmitted by PU, $N_o(n)$ is the additive white Gaussian noise samples collected from the channel, θ is the activity indicator, which can take one out of two values:

$$\theta = \begin{cases} 0 & \text{for } H_0 \text{ hypothesis} \\ 1 & \text{for } H_1 \text{ hypothesis} \end{cases} . \tag{2}$$

The presence and absence of PU is referred to as hypothesis H_1 and H_0, respectively. The probabilities of a false alarm and of detection are calculated by comparing the detector decision metric with a pre-defined threshold λ. The decision metric E_j is defined as the accumulated energy of the tested samples during the monitoring window t:

$$E_j = \frac{1}{N} \sum_{n=1}^{N} |x(n)|^2 \ . \tag{3}$$

In the above equation, N is the total number of sensed samples, $N = tF_s$, where F_s is the sampling frequency. The probability of a false alarm and the probability of detection are:

$$P_f = P_r(E_j > \lambda | H_0) \ , \tag{4}$$

$$P_d = P_r(E_j > \lambda | H_1) \ . \tag{5}$$

3. Design of Spectrum Sensing

3.1. The Single Stage Energy Efficient Spectrum Sensing

In this case the energy consumption improvement is achieved by decreasing the number of sensed samples to reduce the computational resources relied upon by the energy detector technique before making a decision. It also leads to a decrease in the sensing time, and it is worthy if the sensing reliability of the CR network is maintained within satisfactory limits. The reliability of sensing means that the maximum probability of detection and the minimum probability of a false alarm can be obtained. Figure 1 explains the way of choosing the samples to be sensed. Sensing of 50% of all samples is performed by sensing only even (or odd) numbered samples. To compute the amount of energy consumed by the cognitive user C_j, we use the procedure from [12], [13]:

$$C_j = N_s C_{ssj} + (1 - \rho_i) C_{tj} \ , \tag{6}$$

where C_{ssj} and C_{tj} are the energies consumed by the j-th cognitive radio in sensing per sample and transmission per bit, respectively, ρ_i is the average censoring rate, and N_s is the total number of sensed samples. As we compute the amount of energy consumption in the C_{sj} sensing stage only, Eq. (6) reduces to [12], [13]:

$$C_{sj} = N_s C_{ssj} \ . \tag{7}$$

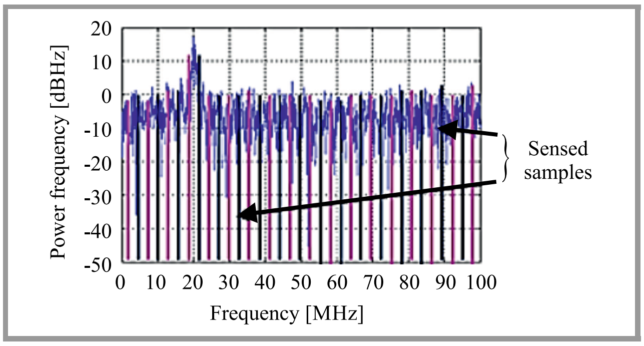


Fig. 1. The first method proposed (selecting 50% of the sensing samples). (For color pictures visit www.nit.eu/publications/journal-jtit)

Let's assume that $P_d = 1$, i.e. $C_{ssj_{|P_d=1}}$. When P_d is decreased, C_{ssj} is increased, since the energy detector will produce a false decision which leads to repeating the sensing sequence. Hence, C_{ssj} can be written as:

$$C_{ssj} = C_{ssj_{|P_d=1}} + C_{ssj_{|P_d=1}}(1 - P_d) \ . \tag{8}$$

After substituting Eq. (8) in (7) we have:

$$C_{sj} = kN_s \left[C_{ssj_{|P_d=1}} + C_{ssj_{|P_d=1}}(1 - P_d) \right] \ . \tag{9}$$

One can note that when $P_d = 1$ Eq. (9) becomes $C_{sj} = N_s C_{ssj_{|P_d=1}}$ where k is the sensing ratio, i.e. the number of selected samples sensed to the total number of samples in the band. Energy consumption per bit in the transmission stage is computed as described below. According to [14], the energy consumed in relation to the signal processing part of the transmission mode, for a data rate of 250 kbps and a 2.1 V/17.4 mA power supply, is approximately 150 nJ/bit. To transmit one bit over a distance d, the radio spends:

