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System on Chip implementation of dual-band spectrum sensing using energy detection algorithm

Sesham Srinu*, Venkata Siva Kumar K †, Leokadia Nepaya*, Samrat L.Sabat †, Abisai.F.M.S*
* Department of Electrical and Computer Engineering, University of Namibia, Namibia
† CASEST, School of Physics, University of Hyderabad, India
Email: ssesham@unam.na*, 18phpe04@uohyd.ac.in †, lpnepaya@unam.na*, slssp@uohyd.ac.in†, mabisai@unam.na *

***Abstract*—Due to a rising number of wireless devices with the advent of the internet of things (IOT), there is a huge demand for radio spectrum. Numerous techniques were developed to use the limited radio spectrum efficiently, such as multiplexing and multiple access techniques. However, these techniques do not provide statistical information about utilization efficiency and spatio-temporal usage of vacant bands. In the recent past, cognitive radio technology has emerged as a favourable technology that can provide vacant band information temporally, which is useful to utilize the radio spectrum more efficiently. The crucial unit that can provide vacant band information is the spectrum sensing unit. Quite a few signal processing algorithms have been implemented and reported for single-band and multi-band sensing. However, very few works are reported on real-time implementation of multi-band detection using reconfigurable hardware such as SoC/FPGA. Hence, this paper presents System-on-Chip (SoC) implementation of single-band and dual-band sensing using an energy detection algorithm. The rationale for considering PYNQ SoC is due to its advanced features that are essential for the evolution of cognitive radio technology. The resource utilization and power required for the proposed prototypes are estimated and compared with the prior works. The results reveal that the performance of the developed prototype is in good agreement with the simulation results based on Monte-Carlo methods of 1000 iterations.**

***Index Terms*—Advanced wireless systems, Internet of things, Radio spectrum, Dual-band sensing, FPGA Implementation**

I. Introduction

According to the reports/statistics, over 50 billion wireless systems will be accessing wireless channels for internet of things (IOT), while the number of new devices is continuously growing exponentially [1], [2]. The static radio spectrum allocated by regulatory authorities (such as the federal communication commission (FCC), Telecom Regulatory Authority of India (TRAI), and the communications regulatory authority of Namibia (CRAN), etc) will be no longer efficient enough to grant access to new wireless systems [3]. On the other hand, licensed users are using some part of the allocated spectrum efficiently and the remaining part rarely (or under-utilized), leads to poor utilization of limited natural spectrum. Thus, scarcity and under-utilization of spectrum are critical issues that should be solved as soon as possible for the increasing number of wireless connections [2]. One of the prominent solutions to the above problem is to accommodate under-utilized radio bands to the next-generation (NEXGEN) wireless systems using cognitive radio technology. In cognitive radio (CR) systems, sensing units are crucial that can examine spatio-temporal usage of radio bands for opportunistic communications/connections [1], [2]. To improve Quality of Service (QoS) for both primary/licensed user (PU) and CR user communications, the sensing unit should detect multiple bands simultaneously. This unit is also important to avoid interference with the incumbent user's communication by seamless hopping.

Numerous detection algorithms have been developed for wideband/Multi-band cognitive sensing (WCS) units, which include energy, eigen-value, cyclostationary, machine learning, covariance, entropy, wavelet transform, and compressive sensing based methods [1], [4], [5]. However, practical solutions for the proposed techniques will only be observed when these algorithms are implemented in reconfigurable hardware. This can allow us to utilize radio frequency (RF) bands more efficiently by reconfiguring secondary user transmission signals according to the specifications of spectrum holes. In the literature, very little work is concentrated on developing a prototype for the WCS unit using System-on-chip (SoC), which is crucial to ensure real-time applications of cognitive radio technology for NEXGEN wireless applications.

