Cognitive Radio Experiments using Reconfigurable BEE2

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Abstract—The idea of cognitive radios has created a great interest in academic and industrial research. As a result, there are a large number of proposals for their physical and network layer functionalities. However, most of these research results rely on a theoretical analysis or computer simulations. In order to enable this technology and fully understand system design issues in its implementation, these theoretical results should be verified and demonstrated in realistic scenarios through physical implementation and experimental studies. In this paper, we present an experimental platform based on the Berkeley Emulation Engine 2 (BEE2) that can facilitate the development of physical and network layer functionalities for cognitive radios. We take spectrum sensing as an example that incorporates both signal processing and networking techniques to show how this platform could be used to conduct comprehensive research in cognitive radios. In particular, we focus on energy and cyclostationary detectors and indoor network cooperation.

I. Introduction

Recently, cognitive radios have been proposed as a possible solution to improve spectrum utilization via opportunistic spectrum sharing. Cognitive radios are considered lower priority or secondary users of spectrum allocated to a primary user. Their fundamental requirement is to avoid interference to potential primary users in their vicinity. The first application of cognitive radios is studied under IEEE 802.22 standard group [1] in order to enable secondary use of UHF spectrum for a fixed wireless access. Although cognitive radios promise dramatic improvements in spectrum utilization and revolution in the way the spectrum is used, their realization still requires technical proofs of feasibility and regulatory approval [2].

The growing interest in cognitive radio research from signal processing and communication communities has spurred an increasing number of papers in the recent years [8]. There are a large number of proposals for all communication layers, but the system infrastructure has not been clearly defined. In addition, most of these research results rely on theoretical analysis or computer simulations. In order to influence and convince regulators, these theoretical results should be demonstrated in realistic scenarios. One of the most effective methodologies for the simultaneous development of algorithms, their implementation and experimental validation is based on testbed platforms. In this paper, we present an experimental platform based on the Berkeley Emulation Engine 2 (BEE2) platform that can facilitate the development of physical and network layer functionalities in a feasible system architecture for cognitive radios.

We take spectrum sensing as an example that incorporates both signal processing and networking techniques to show how this platform could be used to comprehensive evaluate and verify the theoretical results. The need for experiments of spectrum sensing techniques is stressed by the inability to realistically model all noise sources encountered in the receiver and interference environment. In addition, a comprehensive evaluation of a statistical behavior requires extensive Monte Carlo simulations. A real-time testbed operation allowed us to perform a large set of experiments for various signal types, receiver settings, and network configurations. Besides addressing their performance limitations, a physical implementation of these complex signal processing algorithms provided estimates of their hardware complexity.

The paper is organized as follows: Section 2 introduces new research problems in cognitive radios, overviews theoretical approaches, and derives testbed requirements for their experimental study. The developed testbed system, its capabilities and modes of operation are presented in section 3. In section 4, we describe three experiments using the testbed including: the test methodology, hardware implementation, and measurement results. Summary of the work and conclusions are presented in Section 5.

II. New Research Problems in Cognitive Radios

Unique to cognitive radio operation is the requirement to reliably detect unused spectrum through spectrum sensing [3]. Since the radio does not have primary rights to any pre-assigned frequencies, spectrum sensing must be done in a minimum time and on a periodic basis. In general, cognitive radio sensitivity should outperform primary user receiver by a large margin in order to prevent what is essentially a *hidden terminal problem*. This margin is required because a cognitive radio does not have the direct measurement of a channel between primary user receiver and transmitter and must base its decision on its local channel measurement to a primary user transmitter. Therefore, spectrum sensing functionality involves the design of various analog, digital, and network processing techniques in order to meet challenging radio sensitivity requirements.

A. *Spectrum Sensing at the Physical Layer*

Digital signal processing techniques are needed to increase radio sensitivity through processing gain and provide primary user identification based on knowledge of some signal characteristics. However, signal processing algorithms for very low SNRs in a noise dominated regime are quite different from demodulation and detection processing in conventional digital communications.

