

Radio Testbeds Using BEE2

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Abstract— Flexible Radio Testbeds are being designed using the Berkeley Emulation Engine (BEE2) platform. Narrow-band and wide-band platforms are discussed which can accommodate a full spectrum of wireless multiple radios for wide and narrow-band applications. The BEE2 programming and debugging capabilities, using Simulink and Linux augmented with the BORPH operating system, provide a high level design environment. Applications are discussed which portray the flexibility of these testbeds and the ability to demonstrate realistic scenarios, as well as comprehensively evaluate and verify theoretical results.

I. INTRODUCTION

This paper describes a set of flexible wireless testbeds using the Berkeley Emulation Engine (BEE2), shown in Fig. 1. These testbeds have been developed at the Berkeley Wireless Research Center. Both wide-band and narrow-band testbeds are discussed. The wide-band testbed is modular and scaleable. The modules include an Interface Breakout Board (IBOB), ADC, DAC, and analog I/Os. Two frequency bands of interest are discussed. One band is in the TV/ISM band from 600MHz-1GHz. The second band is around 2.45GHz with a 500MHz band. The narrow-band system has 2.4GHz reconfigurable RF modems. One can use up to 16 radios and antennas in parallel with the narrow-band system. Phase synchronization and digital synchronization are provided with the narrow-band testbed. Both the wide-band and narrow-band testbeds have fiber link interfaces to the BEE2.

The focus of this paper is on the hardware, programming environment, and applications of the narrow and wide-band testbeds using BEE2. This paper is organized as follows: Section 2 presents the hardware for the narrow-band and wide-band testbeds. Section 3 discusses the programming

environment. Section 4 describes applications using both the narrow-band and wide-band test beds including: cognitive radio spectrum sensing, verification of a multiband sensing algorithm, wireless research for the energy commission (the agile radio) and a radio telescope array. Section 5 presents the summary and conclusions.

II. HARDWARE TESTBEDS TO SUPPORT FLEXIBLE RADIO RESEARCH

Both the narrow-band and wide-band flexible radio testbeds connect to the BEE2. Both testbeds have a fiber link interface for connection between BEE2 and radios. This fiber link allows remote radios and antennas. The wide-band testbed is a modular design with transceivers, an Interface Breakout Board, custom boards for wide-band, high speed ADC and DAC, and an analog frontend. I/Q processing is done digitally. The narrow-band system consists of a reconfigurable 2.4GHz radio modem. I/Q may be done in analog or digitally.

The BEE2 Platform

The BEE2 Platform shown in Fig. 2 contains five FPGAs, 20 GBytes of DDR2, 64 GBytes per sec of memory bandwidth, 180 GBits of full duplex IO bandwidth, serial interconnections, transceivers, optical fiber connections, and 18 XAUI ports (10Gbit). The only high speed I/O is thru the XAUI connection.