Various prototypes have been developed for narrowband/single-band sensing and very few works are reported on implementations of wideband/multiband spectrum sensing in the literature. The authors in [6], developed a field programmable gate array (FPGA) architecture for single-band sensing using energy detection. A real time analysis of narrowband sensing using a software defined radio (SDR) platform by considering FM frequency bands (97 MHz and 120 MHz frequency band) was investigated in [7]. The authors in [8], designed and implemented a cyclostationary feature-based detector using the GNU-Radio framework and the universal software radio peripheral (USRP) by considering various modulated PU signals such as single carrier (QPSK, 64QAM, and 256QAM), multi-carrier (OFDM with 64 subcarriers), and without a carrier (i.e., Gaussian noise alone in a channel under test). The authors in [9], implemented two spectrum sensing techniques in low cost FPGAs to detect an ATSC signal, such as spectral correlation and Pilot sensing technique. The authors in [10], implemented energy detection based on single node and multi-node spectrum sensing algorithms in SoC hardware architectures using finite state machine-based approach. Prototypes of the architectures are also implemented on the Xilinx Virtex-IV (XC4VLX25) FPGA board using Verilog HDL. The authors in [11], developed a prototype of an adaptive threshold energy detector using a USRP and SDR platform. All these above works, developed prototypes for single-node sensing, while multi-band sensing is more important to improve QoS.

The authors in [12], developed a fast compressed power spectrum estimation method to sense signals in multi-bands. And it was also reported that the computation complexity of their proposed algorithm is less when implemented in FPGA. However, it did not provide details of practical FPGA implementation. The authors in [13], implemented multi-band spectrum sensing (MBSS) using SDR communication framework. However, the prototype performance can be improved with parallel processing and with lower number of resources. The efficient prototype can be developed using Python Productivity for Zynq (PYNQ) FPGA. This is owing to its advanced features such as software programmability, hardware acceleration, parallel processing, rapid embedded system design, low power consumption, and reconfigurability that are essential for the evolution of cognitive radio technology [14]. The hardware prototype of WCS unit on reconfigurable SOC is necessary for rapid prototyping and to use it for real-time applications for NEXGEN wireless systems (like cognitive radios and software-defined radios), which is not yet developed. Hence, we focus on developing a framework to efficiently implement multi-band sensing units by exploiting the PYNQ FPGA platform, which was recently released by Xilinx [14].

The main objective of this work is to design and implement a multi-band sensing unit, which can detect deterministic signals in single-band and dual-band simultaneously on PYNQ-Z1 SoC.

The rest of the paper is organised as follows: In section II, we provide problem statement and methodology (theoretically and practically) to sense signals in single-band and dual-band. In Section III, simulation and hardware results are presented and discussed. Finally, our conclusions are listed in Section IV.

II. Problem statement and methodology

Figure 1 illustrates the proposed dual-band sensing process using energy detection. Here, the dual-band cognitive sensor (DCS) receives the licensed user-transmitted signals in a wideband. Here, it is assumed that the narrowband channels are adjacent to one another within the considered range of RF bandwidth. The signals are contaminated with additive white gaussian noise (AWGN) within the considered bandwidth of interest. The RF front-end unit, re-configurable/Tunable Multiband Band pass filter (R/T MBPF) unit is an important front end unit which is assumed, ideal, meaning that it can separate the narrowband signals with zero signal leakage (or no adjacent channel interference) power over a wideband of interest. The ADC unit converts analogue signals in each sub-band into discrete time samples (data) in accordance with the band-pass sampling theorem. The test statistic (energy/power) is computed using collected data and compared with a pre-determined threshold in a dual-band detection unit to find out the status of a deterministic signal in two consecutive narrow-bands.

A. Detection criterion for energy detection

Let us assume, the primary user (PU) signal, Additive white Gaussian noise (AWGN) present in each sub-band, and received signal in each sub-band will be $s(n)$, $w(n)$, and $r(n)$ respectively. Where, n is the sample index.

Then the signal received by dual-band cognitive sensor (DSC) in k sub-bands (k = 1, 2) will be $r^k(n)$. The problem of sensing signals in multiple sub-bands can be represented hypothetically as [15],

$$H_0 : \mathbf{r^k(n)} = \mathbf{w^k(n)}, \forall n = 0, 1, \ldots, (N-1)$$
$$H_1 : \mathbf{r^k(n)} = \mathbf{Hs^k(n)} + \mathbf{w^k[n]},$$

where, the letter H represents channel matrix, which is assumed ideal (perfect channel). $\mathbf{r}^k$, $\mathbf{w}^k$ and $\mathbf{s}^k$ are the received signal, noise, and primary user signal in k^{th} sub-band ($k \in \{0, ..., (K-1)\}$), $m = 1, 2, ..., M$, $n = 0, 1, ..., (N-1)$. N represents is the total number of samples considered for test.

