

**Automatic Mapping of Real Time Radio Astronomy Signal Processing  
Pipelines onto Heterogeneous Clusters**

by

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University of California, Berkeley

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by  
Terry Filiba

## Abstract

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Doctor of Philosophy in Electrical Engineering and Computer Sciences

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Traditional radio astronomy instrumentation relies on custom built designs, specialized for each science application. Traditional high performance computing (HPC) uses general purpose clusters and tools to parallelize the each algorithm across a cluster. In real time radio astronomy processing, a simple CPU/GPU cluster alone is insufficient to process the data. Instead, digitizing and initial processing of high bandwidth data received from a single antenna is often done in FPGA as it is infeasible to get the data into a single server.

I propose to develop a universal architecture where each problem is partitioned across a heterogeneous cluster, taking advantage of the strengths different technologies have to offer. I propose we take an HPC approach to instrument development with a heterogeneous cluster that has both FPGAs and traditional servers. This cluster can be reprogrammed as necessary in the same way an HPC cluster is used to run many different applications on the same hardware.

The challenge in this heterogeneous of approach is partitioning the problem. Normal HPC uses a homogeneous cluster where the nodes are interchangeable. In a heterogeneous cluster, there is an additional issue of determining how to partition the problem across different types of hardware. I propose to design a tool that automatically determines how to partition instruments for radio astronomy. In order to do this work, I will need to model the platforms and based on a description of the final instrument, generate a processing pipeline. The partitioning needs to be done using a variety of techniques to assess the hardware. A static model of the hardware is useful to determine the amount of processing available in different types of hardware. Dynamic benchmarking would also be needed to deal with varying server architectures and determine how much processing and bandwidth the cpu/gpu servers can handle. Finally, to capture any overlooked subtleties or deal with things the tools cannot handle, the user will be able to input hints as to how the instrument should be generated.

The development of this tool will be driven by 2 instruments. First, the design of the GBT spectrometer, a spectrometer designed to support many different modes using the same cluster. By using the tool to design this spectrometer, additional modes can be easily added and if the cluster is expanded the each mode can be redesigned to do additional processing that takes advantage of the extra hardware. I will also be working on the LEDA correlator. This is a low bandwidth, large N correlator, which is an ideal application for heterogeneous clusters.

We can assess the performance of this automatic partitioning tool in a number of ways. First, this tool should significantly reduce NRE and time to science. By automatically generating the instrument the need for engineers who understand both science goals and programming is removed. However, this benefit should not come with a large increase in cost. The instruments produced by this tool will be compared to optimized implementations with the same parameters on the basis of hardware utilization and power consumption.

To TODO  
TODO

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TODO

# Chapter 1

## Introduction

### 1.1 Motivation

## Chapter 2

# Real Time Radio Astronomy Algorithms

Radio astronomy simply refers to the type of science that can be done by observing astronomical objects at radio wavelengths, rather than a specific scientific goal. There is a huge variety of different experiments, such as searching for gravity waves (TODO: ref nangrav), traces of the first stars (TODO: ref PAPER/LEDA), or aliens (TODO: ref SETI). But, despite this variety, the small number of algorithms detailed in this chapter serve as the first step in processing the data for many such projects.

Radio telescopes produce very high amounts of data (TODO: add estimates, how much data?). The reason for this high influx of data is twofold. First, to enable new science, new radio antenna observe increasingly higher bandwidths of data. Second, to sate the need for larger collecting area, rather than designing a large single dish, many new telescopes are being designed as antenna arrays, where the data from multiple antennas is combined to act as a single large dish. While it may be cheaper and easier to get a larger collecting area using small dishes rather than a single large dish, this adds additional complexity processing the data coming off the telescope. Rather than processing a single stream of data, now the instrument must process and combine multiple streams to make the array seem like a single large dish. As the size of the arrays and bandwidths for single dishes simultaneously increase, the data produced cannot be feasibly recorded in real-time. To cope with the progress in science and antenna technology, there is a constant need for new systems to process, rather than record, this data in real time. Each of these instruments begin processing the data immediately after it is digitized, and needs to reduce the data without losing scientific information. Once the data is partially processed, and reduced to a manageable bandwidth, it can be stored and processed further offline.