The simplest non-coherent detector is energy detector which only integrates squared samples. The processing gain for energy detectors scales with number of samples as:

$SNR_{out}=N\cdot SNR_{in}^2$. In the case of a very small SNR_{in} quadratic scaling becomes dominant, and increasing the observation time helps less [3]. The signal is detected by comparing the output of the energy detector with a threshold dependent on the estimated noise power. As a result, a small uncertainty in the noise power due to estimation error or interference in the channel could limit the detection of weak signals and cause the detector to fail [9]. Even though the implementation simplicity of the energy detector makes it a favorable candidate, the experimental study is needed to characterize performance of this detector in low SNR regimes. Experiments should be performed with an actual radio implementation including RF transceiver and real time estimation of noise and interference power.

In order to gain robustness with respect to noise and interference, more sophisticated detectors could be devised if additional information on primary user signal is exploited. One example is a cyclostationary feature detector that has the ability to extract distinct features of modulated signals such as sine wave carriers, symbol rate, and modulation type [3]. These features are detected by analyzing a spectral correlation function that discriminates that noise being wide-sense stationary signal with no correlation against cyclostationary modulated signals. A spectral correlation function is a two-dimensional transform, in contrast with power spectrum density used by an energy detector which is one dimensional. Therefore, the implementation complexity is increased to N^2 complex multiplications to perform the cross-correlation of the N point FFT outputs, while the energy detector has complexity of N point FFT. There are two outstanding issues with feature detectors that have to be addressed through implementation and experiments: i) an efficient and flexible VLSI architectures and ii) a proof of orthogonality between the signal and noise features in real radios.

B. Spectrum Sensing at the Network Layer

In fading channels, single radio sensing requirements are set by the worst case channel conditions introduced by multipath, shadowing, and local interference. These conditions could easily result in SNR regimes where the detection would not be possible. However, due to variability of signal strengths at various locations, this worst case condition could be avoided if multiple radios share their individual sensing measurements via network cooperation. Theoretically, it has been shown that if *n* radios combine independent measurements, then a probability of detection of the system Q_D monotonically increases as $Q_D=1-(1-P_d)^n$. In addition, the probability of false alarm for the system Q_F also monotonically increases as $Q_F=1-(1-P_{fa})^n$ [6]. These theoretical results rely on independent channel assumption and identical radio detection rules. However, these conditions might not necessarily hold in practical situations. It is important to understand the robustness of these theoretical results under realistic wireless channel and radio models.

C. Testbed Requirements

As presented in the earlier sections, there are a number of new functionalities involved in cognitive radio design from algorithms and architectures to networking. One approach for system design exploration is to use a testbed platform that provides flexibility and rapid reconfiguration for testing systems under controlled but realistic environments. Using a testbed experiment has become a common strategy in research communities and industry. Testbeds have been predominantly used to test point to point links and measure established metrics such as BER vs. SNR and effective throughput under different wireless channel propagation environments. However, cognitive radio research requires new testbed capabilities due to interaction between different layers.

Experimental studies of spectrum sensing techniques require spectrum measurements in real-time, as the critical parameter is the minimum sensing time. This involves high computational capabilities to support complex signal processing algorithms. Wireless experiments should be carried out using sufficiently wideband radio front-ends in order to incorporate real noise and interference sources and allow detection of various signal types. An investigation of cooperation techniques demands a large number of parallel radios centrally connected for information exchange and processing. Furthermore, the testbed should allow flexible spatial distribution of multiple radios in order to perform experiments in different environments. Lastly, the programming model and design flow should be simple enough to allow testbed use by algorithm and protocol developers.

III. COGNITIVE RADIO TESTBED

The cognitive radio testbed that fulfils the requirements presented in the earlier section was developed at Berkeley Wireless Research Center (BWRC). It consists of Berkeley Emulation Engine BEE2, reconfigurable 2.4 GHz radio modems, and fiber link interface for connection between BEE2 and radios. Top level block diagram is presented in Figure 1. The Simulink based design flow and BEE2 specific operating system provide an integrated environment for VLSI implementation and simple data acquisition, respectively.