$$\mathbf{r}^k(n) = [\mathbf{r}^1(n), \mathbf{r}^2(n)], r(n) = [r(0), r(1), \ldots, r(N-1)]$$
$$\mathbf{s}^k(n) = [\mathbf{s}^1(n), \mathbf{s}^2(n)], s(n) = [s(0), s(1), \ldots, s(N-1)]$$
$$\mathbf{w}^k(n) = [\mathbf{w}^1(n), \mathbf{w}^2(n)], w(n) = [w(0), \ldots, w(N-1)]$$

where, the vector $\mathbf{r}^1(n)$ represents sample data/vector captured in sub-band-1. The noise in each sub-band is assumed/follows Gaussian, independent and identically distribution $(i.i.d)$ with zero mean and unit variance.

Compute Power of the received signal in each sub-band and compare with pre-determined threshold (γ_{ED}) to detect PU signal, given by [15],

$$P = \frac{1}{N} \sum_{n=0}^{N-1} |r(n)|^2 \underset{H0}{\overset{H1}{\gtrless}} \gamma_{ED} \tag{1}$$

where, γ_{ED} can be calculated using sample size (N) and Probability of false alarm P_{fa} [15], [11],

$$\gamma_{ED} = F^{-1}[(P_{fa})/\sqrt(N)] + 1, \tag{2}$$

where $F^{-1}(.)$ denotes the inverse of gamma function.

B. Implementation of sensing unit in PYNQ SoC

The Vivado Design tool is used to design DCS and configure the Processing system (PS), programmable logic (PL), and developed Overlay [16]. An Overlay is a kind of hardware library which establishes a connection between hardware and software through a Python-based application programming interface (API). Here, the data transfer between the software program and logic hardware through API that permits you to build an accelerator for single-band and dual-band sensing algorithms. Fig. 2 illustrates the SoC architecture of the

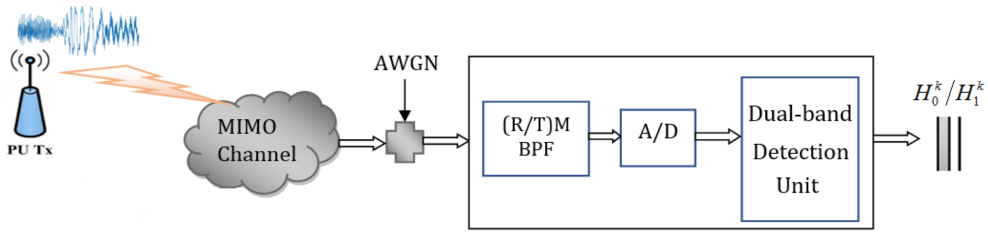

Fig. 1. Block diagram of dual-band detection process

energy detector on PYNQ SoC. In this architecture, the energy detection based Intellectual Property (IP) receives data from the PS. Then, the acceleration operations are performed in PL. Consequently, the detection results can be obtained from the processing system [17].

We have adopted the following development process for implementation [17]:

1. Design the hardware for the energy detection algorithm and validate its functionality.
2. Synthesize the design and create the hardware IP (Energy-Detec-IP).
3. Create Overlay for single/dual-band sensing units. Here, the IP block should be integrated with ZYNQ IP core. Then synthesize, implement and generate bit-stream to estimate actual resources and power required for proposed single-band and dual-band sensing units.
4. Realize the proposed DCS design on the PYNQ-FPGA in a Jupyter Notebook using Python.
5. Finally, the DCS algorithm can be implemented (32-bit floating-point data type) on a PYNQ-Z1 board that has a 650 MHz dual-core Cortex-A9 processor with AXI-Lite interface.