There is a small number of real time algorithms commonly used to reduce the data. In this work, we specifically focus on spectroscopy, pulsar processing, beamforming and correlation. Spectroscopy and pulsar processing are both spectral methods of analyzing data from a single beam. They both can be used on antenna arrays but would either need to treat the array as separate dishes rather than one large dish, or the data from the dishes would need

to be combined into a single beam, which can be done using the third algorithm on the list, beamforming. The last two techniques, beamforming and correlation, are both ways of combining data from multiple antennas. Beamforming combines the data into a single beam by delaying and summing the data from each antenna. Correlation doesn't aim to form a single beam, but instead is the first step towards getting an image of the sky.

## 2.1 Spectroscopy

A spectrometer is simply an instrument that produces an integrated, or averaged, frequency domain spectrum from a time domain signal. A real time spectrometer works by constantly computing a spectrum over short windows of data (channelization), then each channel is summed for a predetermined amount of time to compute the average power in that channel (accumulation). Figure x shows a block diagram for a simple spectrometer design. After digitization, there is the channelization step, where the signal is processed by a digital filter bank, and then the channels are accumulated.

### High resolution spectroscopy

Increasing resolution often requires an increase in complexity in the spectrometer design. Once the number of required channels is sufficiently high, it becomes infeasible to compute the spectrum using a single filter bank. To cope with this, the channelization is done in two steps as shown in figure (TODO: add hi res spectrometer block diagram). In the first step, the signal is divided into coarse channels using a filter bank. At this point the channels are much wider than intended and can't be accumulated yet. After coarse channelization, the spectrometer treats the data from a single channel as time domain data and passes it through a filter bank again. This step breaks up the wide channel into a number of smaller channels. At this point the data can be accumulated, since it has the desired resolution.

### Applications

This high resolution spectroscopy technique is used in the SERENDIP V.v (Search for Extraterrestrial Radio Emissions from Nearby Developed Intelligent Populations) project. This project is part of the SETI (Search for Extraterrestrial Intelligence) effort to detect extraterrestrial intelligence. The SERENDIP V.v project is a commensal survey at the Arecibo observatory, meaning anytime the ALFA receiver is used for any observation, the SERENDIP spectrometer will also process and record data.

The project is focused on detecting strong narrow band radio signals, requiring a high resolution spectrometer installed at the observing telescope to analyze the data. The spectrometer should resolve channels of less than 2 Hz, so that natural astronomical signals that typically have a wider bandwidth can easily be distinguished from narrower, possibly

extraterrestrial, signals. The SERENDIP V.v spectrometer meets this by providing 128 million channels across 200MHz of bandwidth, for an resolution of 1.5 Hz per channel. Since it would be infeasible to channelize a 200MHz into 128 million channels using a single filter bank, the SERENDIP V.v spectrometer uses the high resolution architecture described in figure x.

## 2.2 Pulsar Processing

A pulsar processor is an instrument designed specifically to observe transient events, such as pulsars. A pulsar is a rotating neutron star that emits an electromagnetic beam. When the beam sweeps past Earth, due to the rotation of the star, it is observed as a wideband pulse. As the pulse travels through the interstellar medium (the matter filling interstellar space), the pulsar gets dispersed, meaning the low frequencies arrive before high frequencies, despite the fact that they were emitted at the same time.

A spectrometer, as described in Section 2.1, that accumulates the spectrum would smear the pulse, so there will need to be a few adjustments to the spectroscopy algorithm to make it suitable for processing transient events. In the case of pulsars, the algorithm starts with a high-resolution spectrometer without an accumulator. Instead, the algorithm becomes specialized to detect this type of quickly occurring event.

The high resolution data is then sent to a process called dedispersion, which undoes the dispersion caused by the ISM, realigning the pulse. There are 2 techniques to do this. First, the pulse can be dedispersed by shifting the frequency channels by different amounts to compensate for the different delays as shown in figure x, in a process called *incoherent dedispersion*. This process can't be used to reconstruct the original pulse, but due to its relatively low compute cost, is a useful algorithm to search for new pulsars. The second technique, *coherent dedispersion*, models the effect of the ISM as a convolving filter. To remove this effect, the signal is deconvolved with the model. This is more compute intensive than incoherent dedispersion, but can recover the original pulse.