A. Berkeley Emulation Engine (BEE2)

Berkeley Emulation Engine 2 (BEE2) is a generic multi-purpose FPGA based, emulation platform for computationally

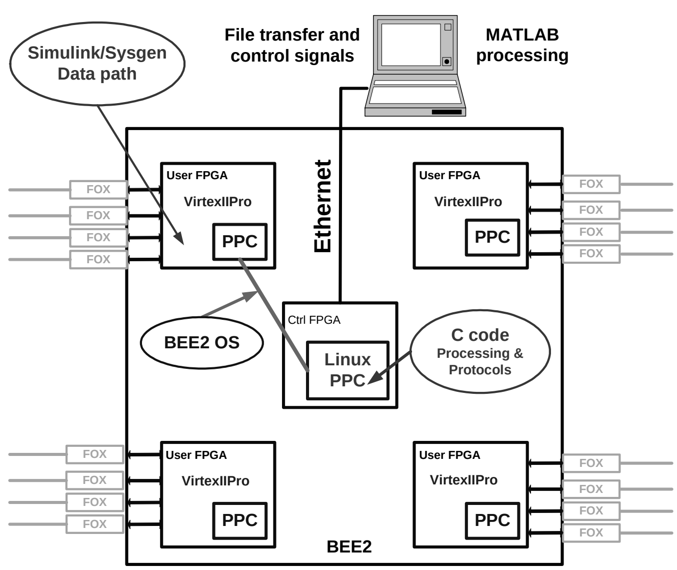

Figure 1. Top-level block diagram of BEE2 testbed, software design flow, and 16 fiber connections (FOX)

intensive applications [4]. The BEE2 consists of 5 Vertex-IIPro70 FPGAs and integrates 500 giga-operations per second. One FPGA is used for control, while the other four are targeted for user applications. The control FPGA runs Linux and a full IP protocol stack convenient for connection with laptops and other network devices. User FPGAs are connected to 4GB of DDR2-SDRAM. In addition, BEE2 can connect up to 16 front-end boards via 10 Gbit/s full duplex Infiniband interfaces.

B. *Reconfigurable 2.4 GHz Radio Modem*

The radio front-end system operates in 2.4 GHz ISM band over 85 MHz of bandwidth with programmable center frequency and several gain control stages. The analog/ baseband board contains a 14-bit 128 MHz D/A converters, 12-bit 64 MHz A/D converters, and 32 MHz wide baseband filters. On-board Virtex-IIPro20 is used to implement radio control functions, calibration of analog impairments and real time access to programmable radio registers. In addition, this on-board FPGA provides optical transceiver interface to BEE2 for sample processing. High level model of the modem is shown in Figure 2. Multiple radios can be connected to compose the parallel multiple antenna front-end. The radio center frequency and digital clock can be distributed to each of the board in order to ensure synchronous operation.

C. *Fiber Link Interface*

In order to support a transfer of raw A/D bits (2 channels of 12 bits @ 64 MHz) and D/A bits (14 bits @ 128 MHz), a 2.5 Gbps fiber link between BEE2 and radio modem is deployed using optical transceivers compatible with Infiniband connectors. An optical cable can connect front-end boards at distances up to 100m away from BEE2 in order to perform different scenario experiments and implement network cooperation. In addition, the optical link provides good analog signal isolation on the front-end side from the digital noise sources created by BEE2. However, this optical interface introduces asynchronous operation between BEE2 and radio modem. The XAUI interface and protocol is implemented on both sides of the link for the synchronization of data packets.

D. *Simulink-based Design Flow*

All FPGAs in the testbed system are programmed using BWRC-developed automation tool based on Xilinx System Generator library. This environment supports simultaneous development of signal processing algorithms and digital design description for their hardware realization. Therefore, no translation is required, which allows signal processing researchers to realize hardware implementation of developed algorithms. The original System Generator library is enhanced by a set of parametrizable blocks to support interfaces with hardware components such as A/D converters, radio configuration registers and DDR memory. Simulink design is translated directly to FPGA configuration through BEE2 enhanced Xilinx Platform Studio (BPS). Further, the tool provides the developer with hardware estimates of the design in terms of number of multiplications, logic, and memory. This is extremely important in the design optimization process.