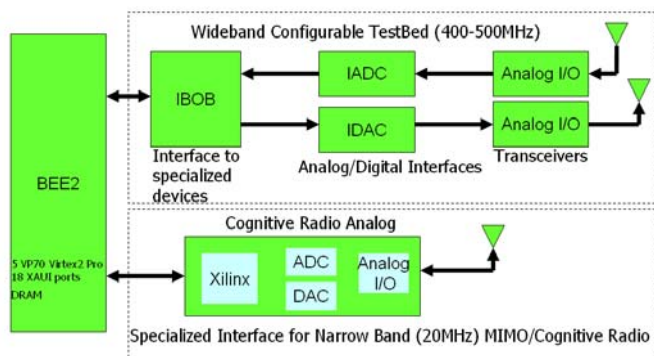


Fig. 1. Block Diagram of the Radio TestBed Components

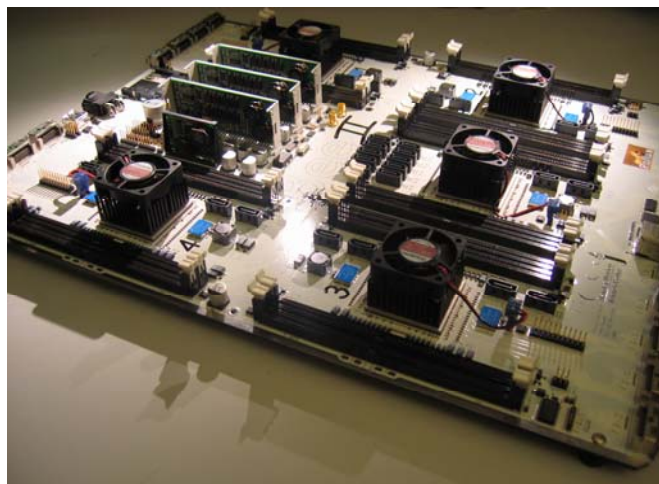


Fig.2. The BEE2 Processor Board

The BEE2 is highly scalable due to the reliance on gigabit serial I/O for inter-board communication. This scalable system architecture allows the BEE2 to support a broad

variety of applications including wireless research, and has lead to the development of two key wireless testing environments: the Wide-Band testbed, and the Narrow-Band MIMO/Cognitive Radio testbed.

The Wide-Band Testbed

The wide-band testbed targets broad-band radio applications by using the Interface Breakout Board (IBOB) interface with high-performance ADC and DAC cards connected to an RF front-end.

The BEE2 has limited I/O options, depending almost exclusively on the Gigabit serial interfaces for high-bandwidth off-board I/O. To support specialized I/O needs, the Interface Breakout Board (IBOB) was developed (Fig. 3), providing an on-board Xilinx 2VP50 for preprocessing capability as well as multiple interfaces. The interfaces include ZDOCs (40 LVDS pairs each running at 256 MHz or 40.96Gbits per sec) and XAUI (20 Gbits per sec full duplex, 10/100 ethernet, RS232, and 80x GPIO).

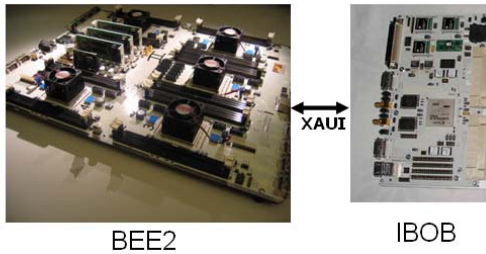


Fig. 3. IBOB: Interface Breakout Board with XAUI connection to the BEE2 Processor Board

The custom ADC and DAC boards in Fig. 4 connect to the IBOB through high speed ZDOC connectors. Each ZDOC connector has 40 LVDS pairs, 36 differential pairs for IO and 4 pairs for clock. The IADC has a high speed ADC with a sampling rate of 1Gbps or 2 Gbps in interleaved mode. Each ADC has 8 bit resolution. The high speed DAC has a sample rate of 1.2Gbps, a high bandwidth of 550MHz, and a high resolution at 10 bits.

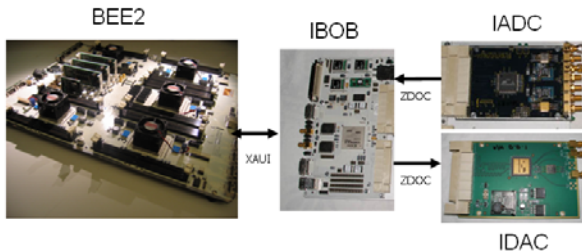


Fig. 4. IADC and IDAC with high speed connections

RF Frontend System

Wide-band experiments at the BWRC include two bands of interest. One frontend supports TV and ISM bands from 600MHz to 1GHz, and a second 500 MHz bandwidth frontend centers around 2.45GHz. The 2.45 GHz ISM band frontend, used for sensing experiments, is designed with a conventional mixer, whereas subsampling is used for the TV/ISM band frontend.