III. Simulation and Implementation Results

A. Simulation results

In the simulation work, performance analysis of single-band and dual-band detectors is carried out in AWGN channel environment. Licensed user signals are generated with QPSK modulation with varying noise strength to verify the accuracy of the proposed detectors. As discussed in the algorithmic section, the threshold is calculated based on sample size (N) and (P_{fa}). Different sizes of sample data (N = 256, 512, and 1024) are considered. The threshold (γ_{ED}) is computed based on the formula given in Eqn.2 at different P_{fa} values which, ranges from 0 to 1. The other simulation parameters considered during DCS detection process are: the number of sub-bands are 2 (k = 1, 2), a rectangular window of size N, tolerable $P_{fa} \leq 0.1$, SNR range is from -20 to 0 dB. The channel matrix (H) is an Identity matrix. The sensing performance of single-band and dual-band is examined based on receiver operating characteristic (ROC) curves (P_{fa} vs. P_d) and SNR vs P_d curves. Monte-Carlo methods are used to verify the accuracy of proposed sensing unit with 1000 iterations. The results are presented based on extensive simulations that were performed using Matlab/Python.

Fig. 3 shows the performance comparison in terms of P_d against SNR (dB) for single-band energy detection with variable sample size (N = 256, 512, and 1024) at fixed P_{fa} = 0.1. Results clearly present that the P_d increase with increase in sample size. Moreover, detection probability increases with increase in SNR and is above 90% when SNR value is $\geq$ -10 dB with sample size of 1024.

Fig. 4 shows the Receiver operating characteristics (ROC) curves of the dual-band detector. Two different PU signals with different noise strength (SNR = -5dB and -7dB) are generated and applied to the DCS unit to verified accuracy of sensing. The value of P_{fa} is varied from 0 to 1 in steps of 0.05. Results clearly show that the proposed unit can detect signals in two different sub-bands, simultaneously. Moreover, the accuracy of the DCS is high when the signal strength in that particular sub-band is high.

B. Hardware results

Fig. 5 illustrates the overlay of the dual-band detector in Xilinx-Vivado design tool. The energy detector IP is generated using a high level synthesis (HLS) tool. After importing the base PYNQ block design, we started to add the accelerator overlay to it. The accelerator Overlay needs an AXI-Lite interface to communicate with the PS for data transferring. We have integrated one Energy-detec-IP for single-band sensing. The same IP is integrated twice in the case of dual-band sensing that can detect two sub-bands simultaneously owing to parallel processing feature of PYNQ SoC. In order to use the Overlay, .bit and .tcl files should be used, which are generated using Vivado design suite and import the .tcl file and bit-stream file for implementation.

The resource utilization and power required for two different designs (single-band and dual-band units) are reported based on post-implementation results in Table.1 and Table.2

Figures. 6 and 7 illustrate the performance of simulation and implementation (hardware) results of proposed dual-band sensing in terms of detection probability against average SNR in two consecutive sub-bands at P_{fa} = 0.1. Fig. 6 shows the performance of DCS unit using Matlab, while Fig. 7 presents performance of implemented DCS unit using Python. Number of Monte Carlo trials are 1000. Sample size (N) = 1024. It is clear from the figures that both simulation and implementation performance increases with increase in SNR and can detect signals in two sub-bands up to -10 dB at desired

