Radio Astronomy Signal Processing for Pulsar Science using High Performance Reconfigurable Computers

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Introduction

The CASPER group at UC-Berkeley specializes in the development of open source reconfigurable computing hardware and software technology to build instruments for radio telescopes. The group is involved in the development of beamformers, correlators, spectrometers and pulsar machines for the Allen Telescope Array, the Karoo Array Telescope, and different SETI projects, amongst others.

In this poster, we report on our efforts to use a high performance reconfigurable computing platform to accelerate the signal processing required for performing pulsar searching and timing on data from a radio telescope.

Signal Processing for Pulsar Science Applications

Radio pulsars are the compacted cores of massive stars, formed in 'supernova' explosions. Due their extreme density, gravity, spin frequencies and magnetic field strengths, they are among the most exotic physics laboratories known to man. They emit very strongly at radio frequencies, but as they are hundreds of light years away, their periodic radio pulses are distorted and only seen very weakly over the background noise. The computational problem can essentially be broken into two stages: channelizing the received signal, and performing dedispersion and the searching and timing algorithms on the channelized data. Channelizing the data involves decomposing the received signal into a range of frequency bins. Dedispersion attempts to reverse a smearing effect that the Interstellar Medium (ISM) has on the signal as it travels to Earth.

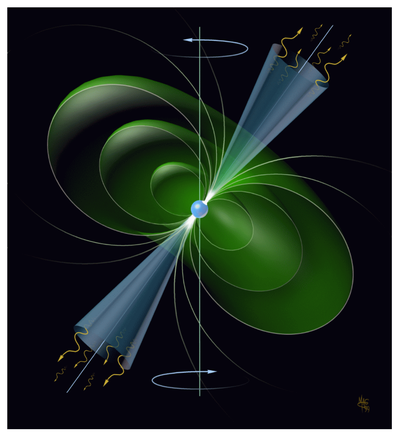

Figure 1. An artistic representation of a pulsar. The green shaded lines represent the magnetic field lines, and the blue shaded lines represent the angular region from which photons are emitted. From ref. [1].

Channelization has, in most recent radio telescope projects, been performed using specialized hardware. However, the BEE2 reconfigurable computer is an ideal platform for implementing and accelerating channelization. It has the I/O and processing resources that are necessary, and the BEE2 is already being used for various other radio telescope signal processing tasks.

Reconfigurable Computing Hardware and Toolchain

We are developing our accelerated packetized channelizer on the Berkeley Emulation Engine (BEE2) [2] and Internet Break-Out Board (IBOB) hardware. The BEE2 is intended as an open source general-purpose high performance reconfigurable computer, and the IBOB is an accessory processing board that is used for digitizing analog data, and doing relatively small processing tasks.

BEE2 is a Virtex 2 Pro-based reconfigurable computer that was designed primarily to perform chip emulation and signal processing, tasks at which it excels. Each BEE2 board has five Virtex 2 Pro FPGAs, with the PowerPC core of one FPGA being used to run the Linux-based operating system, "BORPH". Each FPGA has up to 8GB of memory, and the board has 18 10Gbit/s I/O connections, which can implement 10Gb Ethernet and use standard 10GbE switch hardware.

A well-tested toolflow for the BEE2 and IBOB, based on MATLAB/Simulink and Xilinx EDK and ISE, exists, and has been used in the development of multiple instruments. CASPER has developed an open source DSP library that caters specifically for high-bandwidth, parallel streaming applications.

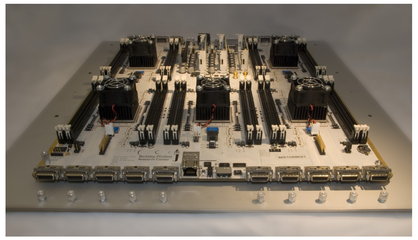

Figure 2. BEE2: The Berkeley Emulation Engine. Rows of CX4 I/O connectors are on the outside. Each FPGA has four DRAM banks, clearly visible in this picture.