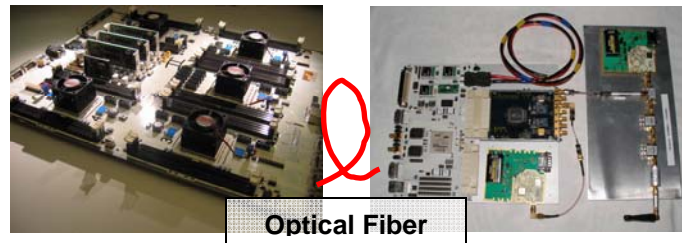


Fig 5. RF Frontend Radio Boards: Analog I/O, IADC, and IBOB, which connect to BEE2 via optical fiber.

The Narrow-Band System

The narrow-band Cognitive Radio/MIMO testbed shown in Fig. 6 has a 2.4GHz radio modem which connects to the BEE through a fiber or Infiniband cable. This testbed is used for multiple radio or multiple antenna applications, where the multiple units may be used in parallel or independently. The testbed has a local oscillator (LO) distribution board to provide the same LO to 16 radios simultaneously, key to radio tuning and phase synchronization. There is also a digital clock board for synchronizing the digital components on up to 16 boards. The data is synchronized at the ADC and DAC between digital boards. The 2.4 GHz radio provides 20MHz channels that can be programmed to operate anywhere within the entire 80MHz ISM band. The optical connection between the RF modem and the BEE2 allows for a remote analog front-end.

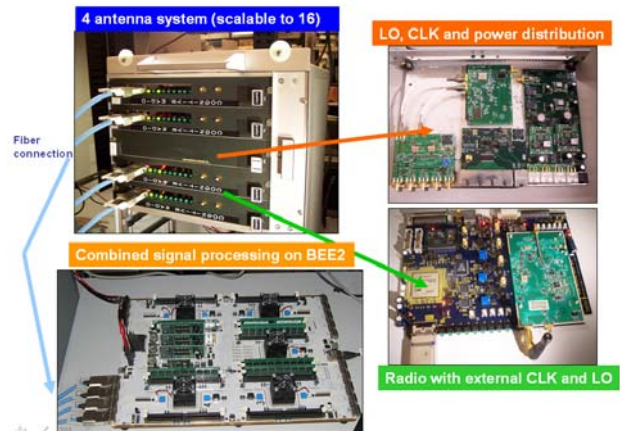


Fig. 6. Components of the Cognitive Radio/ MIMO TestBed

The RF Modem shown in Fig. 7 contains the analog I/O (2.4 GHz radio programmable over 85 MHz of bandwidth), analog I/Q, a Xilinx FPGA Virtex 2 Pro, a 14-bit 128MHz -bit

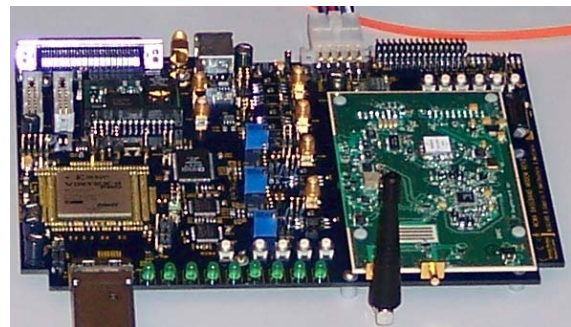


Fig. 7. RF Modem with Narrow band radio daughter card

DAC, a 12-bit 64MHz ADC, 32MHz wide baseband filters, and the XAUI high speed interface. I/Q may also be processed digitally. Multiple RF modems can be connected to create the parallel multiple antenna front-end.

III. PROGRAMMING ENVIRONMENT

The highly reconfigurable BEE2 platform and related interfaces depend on a high-level programming environment to fully utilize the capabilities of the testbeds described previously. A block-diagram-based programming model was selected and extended to include support for high-level operating system interfaces and debugging abstractions.

Programming Model and Support – Programming with Block-Diagrams

Traditionally, FPGA-based systems are configured using hardware description languages such as Verilog or VHDL, requiring detailed knowledge of the reconfigurable platform. Rather than requiring a wireless testbed user to learn low-level HDL programming techniques, the Matlab Simulink block-diagram editor [1] was employed instead. This environment is familiar to many architectural, signal processing, and hardware designers, making it a natural unified environment for programming the BEE2 and related system components.