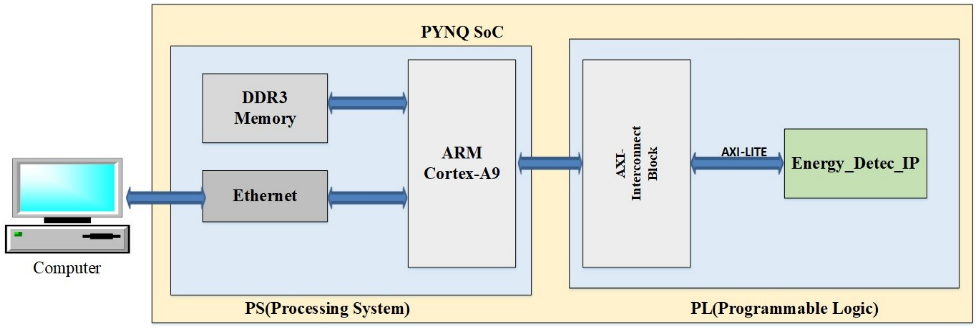

Fig. 2. SoC Architecture of energy detector on PYNQ SoC

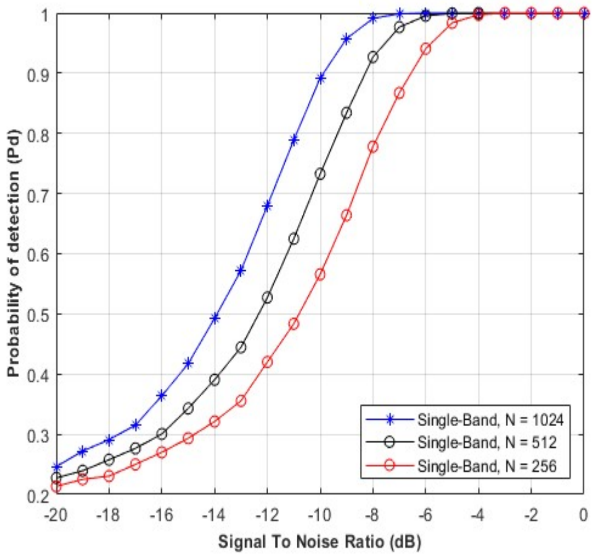

Fig. 3. SNR vs P_d of dual-band energy detector with different sample size (N = 256, 512, 1024)

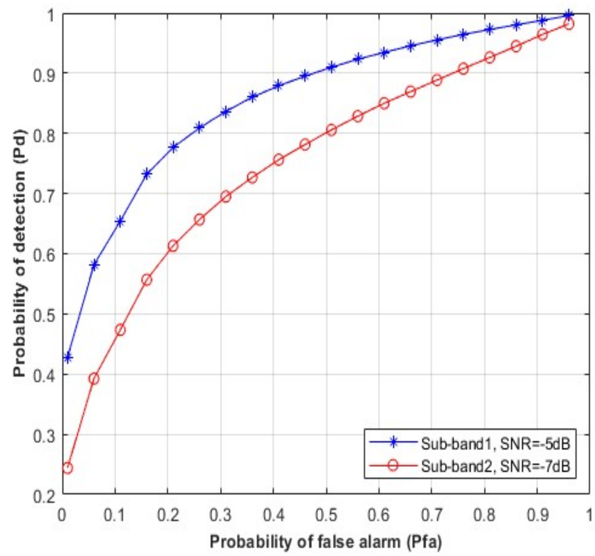

Fig. 4. ROC curves of the dual-band detector with different SNR in each sub-band (SNR = -5 dB and -7 dB)

value of tolerance (P_{fa}). Most importantly, the simulation and hardware results are in good agreement at all different strengths of received signal.

From Table.1, it is clear that the percentage of resource utilization increases with increase in the number of sub-bands to be scanned. For instance, the number of LUTs required is 3362 and 6034 for single-band and dual-band sensing units, respectively. The average/overall utilization is 3.86 % for single-band sensing and 6.77 % for DCS unit. When we compare resources required for single band sensing, the proposed implementation of SoC takes more compared to other implementation methods reported in [6], [7]. The frequency of operation of a single-band detector is 144 MHz using PYNQ, which is better than an energy detector based design reported 70.028 MHz in [6]. Table. 2 provides the SoC power utilization of single-band and dual-band sensing units. From Table 2, it can be observed that the power required for the Energy-Detec-IP is 52 mW and increases with increase in the number of sub-bands. In the case of DCS unit, it requires almost twice the power of 105 mW.

IV. Conclusions

This paper presents the design and implementation of single-band and dual-band sensing units based on signal energy measured at the desired radio frequency. Design verification of the proposed model and implementation has been performed by considering different modulated signals with varied strengths of noise. The Python language is used to design proposed units in PYNQ-Z1 FPGA, which greatly accelerates the sensing process. An IP core is developed and implemented in PL part of SoC, which can interact with a PS through overlay form with AXI stream interface. We have successfully implemented a dual-band sensing unit on PYNQ SoC that can accelerate design and improve the performance of the proposed sensing unit. The results show that the proposed model can detect two narrow-band signals independently and simultaneously. The detection probability of the proposed model can detect signals up to -10 dB with a tolerance probability of $P_f \leq 0.1$. Most importantly, the