$$C_{tbj} = C_{t\text{-}elecj} + e_{ampj} d^2 \ , \tag{10}$$

where $C_{t\text{-}elecj}$ is the level of energy consumption in the transmitter's electronics, and e_{ampj} is the amplification needed to satisfy a given receiver sensitivity level. Assuming a data rate of 250 kbps and a transmitter power of 20 mW, $C_{t\text{-}elecj} = 80$ nJ with a receiver sensitivity of –90 dBm at SNR of 10 dB e_{ampj} is 40.4 pJ/m^2. So, the transmitted energy per bit per for the j-th CU would be:

$$C_{tj} = C_{tbj} + 150 \text{ nJ/bit} \ . \tag{11}$$

3.2. Two Stage Energy Efficient Spectrum Sensing

The second method consists of two stages: in the coarse stage, the CU senses a fixed spectrum length and a constant number of channels using a small number of sensed samples (e.g. 16%). The energy levels obtained from all channels during coarse sensing are collected, and then fine sensing is performed for the channel that has the maximum energy level. Fine sensing uses all samples in the selected channel to confirm the existence of PU, as shown in Fig. 2. To ensure that this signal is truly generated by PU and is not noise only, the level of energy accumulated in the channel is compared with threshold λ to produce a final decision about the presence of a PU signal. While detecting a spectrum hole, the same procedure is repeated, but fine sensing is employed to the channel with a minimum energy level. Such a method can be applied to all channels that may potentially have PUs (or holes), by finding the maximum (or minimum) energy channels and subtracting the accumulated energy contained in these channels from all other channels. If the difference is small, the particular channel also has a PU or a hole. The energy consumption level achieved by the cognitive user C_j is [15]:

$$C_j = \left(k + \frac{1}{m}\right) NsC_{ssj} + C_{tbj} + 150\ \text{nJ/bit}\ , \qquad (12)$$

where k is the sensing ratio N_s, and m is the number of channels in the spectrum.

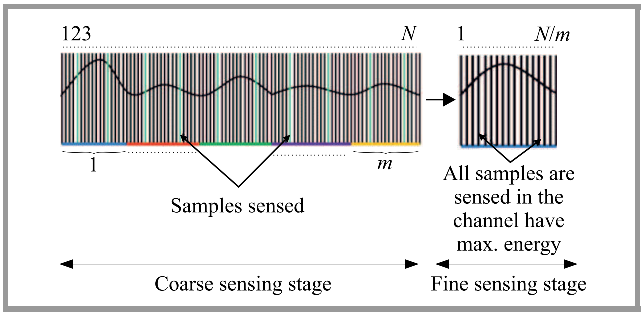


Fig. 2. Division of the spectrum using the second method proposed.

The threshold value comes from [16]:

$$\lambda = \left[Q^{-1}(Pf) + \sqrt{Ns}\right] 2\sqrt{Ns}(N_s)^2\ , \qquad (13)$$

where Q^{-1} is the inverse of the complimentary error function $Q(.)$, Ns is the total number of sensed samples and Pf is the probability of a false alarm.

4. Matlab Simulation Results

This section shows the results of a simulation of the energy detector's performance using the Receiver Operating Characteristic (ROC) curve, and energy consumption for a single user CR in AWGN, with the two methods proposed applied. The simulation parameters used are shown in Table 1.

Table 1
Simulation parameters

Parameter name	Value
Bit rate	2 Mbps
Carrier frequency	20 MHz
Modulation type	QPSK (PU signal)
Probability of false alarm	10^{-3}
Spectrum band	0–100 MHz
Sampling frequency	200 MHz
Bits per symbol	2
Sample per symbol	100
C_{ssj}	8 nJ [15]

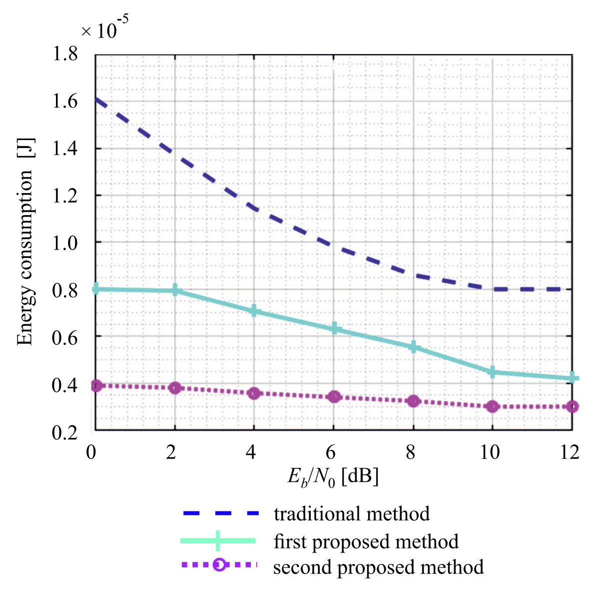


Fig. 3. Energy consumption versus E_b/N_0 in an AWGN channel.