After dedispersion, there is still a lot of data and the pulse has very low SNR. The next step in processing is *folding*, or adds together many pulses, reducing the amount of data and improving the SNR. At this point, the data has been significantly reduced and can be recorded.

## Applications

Some pulsars serve as a very accurate astronomical time keeper. There are millisecond pulsars with extremely stable periods, allowing any perturbations in the observed pulse period to be attributed to some external effect. This makes pulsars extremely useful for conducting relativity experiments. One such example is the North American Nanohertz Observatory for Gravitational Waves, or NANOGrav, Project, which uses pulsars in an attempt to make the first detection of gravitational waves. The project will try to detect gravitational waves by

observing an array of pulsars, measuring the effect of the waves passing between Earth and the pulsars as changes in observed pulse periods.

## 2.3 Beamforming

Beamforming is one technique for combining data from an array of antennas. The beamformer combines the data from multiple antennas into a single beam pointed at a single point in the sky. This is achieved by delaying the signal from each antenna by a different amount and then summing the delayed signals. As illustrated in figure x, the signal from the intended source will not arrive at all the antennas at the same time. The delay compensates for the disparity between the arrival times, and once the signals are summed it creates constructive interference in the direction of the source, and destructive interference in other directions. These delays can be changed to point the beam at a different source or to track a single source moving across the sky.

### BF Beamforming

Since the signal is discrete, and the amount of delay might not be an integer multiple of the sample period  $s$ , the delay  $d$  is applied to the signal,  $f[n]$ , in 2 steps. The delay in clock cycles is represented as  $d/s$  and broken up into its integer and fractional parts. First, the integer part is applied as a coarse delay,  $n_f = \lfloor d/s \rfloor$ . This can simply be implemented by buffering the signal. Applying the fractional delay  $p \bmod s$  is more complex. Since there is no observed data at that time, the signal fractional samples are calculated by convolving the signal with an interpolation filter  $b$ . Applying these 2 steps, results in a new delayed signal  $f[n] = f[n - n_f] * b_{fi}$

In practice, it is common to calculate the spectrum of the beamformed signal. A typical 2 element beamformer, with discrete input signals  $f[n]$  and  $g[n]$  is trying to calculate the spectrum of beam  $i$ ,  $H_i$ , using coarse delays  $n_{fi}$  and delay filters  $b_{fi}$  and  $b_{gi}$ , as follows:

$$H_i(x) = FT(f[n - n_{fi}] * b_{fi} + g[n - n_{gi}] * b_{gi})$$

We describe this as BF beamforming because the delay operation (B), happens before the FT operation (F).

### FB Beamforming

In the case where many beams are required, each beam needs a different FIR filter for every antenna, and a separate FT. This is called FB beamforming because the FT operations (F) occur before the delay (B). Using linearity of the fourier transform and the convolution theorem, the computation can be rearranged as follows:

$$H_i(x) = F[x] \cdot B'_{fi} + G[x] \cdot B'_{gi}$$

Where  $F[x]$  and  $G[x]$  are the fourier transforms of the signals  $f$  and  $g$ . The signal delay becomes a phase shift in frequency domain that is represented by  $B'_{fi}$  and  $B'_{gi}$ . In this case, there is a FT for each antenna, rather than one FT per beam. When forming multiple beams, there is no need to recalculate the Fourier transform of the signals. So, as the number of beams increases, it can be advantageous to use this algorithm rather than the BF algorithm described in the previous section.

## Applications

### 2.4 Correlation

Aperture synthesis is another technique to combine that data from many antennas. The goal is to form an image of the sky, using 2 steps, correlation followed by imaging. In the correlation step, the cross-correlation of each pair of antennas is calculated. Once the cross-correlation is calculated, it is possible to accumulate the data, greatly reducing the amount of data that needs to be processed in the imaging step.

The uv plane represents the Fourier transform of the 2-dimensional sky image. The cross-correlation of an antenna pair represents a point in the uv plane, called a *visibility*. Since the visibilities are not evenly or continuously sampled, the imager must interpolate points on the uv plane in an evenly spaced grid so the FFT algorithm, which relies on even spacings, can be applied to the data. The imager must also account for the fact that the response of the telescope distorts the image, undoing the effect using iterative algorithms like CLEAN or Maximum Entropy. Once this is done, a two dimensional inverse Fourier transform can be applied to recover the sky image.