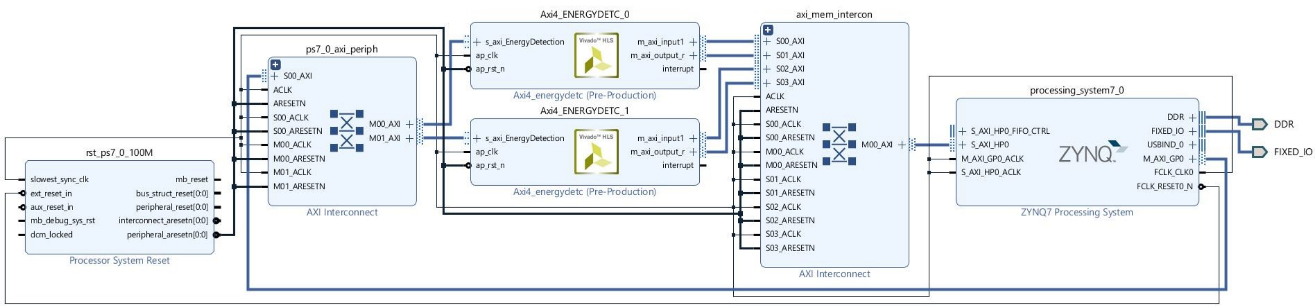

Fig. 5. Overlay of DCS unit in Xilinx-Vivado design suite

TABLE I
RESOURCE ESTIMATION FOR SINGLE-BAND AND DUAL-BAND SENSING UNITS

Resources	Available Resources	Single-Band		Dual-Band	
		Used	Utilization%	Used	Utilization%
Slice LUTs	53200	3362	6.32	6034	11.34
LUTRAM	17400	197	1.13	326	1.87
FF	106400	4061	3.82	7196	6.76
BRAM	140	4	2.86	8	5.71
DSP	220	13	5.91	26	11.82
BUFG	32	1	3.13	1	3.13

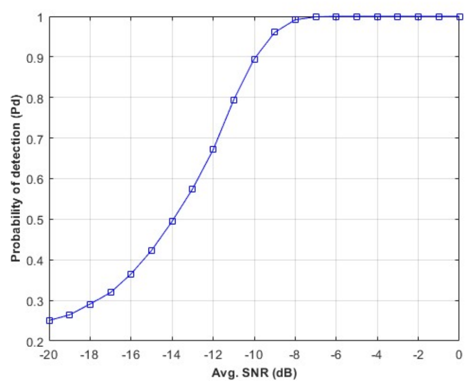

Fig. 6. Simulation performance of dual-band sensing unit

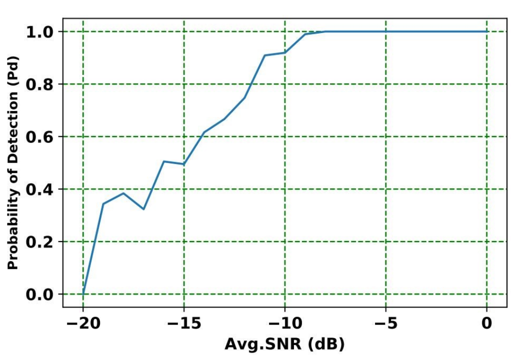

Fig. 7. Hardware performance of dual-band sensing unit

TABLE II
SoC POWER UTILIZATION FOR SINGLE-BAND AND DUAL-BAND SENSING UNITS

Power Utilization	Single-Band	Dual-Band
IP Power (mW)	52	105
Static Power (mW)	136	138
Dynamic Power (W)	1.322	1.380
Total On-Chip (W)	1.458	1.518

simulation results are in good agreement with hardware results. We have presented resources and power required to implement the proposed units. The utilization of resources increases as we increase the number of sub-bands. The average/overall utilization is 3.86 % for single-band sensing and 6.77 % for dual-band sensing. The power required for the Energy-Detec-IP is 52 mW and it increases linearly with the number of sub-bands. Future research work should consider more sub-bands to scan a wider part of the radio spectrum. In addition, we have to reduce the number of resources required by investigating how to make a single IP and share possible detection parameters (threshold, detection logic, etc.) for multi-band sensing.

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