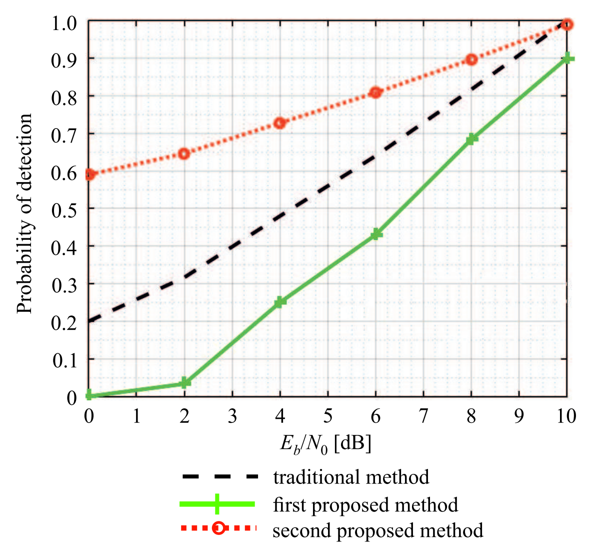


Fig. 4. P_d versus E_b/N_0 in an AWGN channel.

Figure 3 shows the energy consumption performance curves of CU versus E_b/N_0 in AWGN, as a comparison between known and proposed methods. It can be seen that an improvement in energy consumption is obtained when E_b/N_0 is increased since at high values of E_b/N_0 a low number of sensing samples is required by CU to detect the PU signal. For example, at E_b/N_0 0 dB, energy consumption decreases by 50% and 72% in the first and second method proposed, respectively (compared to traditional methods). Hence, the second proposed method is more efficient at low E_b/N_0. Figure 4 shows the detection probability versus E_b/N_0. It can be noted that the detection probability is increased at higher E_b/N_0. Also, it shows that when comparing the first proposed method and the traditional method, P_d is increased, as the number of sensed samples is increased since the number of sensed samples in the traditional method is 100% ($k = 1$), and in the first proposed method it equals

50% ($k = 0.5$). The improvement in detection probability introduced by the second proposed method become more significant at low E_b/N_0, because of the use of two stages increases detection probability.

5. Hardware Implementation

Figure 5 shows the design procedure relied upon to implement the spectrum sensing methods using FPGA. It consists of five subsequent steps. First, the system specifications are set up, and next the VHDL description language code and the test benches of the traditional and proposed methods are written. Functionality of the design is then tested once again, using ModelSim. After successful verification, the generated VHDL is synthesized using the Quartus II tool. The synthesis produces a bit stream file which is downloaded into the FPGA board and experimental testing is performed.

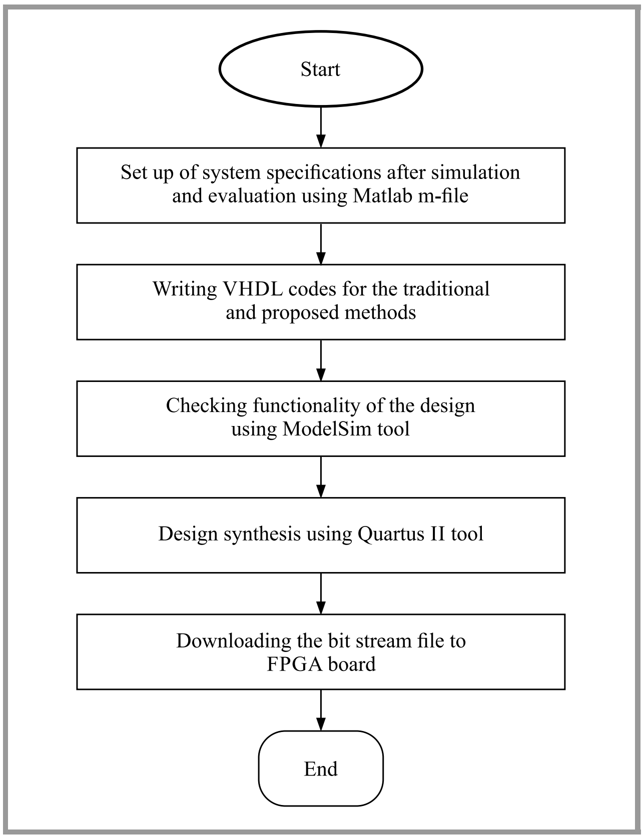


Fig. 5. Spectrum sensing method design flow using FPGA.