The BEE Platform Studio [2] was developed around the Xilinx System Generator blockset and tools, combined with the Xilinx EDK Embedded microprocessor design tools [3]. A library of BEE-specific blocks (Fig. 8) is used to provide a high-level abstraction for several FPGA platforms, allowing the designer to easily add microprocessor register or memory interfaces to a signal processing design by selecting a library component, and configuring the function using Simulink component property menu selections.

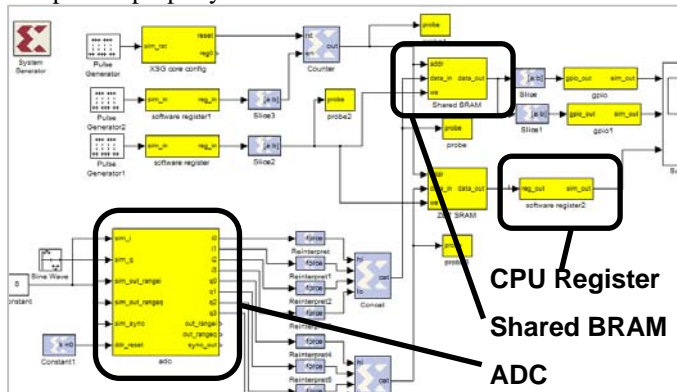


Fig. 8. The Simulink Block-Diagram-Based Programming environment with library components for microprocessor and I/O interfaces.

Once a design is described in Simulink, it can be compiled and mapped onto the BEE2 or other platform using the BEE Platform Studio. The compiler sets platform-specific parameters for the Xilinx System Generator tool flow, which is used to generate the hardware description for the dataflow blocks. CPU interfaces are identified in the design, and a set of files is generated with a complete description of the embedded CPU. This description is automatically compiled to produce FPGA bit files and embedded software header files.

The BORPH FPGA Operating System

With conventional FPGA design flows including embedded microprocessors, the designer must develop the corresponding software interfaces. To simplify this effort, the BORPH operating system was developed [4], leveraging the embedded processor designs described previously. BORPH is an extension to Debian Linux running on an FPGA, providing a process and file system abstraction for the user-defined hardware. When the user “executes” an FPGA bit file, a Linux process number is associated with the design, and the corresponding hardware can be accessed using the /proc filesystem. As a simple example, assume that the hardware has a 32-bit software register named “FILTER_ENABLE.” To set a bit in the register, the user can run the command line:

```
echo 1 > /proc/123/hw/ioreg/FILTER_ENABLE
```

By using the file system to represent hardware, the designer can use any programming language, without a need for a design-specific programming interface.

The BEE2 platform supports up to four simultaneous hardware processes, one on each User FPGA, communicating with the BORPH Linux operating system on the Control FPGA. Combining the block-diagram programming style in Simulink with the convenience of BORPH, the designer is able to quickly develop FPGA applications without becoming an experienced FPGA or embedded system designer.

BDB: The BEE Debugger

Debugging of a design is performed using a custom, integrated framework which utilizes debug components inserted into the hardware netlist in combination with an external remote user interface. Layered on top of the BORPH operating system, the designer can use the BEE Debugger, BDB[5] to easily add hardware trace variables to the Simulink design (Fig. 9), and record related signal activity at near real-time speeds to on-board DRAM during design operation. In addition, though BORPH, the user can control the debugging process from any location over the network. Beyond the simple convenience of being decoupled from the hardware location, this also allows debugging to take place in the original design environment (i.e. Matlab/Simulink), which greatly improves bug detection and data analysis compared to traditional hardware capture techniques.