Typically, large telescope arrays do correlation in real time and finish the imaging offline, but there are a few notable exceptions. One of these is the VLBA, or Very Long Baseline Array. When designing antenna arrays, one important parameter is the distance between the antennas, or *baselines*. Arrays with longer baselines provide images with better angular resolution. The VLBA is an extremely high resolution array, achieving this resolution by using telescopes on opposite ends of the Earth. The distance between the antennas, while useful for science, creates a logistical issue for any real time processing that depends on data from different antennas. Instead of correlating in real time, the VLBA records the digitized data directly from the telescopes at each site, without any reduction. Later, the recorded data is flown to a central location, where it gets correlated.

The cross-correlation of two signals,  $f[n]$  and  $g[n]$  is defined as:

$$h[n] = f[n] \star g[n] = \sum_{i=0}^m f^*[i]g[n+i]$$

Like in beamforming, it is often desirable to calculate a spectrum, so the correlation step typically also calculates the spectrum of the cross-correlations. So, the final result of the



correlator produces the spectrum of the visibilities,  $H[x]$ .

$$H[x] = FT(f[n] \star g[n])$$

## **XF Correlation**

An XF, or lag, correlator calculates the spectrum by calculating the cross-correlation first (X), followed by a Fourier transform (F). For an antennal with  $n$  antennas, this would require  $O(n^2)$  cross-correlations, followed by  $O(n^2)$  Fourier transform operations.

## **FX Correlation**

As  $n$  gets larger, the The cross-correlation theorem further extends the parallel between correlation and convolution, relating the Fourier transform of the cross-correlation of two signals to the Fourier transforms of

# Chapter 3

## Related Work

### 3.1 Radio Astronomy

Digital Signal Processing for Radio Astronomy

DiFX

LOFAR

xGPU

CASPER

### 3.2 Tuning

#### Metropolis

Abhijit Davare. Automated mapping for heterogeneous multiprocessor embedded systems. PhD thesis, 2007.

Provides an abstract block based description of the system (Metropolis) Easy to stitch algorithms together Simulation is abstracted from the eventual hardware implementation Mapping is focused on scheduling onto heterogeneous platforms Strong focus on embedded systems

Some people have thought about how to use technology Metropolis works on simulation extensively (supporting Embedded systems we have 1 cpu and 1 dsp lets make it go fast This doesnt solve our problem Just does scheduling

Doesnt help design the cluster A heterogeneous node has a fixed mix of resources Cant reduce costs by throwing away certain types of hardware Optimization is based on a fixed architecture and flexible performance Doesnt match our always running model Performance is good enough, not an optimization target

Lisa Marie Guerra (?)

### **ILP for scheduling**

An integer linear programming model for mapping applications on hybrid systems

# Chapter 4

## High Level Toolflow

### 4.1 Instrument Generation

Automatic Generation of Heterogeneous Spectrometers for Radio Astronomy

We have developed a software package to automatically generate spectrometers with minimal user input. Spectrometer design is often done by building the instrument from scratch. We have automated this design, creating a parameterized spectrometer that only requires a recompile to implement a change in specification. This spectrometer combines FPGAs and GPUs, doing coarse channelization on the FPGA and sending each subband to the GPUs for further processing. The server software is designed for flexibility, allowing astronomers to easily modify the processing algorithm run on the GPU and customize the instrument to fit their science goals.

### 4.2 Introduction

The need for high bandwidth spectroscopy manifests in many different radio astronomy applications. Keeping up with increasing computation demands has often resulted in the specialized design of spectrometers. At the Collaboration for Astronomy Signal Processing and Electronics Research (CASPER), we have developed a software package to automatically generate spectrometers for a variety of applications.

The CASPER FPGA libraries were developed to mitigate the need to redevelop common signal processing blocks for every new instrument [2]. Parameterized blocks such as FFTs and digital down-converters can easily be used to design many different instruments. Coupled with open source FPGA boards, such as the ROACH (Reconfigurable Open Architecture Computing Hardware), the CASPER libraries provide a useful toolbox for radio astronomy instrumentation development. This work extends the CASPER philosophy, demonstrating that entire instruments can be generated with minimal user input. Rather than designing a completely different instrument for every different specification, this software package is parameterized so a change in specification only requires a recompile.