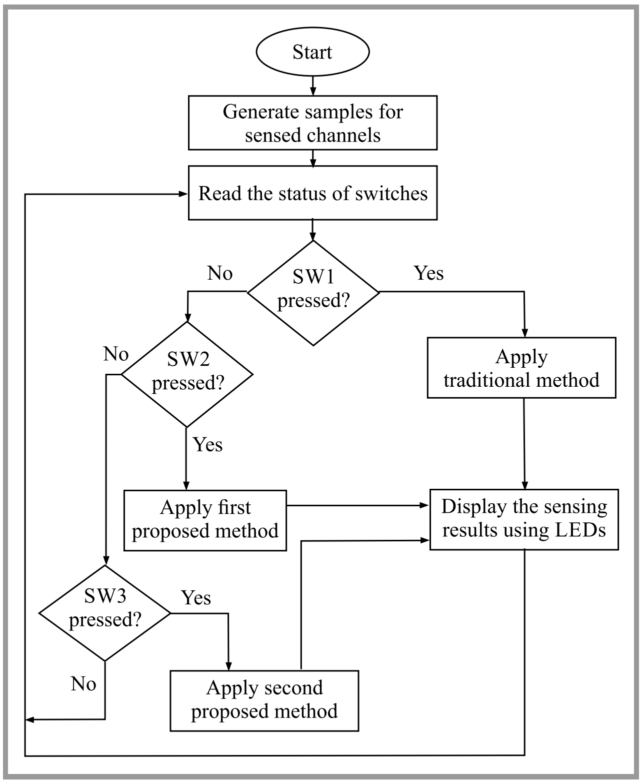


Fig. 6. Flow chart depicting implementation of spectrum sensing methods.

Figure 6 shows the design procedure relied upon to implement the traditional and proposed spectrum sensing methods using FPGA. First, the frequency samples of the sensed channels are generated. Then, the method rules are applied according to the selected switch of a special control circuit. The 8 LEDs available on the board are used to display the presence or absence of a PU in 8 channels. Figures 7 and 8 show the block diagrams that explain the design of the two proposed spectrum sensing methods. It can be seen in Fig. 7 that 50% of samples are sensed (marked green), and then the energy accumulated in each channel is compared with a predefined threshold to make a decision about the presence or absence of PU. The tra-

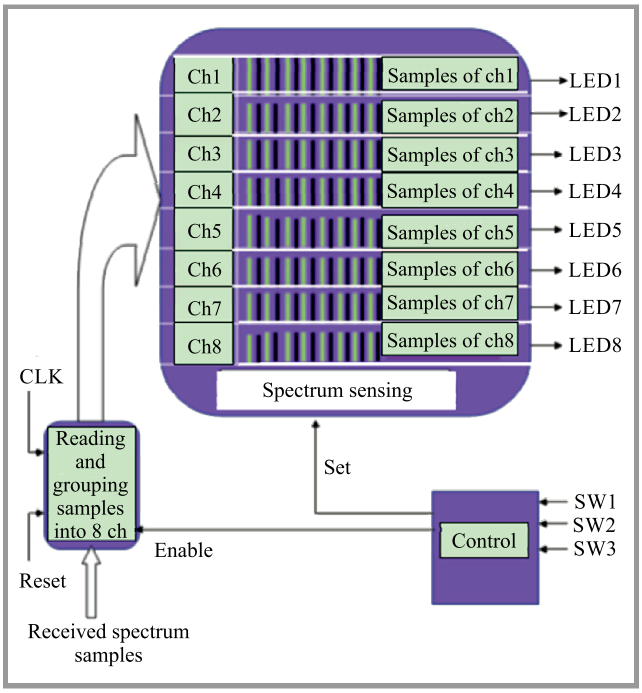


Fig. 7. Block diagram depicting implementation of the first method proposed on FPGA.