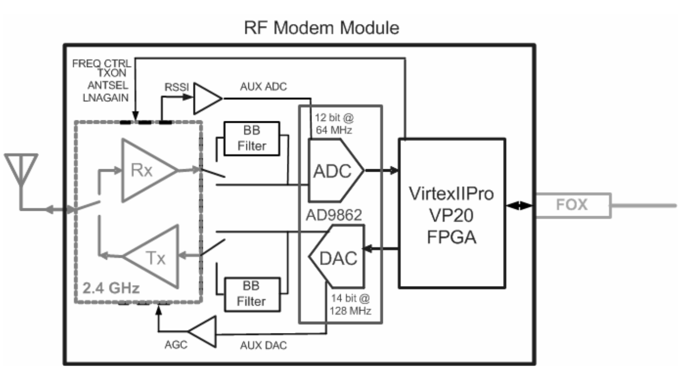

Figure 2. Block diagram of a reconfigurable 2.4 GHz modem

E. *Run Time Control, Data Visualization, and Acquisition*

One of the key features in the design flow is the ability to communicate and control hardware registers, block RAM's, DRAM, and software running on control FPGA in real-time. This feature allows rapid post-processing of acquired signals in MATLAB or access to radio configuration registers in the experiment setup via automated scripts. Furthermore, it allows an implementation of protocols in C programming language and its direct integration with underlying hardware. This was enabled by enhancing Linux operating system through abstraction of hardware registers and memory on the user FPGA using file mapping [5]. BEE2 can be connected to the local area network so that registers and memory can be accessed and transferred to laptops or PCs via Ethernet.

IV. Design Examples and Experimental Results

In our experimental study, we used the testbed to characterize three spectrum sensing techniques:

A. Required sensing time needed to achieve the desired probability of detection and false alarm using energy detector.

B. Robustness of cyclostationary feature detector in the presence of real noise and receiver impairments.

C. Performance gains obtained by network cooperation.

A. *Energy Detection Characterization*

The energy detector is implemented using K=256 point FFT with a fully parallel pipelined architecture for the fastest speed. Due to A/D sampling at 64 MHz, this implementation has 250 kHz FFT bin resolution (Figure 3). Each block of FFT outputs is averaged using an accumulator with run-time controllable number of averages. A result of the computation is stored in the memory block RAM. The design runs at 100 MHz speed, while the signal samples from the radio are fed at 64MHz. Thus, there is an insignificant latency in the signal processing. For example, executing 1000 experiments with 3200 spectral averages (51.2 ms) of 256 point FFT takes less than 15 seconds.