Figure 3. IBOB: The Internet Break-Out Board. The IBOB has two CX4 connectors for high-speed I/O. Two 1GSa/sec ADC boards are attached to the IBOB.

Roadmap for Pulsar Machine

1. *IBOB-only channelizer*, including Stokes Parameter calculation. 32 channels over 200MHz bandwidth.
2. *IBOB/BEE2 channelizer*. Up to 4096 channels over 200MHz bandwidth.
3. *Channelizer with increased bitwidth* for better performance in noisy (high RFI) environments.
4. *RFI excision in real time*.
5. *"Folding" on FPGA*. Fold incoming data stream at the pulsar period for timing applications.
6. *Dedispersion on FPGA*. Exact if computationally feasible, approximately otherwise.
7. *Digital interface to ATA beamformer*.

System Architecture and Design

A "pulsar machine" is a combination of systems that that extracts weak pulsar signals from the raw radio-telescope data. Those signals are then used to investigate topics such as the fundamental nature of gravity, or matter at densities much higher than can be made on earth.

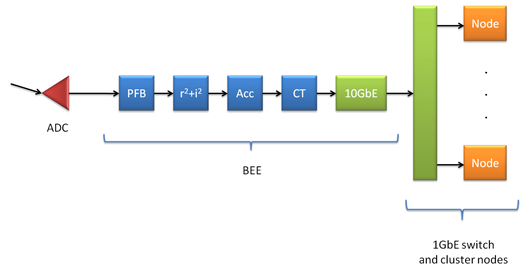

Figure 4. Pulsar machine architecture.

Our reconfigurable computer-based channelizer is required to correctly interoperate with the larger pulsar machine, the "ASP" [3], of which it is a part. Specifically, a cluster of conventional computing nodes need to receive data from the channelizer. Figure 4 shows the architecture we have created to satisfy this interoperability requirement. Specifically, the channelizer will packetize the output data into 10Gb Ethernet packets, and send these to a 10GbE switch that has one 10GbE port, and multiple 1GbE ports. Each node in the cluster is connected to a 1GbE port, and the channelizer load balances the data output by frequency channel.

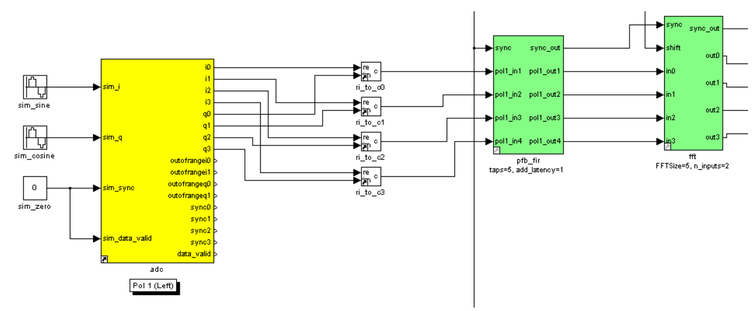

Figure 5. A small portion of the IBOB-only channelizer design. The parallel streaming inputs to the filter bank are shown.

Our design uses an IBOB that has 4 inputs to be digitized (2 polarizations, each with Re and Im components). Each polarization needs to be channelized, then have Stokes parameters calculated. The ADC runs at 4x the speed of the FPGA, so every clock cycle, the FPGA is sent 16 values. These are processed in parallel in a low-latency pipeline using CASPER's DSP blocks.

[1] M. Garlick. URL: http://www.space-art.co.uk.
[2] C. Chang, J. Wawrzynek, and R. Brodersen. *BEE2: a high-end reconfigurable computing system*. IEEE Design and Test of Computers, March 2005, 114-125.
[3] P. Demorest. *Measuring the Gravitational Wave Background using Precision Pulsar Timing*, Ph.D. Thesis, May 2007.

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