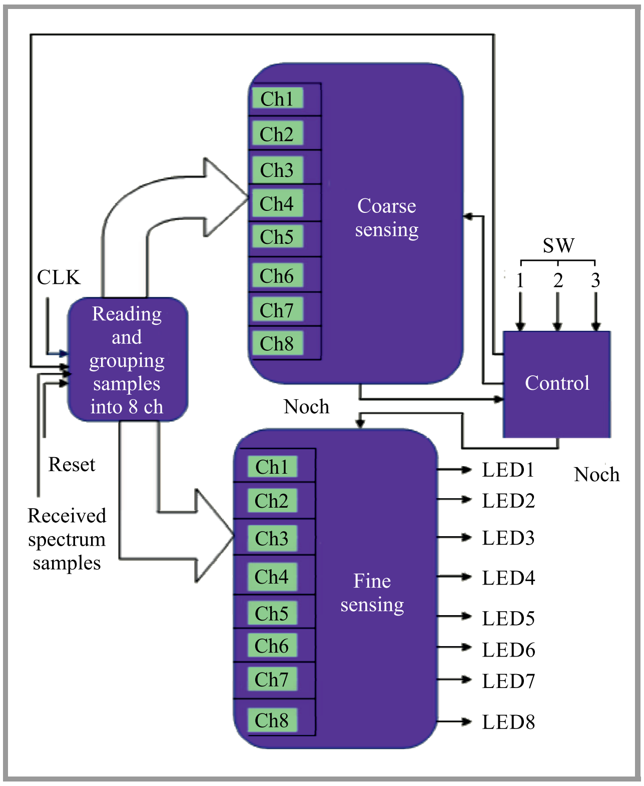


Fig. 8. Block diagram depicting implementation of the second method proposed on FPGA.

ditional method design procedure is similar, but with all samples being sensed.

It can be seen from Fig. 8 that there are two sensing blocks – one for coarse sensing and the other for fine sensing. In the coarse sensing block, the samples of each channel are sensed with a k sensing ratio, and then the index of the "noch" channel that has the maximum accumulated energy is selected in order for the fine sensing block to perform the fine sensing procedure. The final decision about presence or absence of PU in each channel is produced through the board's LED indicators.