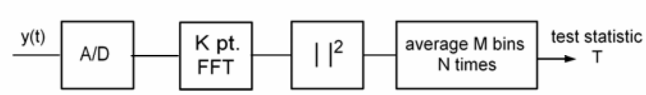

Figure 3. Energy detector implementation using periodogram

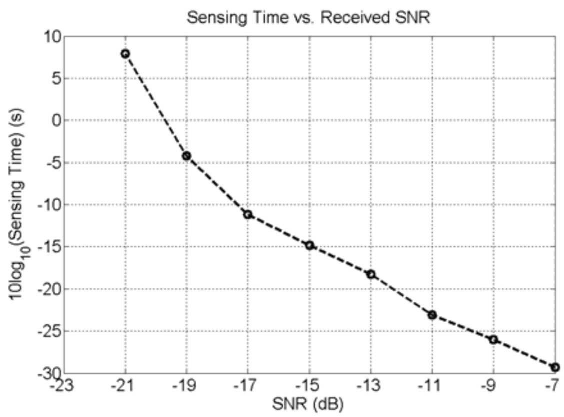

Figure 4. The required sensing time to meet Pd and Pfa

To measure the performance under AWGN we connect signal generator to the RF board antenna input via SMA cable. Prior to all experiments, we calibrated the noise level of the radio receiver, and the measured level is -103 dBm in a 250 kHz FFT bin. Then, we apply a 4MHz QPSK signal with power levels from -94 dBm to -110 dBm, which is effectively SNR from -7 dB to -23 dB. For each signal level, we measure how the probability of detection scales as the sensing time increases based on 1000 identical experiments. The detection threshold is set to meet 10% probability of false alarm. Figure 4 shows how the sensing time must be scaled in order to meet Pd=80% for all signal levels. The scaling law of *Sensing time ~1/SNR*^{2} is consistent with the theoretical prediction. Figure 4 also shows that when the signal becomes too weak, increasing the number of averages does not improve the detection. The limit in QPSK detection happens at -110dBm (SNR= -23dB).

B. *Cyclostationary Feature Detection*

First issue with cyclostationary detectors is their high computational complexity involved in estimating spectral correlation function (SCF) [3]. The frequency domain estimation methods require computation of an N point FFT, cross-correlation of all bins and averaging over a period of sensing time. However, for the detection of a signal of interest only the deterministic region of SCF needs to be computed. We developed a reconfigurable architecture for computation of any portion in NxN SCF. Figure 5 shows the detailed block diagram. In order to match fan-in and fan-out, K frames

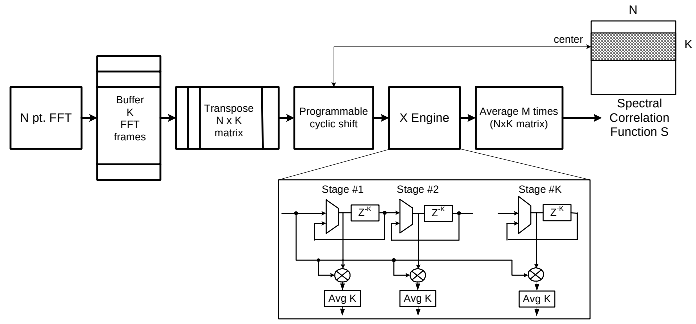

Figure 5. A reconfigurable implementation of feature detectors

Resources	Energy Detector	Feature Detector
18x18 Mult	18	80
16 Kb Block RAM	4	20
4 input LUT	10,353	21,200
Flip Flop	12,155	20,559

Table 1. Implementation complexity comparison

(K<N) are buffered and arranged so that cross-correlation could be performed through a simple scalable data path of multiplexers, delay lines, and multipliers. We have implemented a 256 point FFT and computed SCF of size 256x16 (N=256, K=16). The implementation complexity is compared with 256 point FFT energy detector, and design summaries are reported in Table 1. The number of multiplications has increased approximately 5 times. In case the entire SCF (256x256) is required, the number of multipliers would increase by 16, i.e. 16x80=1280 18x18 multipliers, as the X Engine should have 16 times more stages.

To measure the performance of the cyclostationary, we used the setup similar to the energy detector experiments. We transmitted 4 MHz QPSK signal unconverted to ISM band to the RF board through SMA cable from programmable vector generator. First, we confirmed the orthogonally of signal and noise features. Figure 8a shows the SCF when no signal is sent to the receiver and number of averages M is set to 1000. The diagonal trace is the power spectrum density (PSD) of the signal. Second, we varied the number of averages and studied relationship between M and the feature detection. Figures 8b and 8c show SCF of the 4 MHz QPSK signal with M being 10 and 1000, respectively. Finally, we studied the sensitivity of the cyclostationary detector with respect to sampling clock