The software package includes an FPGA design and server software to do spectroscopy, as well as server benchmarks used to determine an optimal instrument configuration. Both the FPGA and server software are parameterized, allowing for rapid deployment of a working spectrometer that is configured to take full advantage of available computing resources. We implement the instrument on a heterogeneous cluster consisting of both FPGAs and GPUs to take advantage of the benefits provided by both platforms. FPGAs provide high bandwidth processing but can be cumbersome to program. GPUs can't handle the same bandwidths as FPGAs but they are easier to program. The CUDA language, for example, is a C-like language that can be used to develop software for many GPUs. The high level parameters in this package allow us to use FPGAs while abstracting away implementation details specific to the FPGA. To give the user control over their data processing algorithm, an application specific GPU program can be written and easily interfaced with the existing receive software in the package.

### 4.3 Radio Astronomy Applications

This instrument has a wide variety of potential applications due to the flexibility of the server software. In this section, we describe a few specific applications than can make use of this package.

In the search for extraterrestrial intelligence (SETI), the ability to keep up with changes in technology allows searching instrumentation to stay on the leading edge of sensitivity. SETI aims to process the maximum bandwidth possible with very high resolution spectroscopy. This instrument allows SETI projects to easily keep up with improvements on the telescope and increasing computational power. An increase in detector bandwidth, improving the breadth of the search, can be processed simply recompiling the FPGA design and distributing the extra subbands to new servers. As computation improves, the instrument can be reconfigured to send more bandwidth to each computer, reducing the required cluster size, or improve the resolution of the instrument by doing a larger FFT on the server.

This design also has applications in pulsar science. The fast channelization on the FPGA with no data reduction makes it an ideal pulsar spectrometer, since no information is lost before sending the data to the servers. GPUs provide a good platform for pulsar processing algorithms such as coherent dedispersion [3], which can easily be used as the processing function for the server software distributed in our package. Similar to SETI instruments, pulsar instruments designed using this package can also keep up with improvements in technology with a simple recompile.

### 4.4 Instrument Architecture

The instruments generated with this package use a heterogeneous design, allowing us to benefit from the strengths of FPGAs and GPUs. The FPGA board is able to sample and

process very high bandwidths that a single CPU or GPU would not be able to manage; once the FPGA has split up the band the GPU provides a platform that is easier than an FPGA to program but still provides high compute power. A design called the Packetized Astronomy Signal Processor, or PASP, is run on the FPGA. PASP splits up the large band into smaller bands that can be processed using off the shelf servers. The subbands are put into packets on the FPGA and sent over a 10 gigabit Ethernet switch to a cluster of servers. The servers receive the data from the switch and process it using spectroscopy software provided in the software package or special purpose application software written by the user and linked into the provided packet processing infrastructure.

Figure 4.1 shows a high level view of a spectrometer that could be designed with this package. In this example, a ROACH board divides the input band into 64 subbands and sends them out to a 16 server cluster. An ADC is used to digitize data from the telescope and connects to the ROACH board via Z-DOK connectors. The digitized data is split into 64 subbands and sent through a 10 gigabit Ethernet switch. Each server in the cluster receives and processes 4 subbands.