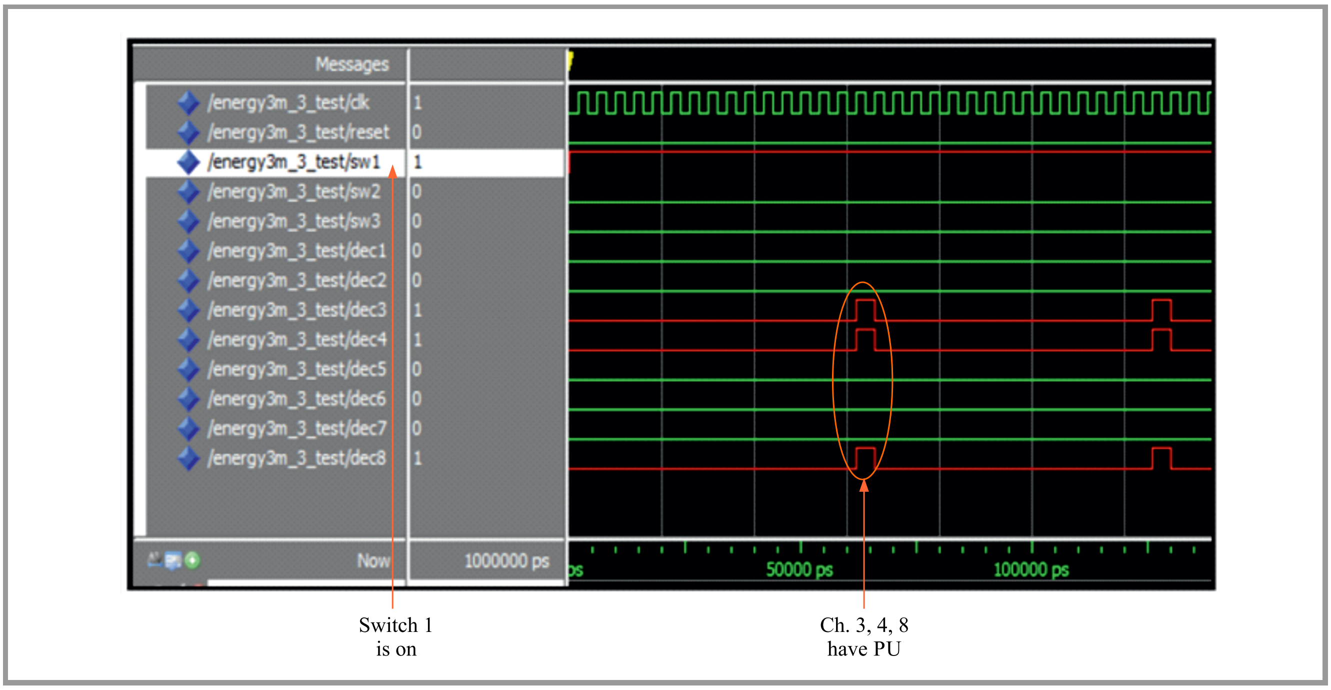
5.1. ModelSim and Real Hardware Results

Figures 9–11 show the ModelSim results of the traditional, the first and the second method proposed, respectively. In all results, the clock signal (CLK) drives the process of sensing samples, so that at each positive edge of the clock, one sample is sensed. Board switches SW1, SW2 and SW3 are responsible for selecting the sensing method. It can be seen that in Fig. 9 dec3, 4 and 8 equal to 1. This means that channels 3, 4 and 8 have a PU signal. In Fig. 10, the PU signal is present in channel 3 only, because of the reduction in detection performance when decreasing the number of sensed samples. Figure 11 shows the results after applying two stage sensing and finding the maximum energy channel. It can be seen that the index of the channel that has the maximum level of accumulated energy "noch" is 3, and dec3 is 1.

The experimental test results obtained with the use of the FPGA evaluation board are very close to those generated by ModelSim.

6. Conclusion

This paper has explained the way in which energy consumption in CR may be improved by applying two spectrum sensing methods. It has also evaluated the effects of



```
/energy3m_3_test/clk    1
/energy3m_3_test/reset  0
/energy3m_3_test/sw1    1
/energy3m_3_test/sw2    0
/energy3m_3_test/sw3    0
/energy3m_3_test/dec1   0
/energy3m_3_test/dec2   0
/energy3m_3_test/dec3   1
/energy3m_3_test/dec4   1
/energy3m_3_test/dec5   0
/energy3m_3_test/dec6   0
/energy3m_3_test/dec7   0
/energy3m_3_test/dec8   1
```

Switch 1
is on

Ch. 3, 4, 8
have PU

Fig. 9. ModelSim results for the traditional method.

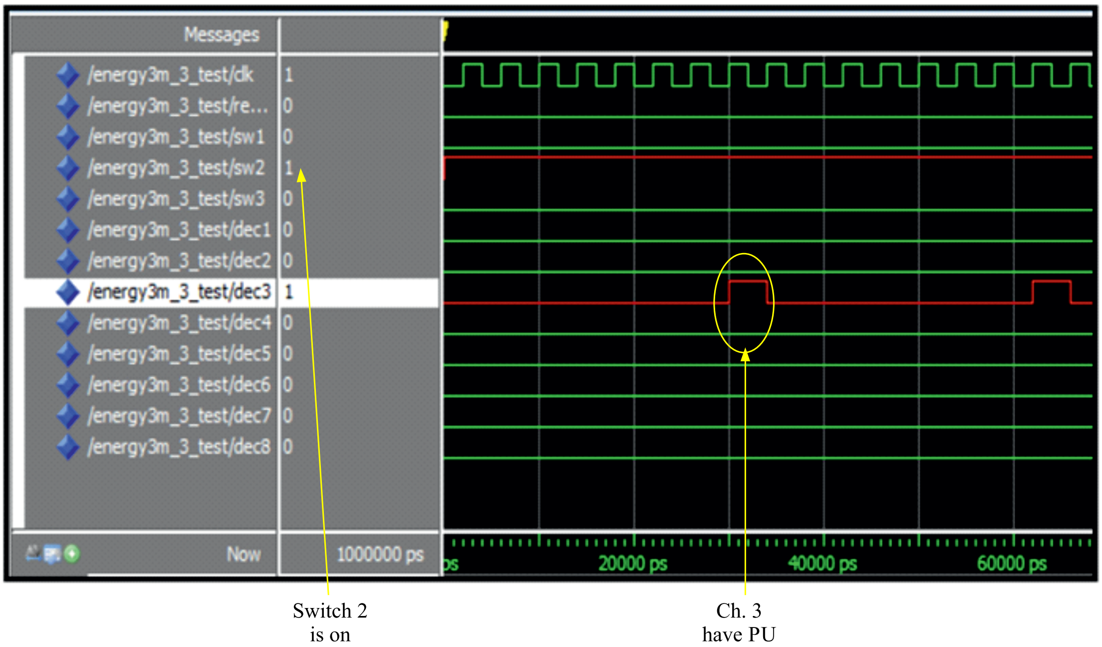


Fig. 10. ModelSim results for the first method proposed.