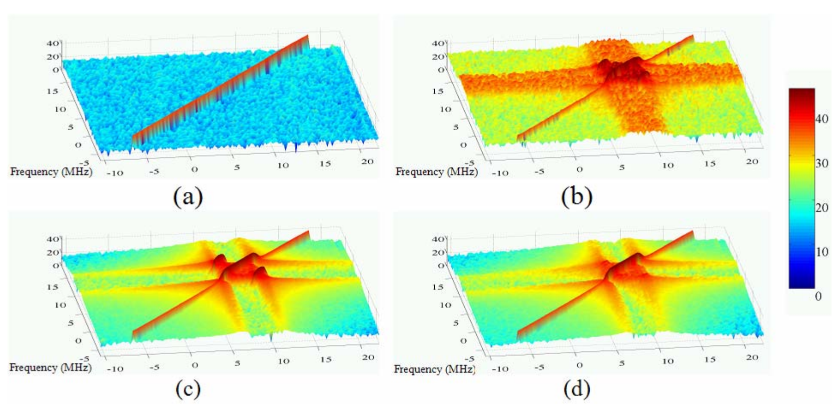

Figure 6. Measurement results of cyclostationary feature detection of QPSK signal

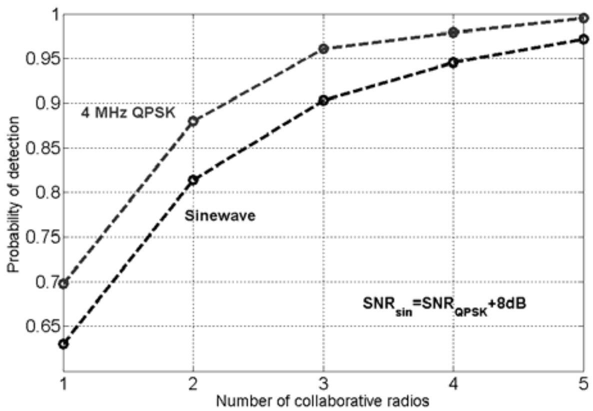

Figure 7. Cooperative gains vs. number of radios for sinewave and QPSK signals

offset from the optimal sampling frequency need to recover symbol data rate feature. Figure 8d shows that with even 100 Hz offset from the optimal sampling frequency, the most significant cyclostationary features of the signal is cancelled out. Therefore, cyclostationary feature detectors require tight synchronization in case of large number of averages is needed. As a result, they do not provide sufficiently robust solution for weak signal detection.

C. Collaborative Spectrum Sensing

The experiments were conducted inside the Berkeley Wireless Research Center. Receivers were place on 54 different locations on a 2m by 2m grid, that covers a cubicle area, library and conference room, where all wireless measurements were taken [7]. In all experiments, the transmitter was located inside the lab. Therefore, the signal path between the transmitter and all receiver positions included propagation through either concrete or wooden walls, supporting beams, medium and large size metal cabinets and general office furniture. The area covers a balanced variation of obstacles which are typical for indoor non-line-of-sight environments.

For each sensing location, data was collected for three different transmitter configurations: idle spectrum i.e. no signal, sinewave signal and QPSK signal. For each location and data type, spectrum was sensed 200 consecutive times using 3200 averages (51.2 ms) in the periodogram. We analyze the cooperation gain as function of the number of cooperating radios. Results are presented in Figure 7 and show that for 10% probability of false alarm, an 18% improvement is observed through cooperation of two radios, then 9% for three, and it saturates to 4% and 3% for four and five cooperating radios, respectively. Overall, going from 1 to 5 cooperative radios detection improves from 63% to 97%.

V. Conclusions

In this paper we present the experimental platform based on the reconfigurable BEE2 that can facilitate the development of multiple layer functionalities for cognitive radio. Advanced capabilities such as real-time high processing throughput and networking capabilities are demonstrated through experimentation of spectrum sensing techniques. The testbed has also been used to do extensive performance analysis of pilot, energy, and collaborative detection under realistic channel and radio impairments [7]. The system is currently being used to investigate a feasibility of the cyclostationary feature detection techniques for cognitive radio spectrum sensing applications. Preliminary results show that a very tight synchronization is required between sampling clock and the signal of interest data rate for the cyclostationary features to be useful in very low signal to noise regimes.

VI. Acknowledgements

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