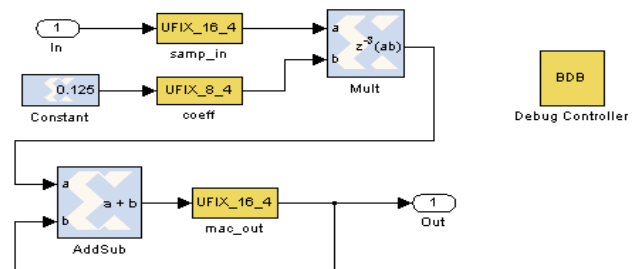


Fig. 9. BDB: A system with inserted debugging trace variables and debug controller block

IV. APPLICATIONS

In this section we provide an overview of a set of applications enabled by the testbeds detailed above. Specifically the availability of the testbeds enables us to experiment and evaluate with different aspects of these applications not possible in simulation. The narrow-band testbed is used for the BWRC cognitive radio experiments. The wide-band front-end is used for verifying the usefulness of multiband sensing algorithms as well as wide band applications.

Cognitive Radio

Cognitive radios have been envisioned as a mechanism for the opportunistic reuse of spectrum. These radios “sense” for the presence of the primary user and use the spectrum only if it is deemed empty. If a frequency band is deemed empty, these radios can transmit in the band at a power level which ensures minimal interference to the primary radio. This kind of reuse is illustrated in Figure 3, where PU_{1-4} are primary users using their respective bands. CR_1 is able to transmit in the empty band between PU_3 and PU_4 . Comparing this to the transmission of CR_2 , CR_2 is unable to sense for the presence of PU_2 and starts transmission. This transmission interferes with PU_2 and is undesirable.

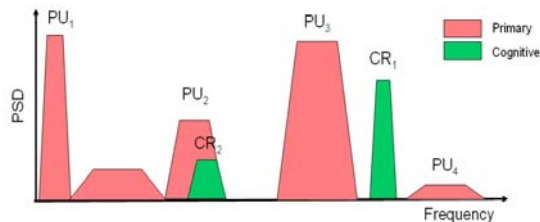


Fig. 10. Cognitive Radio: sensing the spectral environment

As the discussion above illustrates, one of the key aspects of a cognitive radio is the ability to reliably detect the presence of primary users. Furthermore it should do this while ensuring that its ability to find an empty band is not diminished (One can imagine a cognitive radio that always says that a primary is present. Such a radio always ‘detects’ a primary but is never able to use the band). Using the testbeds described earlier, we continue to investigate various aspects of cognitive radio operation.

A. Performance of various single band sensing algorithms:

The testbed was used to measure the performance of various single radio sensing algorithms: Energy detection, Coherent detection and Feature detection. The experimentation used the Agilent Signal generator to generate an appropriate primary signal. This signal was captured by the using the 2.4GHz narrow-band frontend. Since the narrow-band front-end has two antenna ports, one of the ports was always terminated and used for noise measurements. The strength of the primary was varied and the number of samples needed for achieving a target probability of missed detection and probability of false alarm was measured. These experiments allowed us to verify/observe a number of issues with detection:

- For energy detection the number of samples needed to achieve target detection performance scales as $O(SNR^{-2})$. For pilot detection this scaling is $O(SNR^{-1})$
- The energy detector suffers from noise uncertainty. If the PSD (power spectral density) of noise is not known exactly, then the target performance cannot be met irrespective of the number of samples used [6].
- The FFT (Fast Fourier transform) acts as a partially coherent detector for sinusoidal primaries [6].
- Coherent detector performance is limited by frequency mismatch between the transmitter and receiver.
- Feature detector performance is also limited by frequency mismatch between transmitter and receiver. This can be overcome by using a two stage detector [7].

B. Performance of cooperative sensing:

Since single radio performance is limited by noise uncertainty, multiple radios can be used to improve performance. To conduct these experiments we positioned the receiver at a number of places in the BWRC as shown in Figure 4. At each location a number of measurements were made a few wavelengths apart. Cooperation among radios a few wavelengths apart allowed us to get diversity over multipath. Cooperation among radios further apart allowed us to get diversity over shadowing [6].