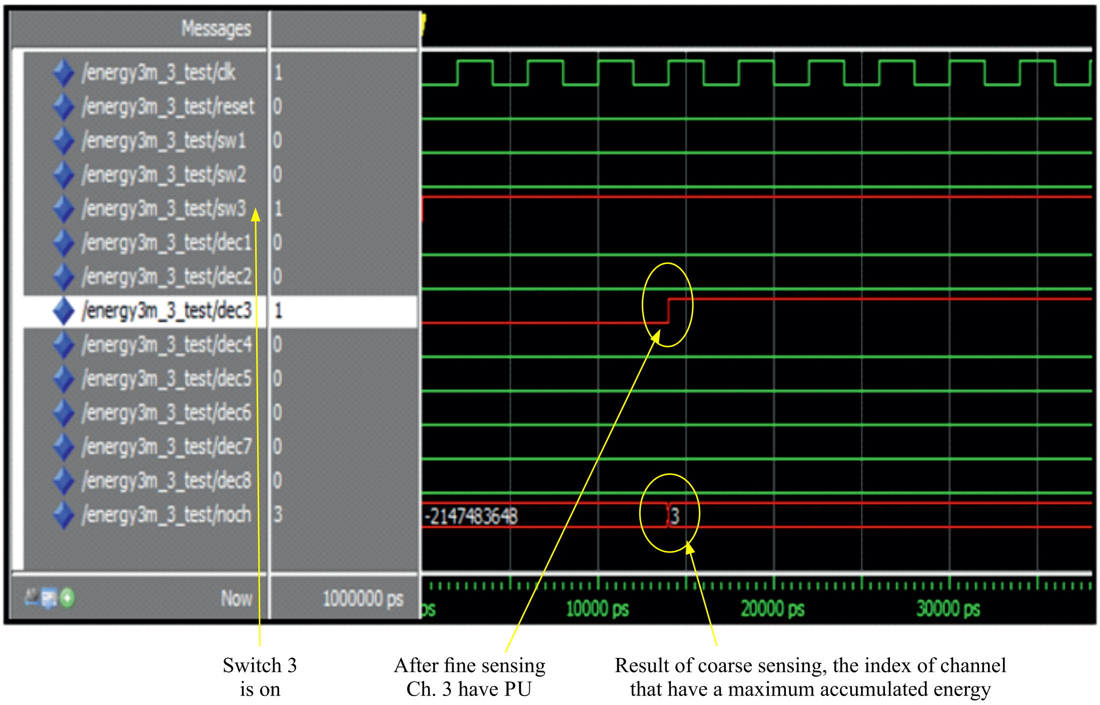


Fig. 11. ModelSim results for the second method proposed.

that improvement on the receiver's operating characteristics, by comparing them with the traditional method, using Matlab simulations. The energy consumption improvement introduced by the two methods proposed has been proved by simulation results, with no corresponding lack of detection probability observed. The results of tests involving experimental implementation of the proposed methods, obtained using the Altera FPGA board, have also been confirmed by the results of simulations obtained via Matlab and ModelSim. This work can be further extended to include implementation of the fusion center for cooperative sensing, as well as to include the entire filtering and frequency transformation of the sensed channels using a single FPGA chip.

References

[1] Y. H. Chye, E. Dutkiewicz, and R. Vesilo, "Adaptive Spectrum Sensing for Cognitive Radio Systems in a Fading Environment", in *Proc. 17th Int. Symp. on Wirel. Pers. Multim. Commun. WPMC 2015*, Sydney, Australia, 2015, pp. 451–456 (doi: 10.1109/WPMC.2014.7014861).

[2] M. Matinmikko *et al.*, "Cognitive radio: An intelligent wireless communication system", Research Rep. No. VTT-R-02219-08, Technical Research Center of Finland (VTT), 2008 [Online]. Available: https://www.vtt.fi/inf/julkaisut/muut/2008/CHESS_Research_Report.pdf

[3] S. Althunibat and F. Granelli, "On results' reporting of cooperative spectrum sensing in cognitive radio networks", *J. of. Telecommun. Syst.*, vol. 62, no. 3, pp. 569–580, 2015 (doi: 10.007/s11235-015-0095-5).

[4] S. J. Kim, G. Li, and G. B. Giannakis, "Minimum-delay spectrum sensing for multi-band cognitive radios", in *Proc. IEEE Global Telecommun. Conf. GLOBECOM 2010*, Miami, FL, USA, 2010 (doi: 10.1109/GLOCOM.2010.5683914).

[5] S. J. Kim and G. B. Giannakis, "Sequential and cooperative sensing for multi-channel cognitive radios", *IEEE Trans. on Sig. Process.*, vol. 58, no. 8, pp. 4239–4253, 2010 (doi: 10.1109/TSP.2010.2049106).

[6] S. J. Kim and G. B. Giannakis, "Rate-optimal and reduced-complexity sequential sensing algorithms for cognitive OFDM radios", *EURASIP J. on Adv. in Sig. Process.*, vol. 2009, no. 2, Article ID 421540, 2009 (doi: 10.1155/2009/421540).