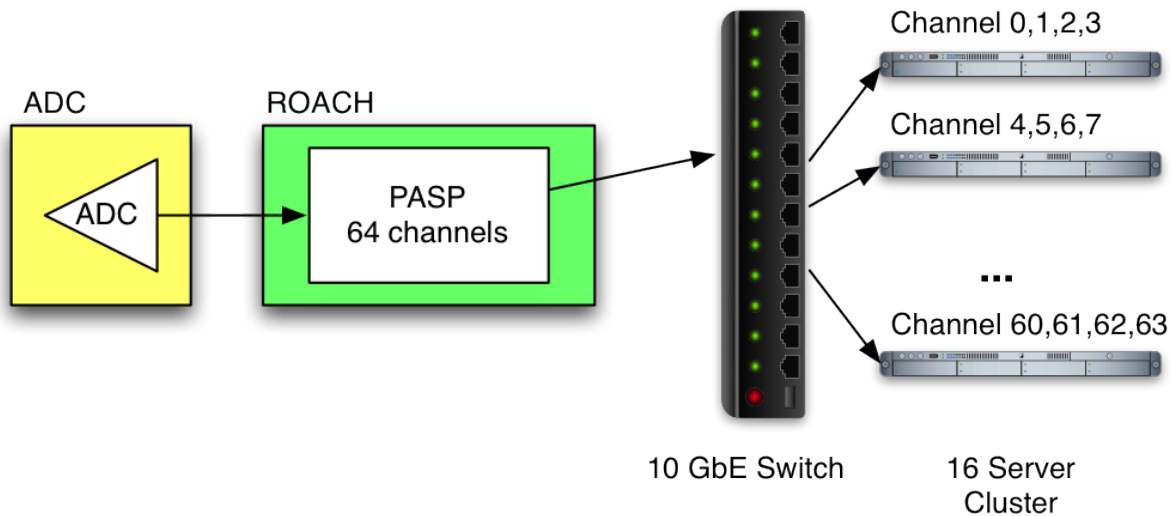


Figure 4.1: Example high level instrument architecture

## FPGA Design

Figure 4.2 gives an overview of the dataflow through the FPGA. The FPGA interfaces to a single ADC board that simultaneously digitizes 2 signals. Each signal can be sampled at a maximum rate of 1MSPS. The samples are sent into a polyphase filter bank (PFB), consisting of an FIR filter and an FFT, which breaks up the entire bandwidth sampled by the ADC into smaller subbands. After dividing up the subbands, each band is rescaled. This step

allows us to compensate for the shape of the analog filter feeding data into the ADC. After rescaling, the FPGA forms packets where each packet contains data from a single subband. The packets are sent out over CX4 ports to a 10 gigabit Ethernet switch.

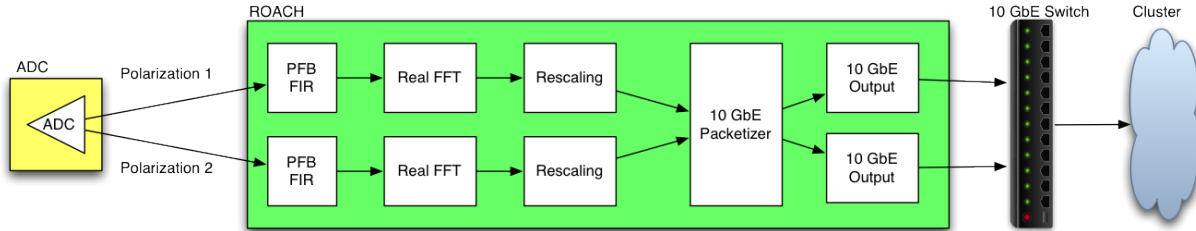


Figure 4.2: PASP Dataflow

PASP uses a PFB to split up the subbands. Figure 4.3 shows a comparison between the FFT and PFB response. The FFT response (on the left) has a lot of spectral leakage while the PFB (on the right) has a much sharper filter shape and a better frequency response. The superior frequency response led us to use a PFB rather than an FFT to extract subbands, despite the additional FPGA resources required by the FIR filter before the FFT.