Fig. 11. Radio placements at the BWRC to measure gains from cooperative sensing

C. Performance of multiband sensing:

For a single radio, we need to set the target detection level to be very low in order to ensure that we can detect the signal even when the cognitive radio is severely shadowed. In multiband sensing we aim to determine the shadowing environment of the radio and then set the detection level dynamically. To do this we utilize the fact that multiple transmitters are positioned on the same tower (especially for TV channels) and that shadowing across frequencies is highly correlated [8]. Thus a detector can sense for channels on nearby frequencies and use these channels to dynamically set the detection level for the channel in question [9]. We are currently in the process of verifying the multiband algorithm using measurements of TV channels in the bay area. For this we are utilizing the wide-band frontend which allows us to

measure all TV channels between 500MHz and 800MHz. The measurements are being made at various locations in Berkeley. At these locations we can measure the TV channels from Mt Sutro and Mt San Bruno.

Wireless Research for the Energy Commission: The Agile Radio

This research is in coordination with the California Energy Commission. The goal is to provide Demand Response Enabling Technology for using wireless communication to interface to all different radio types today and into the future looking for energy efficiency. The network would accommodate existing infrastructure while adapting to future communication technologies. The Agile Demand Response Node would communicate with the home network and access information from sensors and appliances. This node would also communicate with the Utility or service provider thru the internet. This would work within the home, in wired/wireless access networks (in the form of medium-range mesh networks, local area networks, and metropolitan area networks), and wired/wireless backhaul networks.

Radio Telescope Array

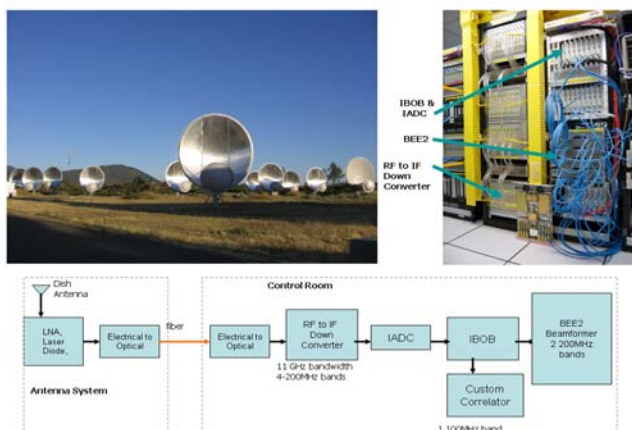


Fig. 12 The Allen Telescope Array receivers and the IBOB, IADC and BEE2 in the control room

The Allen Telescope Array is a set of 42 antenna receivers listening for ET, Quasars, and probing the skies. This work is with the UCB Astronomy Department and the SETI Institute [10]. The modularity, scalability, and ability to upgrade easily with our wide-band testbed provide the configurable fabric desired for this application[11]. One can model a network of devices on this type of topology. In this figure above, a remote antenna system is connected by optical fiber to a custom downconverter and then into the IADC and IBOB. Two 100MHz band signals are sent to a custom correlator from the IBOB. Two 200MHz wide beamformers are created thru the connection of a BEE2 to the IBOB.

V. CONCLUSION

This paper describes a flexible wireless testbed with associated software support, I/O, and network level support. The BEE2 programming environment includes Simulink for our programming model, BORPH as the run-time OS, and

BDB for debugging. We use specialized library modules for our hardware abstraction. For testbed interfaces, high speed gigabit per second digital interfaces are provided by XAUI connectors. The platforms provide both wide-band and narrow-band RF frontends in both the TV and ISM bands including A/D and D/As with 8 bits at 2 Gbps and 12 bits at 64Mbps. The Interface Board, IBOB, provides multiple high speed connection options. For physical network support we provide both multiple radios (may be used in parallel or independently) and optical interconnect (through the 18 XAUIs). These testbeds are the result a combined effort of 6 faculty, approximately 50 students, and 6 staff, and approximately 80 BEEs are deployed around the world.

ACKNOWLEDGMENT

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