[7] Q. Zou, S. Zheng, and A. H. Sayed, "Cooperative sensing via sequential detection", IEEE Trans. on Sig. Process., vol. 58, no. 12, pp. 6266–6283, 2010 (doi: 10.1109/TSP.2010.2070501).

[8] S. Maleki and G. Leus, "Censored truncated sequential spectrum sensing for cognitive radio networks", *IEEE J. on Selec. Areas in Commun.*, vol. 31, no. 3, pp. 364–378, 2013 (doi: 10.1109/JSAC.2013.130304).

[9] S. Srinu and S. L. Sabat, "FPGA implementation of spectrum sensing based on energy detection for cognitive radio", in *Proc. IEEE Int. Conf. on Commun. Control and Comput. Technol. ICCCCT 2010*, Ramanathapuram, India, 2010 (doi: 10.1109/ICCCCT.2010.5670540).

[10] H. N. Abdullah and H. S. Abed, "Improvement of energy consumption in cognitive radio networks using an efficient coarse-fine sensing method", in *Proc. Int. Conf. on Change, Innov., Inform. and Disruptive Technol. ICCIIDT'16*, London, United Kingdom, 2016, pp. 218–230.

[11] M. Emara *et al.*, "Spectrum sensing optimization and performance enhancement of cognitive radio networks", *Wirel. Pers Commun.*, vol. 86, no. 2, pp. 925–941, 2015 (doi: 10.1007/s11277-015-2962-5).

[12] H. N. Abdullah and H. S. Abed, "Improvement of energy consumption in cognitive radio by reducing the number of sensed samples", in *Proc. of IEEE Al-Sadiq Int. Conf. on Multidisc. in IT and Commun. Sci. and Technol. AIC-MITC 2016*, Baghdad, Iraq, 2016, pp. 301–306 (doi: 10.1109/AIC-MITCSA.2016.7759954).

[13] H. N. Abdullah and H. S. Abed,"Energy consumption control in cooperative and non-cooperative cognitive radio using variable spectrum sensing sampling", *J. of Telecommun., Electron. and Comp. Engin. (JTEC)*, vol. 8, no. 9, pp. 7–12, 2016.

[14] S. Maleki, A. Pandharipande, and G. Leus, "Energy-efficient distributed spectrum sensing for cognitive sensor networks", *IEEE Sensor J.*, vol. 11, no. 3, pp. 565–573, 2011 (doi: 10.1109/JSEN.2010.2051327).

[15] H. N. Abdullah and H. S. Abed, "Improvement of energy consumption in spectrum sensing cognitive radio networks using an efficient two stage sensing method", *Acta Polytechnica*, vol. 47, no. 4, pp. 235–244, 2017 (doi: 10.14311/AP.2017.57.0235).

[16] S. Atapattu, "Analysis of energy detection in cognitive radio networks", Ph.D. Thesis, Department of Electrical and Computer Engineering, University of Alberta, 2013 (doi: 10.7939/R33X37).

Hikmat N. Abdullah obtained his B.Sc. in Electrical Engineering and M.Sc. in Communication Engineering from the University of Al-Mustansiryah, Iraq, in 1995 and 1998, respectively, and Ph.D. in Communication Engineering from the University of Technology, Iraq, in 2004. From 1998 to 2015 he worked as a lecturer/associate professor at the Electrical Engineering Department of Al-Mustansiryah University, Iraq. Since the beginning of 2015 he has been working as an associate professor/full professor in the college of Information Engineering, at Al-Nahrain University, Iraq. In the period of 2011–2013 he received research awards from the International Institute of Education (IIE/USA) at Bonn-Rhein-Sieg University of Applied Sciences, Germany. He is interested in wireless communication systems and cognitive radio networks.

E-mail: dr.h.abdullah@ieee.org
College of Information Engineering
Al Nahrain University
Baghdad, Iraq

Hadeel S. Abed obtained her B.Sc. from the Information and Communication Engineering Department at the Al-Khawarizmi College of Engineering, University of Baghdad, Iraq, in 2014, and M.Sc. in Network Engineering and Internet Technologies from the University of Al Nahrain, Baghdad, Iraq in 2017. Since 2016 she has been working as a part time lecturer at the Information and Communication Engineering Department of the Al-Khawarizmi College of Engineering, University of Baghdad. Her research interests include cognitive radio networks.

E-mail: hs_eng1992@yahoo.com
College of Information Engineering
Al Nahrain University
Baghdad, Iraq