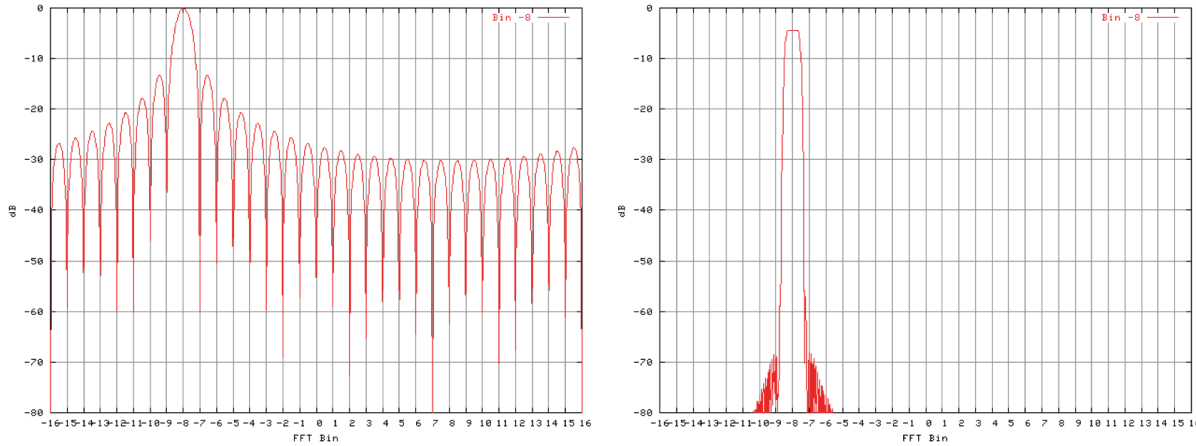


Figure 4.3: A comparison of FFT and PFB response

PASP is designed for flexibility. Building on the CASPER goal to automate the design of commonly used signal processing elements such as FFTs and digital downconverters, PASP automatically designs an entire FPGA instrument using only a few parameters. The user can input the desired number of subbands, CPU/GPU cluster size, and packet size and a new design is automatically generated in Simulink.

## Server Benchmarking

PASP has proven useful in many applications by itself, but the goal of automatically generating a spectrometer for any cluster requires more than just a reconfigurable FPGA design. It is difficult to determine what size the subbands or the cluster should be without knowing how much data the target servers can receive and process. Our benchmarking tools are designed to quickly determine how much bandwidth a server is capable of handling so the PASP parameters can be set appropriately.

We have developed a general purpose benchmark to test the networking capability of a server. This test uses an FPGA design to generate 10 gigabit Ethernet packets and transmits them to the server under test. The FPGA design has a runtime programable packet size and packet rate. The packet size is set to the largest size allowed by the server and the packet rate is initially set low and ramped up while the receive software running on the server checks for dropped packets. By searching for the highest bandwidth with no dropped packets, we find the maximum allowable data rate where the server should reliably receive all the data.

While specific processing algorithms may vary between scientific applications, an FFT benchmark provides insight into possible processing requirements for a variety of radio astronomy applications. We developed an FFT benchmark using CUFFT, the CUDA FFT library, which supports FFT of arbitrary sizes and allows them to be run in batches on the GPU. Our benchmark tests a variety of FFT sizes and batch sizes. In general, we have found that running larger FFTs and batching many FFTs together is necessary to fully take advantage of the computing resources on GPU. Running this benchmark allows us to determine the maximum bandwidth that can be processed with the available resources.

Using these benchmarks, we can see how much compute power is provided by the server and determine the parameters that need to be entered into PASP. The benchmarks also allow us to identify potential bottlenecks by comparing the maximum bandwidth the server can receive to the maximum bandwidth the server can process. If the system is upgraded to reduce bottlenecks, it is easy to retest the server and recompile a PASP design that takes advantage of the new resources.

## Server Software

Our package includes spectroscopy software that interfaces with the PASP design. This software receives data over an Ethernet port and transfers it from the CPU to the GPU. The GPU runs an FFT and then sends the data back to the CPU to be recorded. The GPU software, like the GPU benchmark, uses the CUFFT library to run FFT. The FFT size depends on the desired resolution for a specific application and an efficient batch size can be determined by running the FFT benchmark to find the best batch size for the given FFT size.

The server software was designed so other applications could easily be implemented on the GPU without altering or rewriting the receive code that interprets the packet headers and transfers data to the GPU. Once the data is on the GPU, the software calls a process



function and passes it a pointer to the GPU data. An initialization function is called before the data processing begins to do any setup needed by the processing function, and a corresponding destroy function cleans up once the processing is complete. In the spectroscopy software included in the package, the initialization function creates the FFT plan, the processing function calls CUFFT, and the destroy function deletes the FFT plan. Modifying the application run on the GPU simply requires a redefinition of these three functions. Using this interface, we successfully replaced the CUFFT processing with software developed for SETI searches designed by Kondo et al. [1].

## 4.5 Conclusion and Future Work

In this paper, we describe a radio astronomy instrument that is easily reconfigured to suit a variety of applications. Figure 4.4 shows how this style of instrument design can be extended to a heterogeneous cluster running multiple processing algorithms at the same time. All of these algorithms require the data to be broken up into subbands before it can be processed by the server which can be done on the same FPGA. Using multicast packets, multiple servers can subscribe to the same subbands generated on by PASP and process them in different ways.

This style of instrument design greatly accelerates time to science for many projects. Separating the implementation of the instrument from the hardware specification has created a design that works well for a variety of computational resources and applications. As resources improve, the instrument can improve along with them, providing the opportunity to do new science that wasn't possible before.

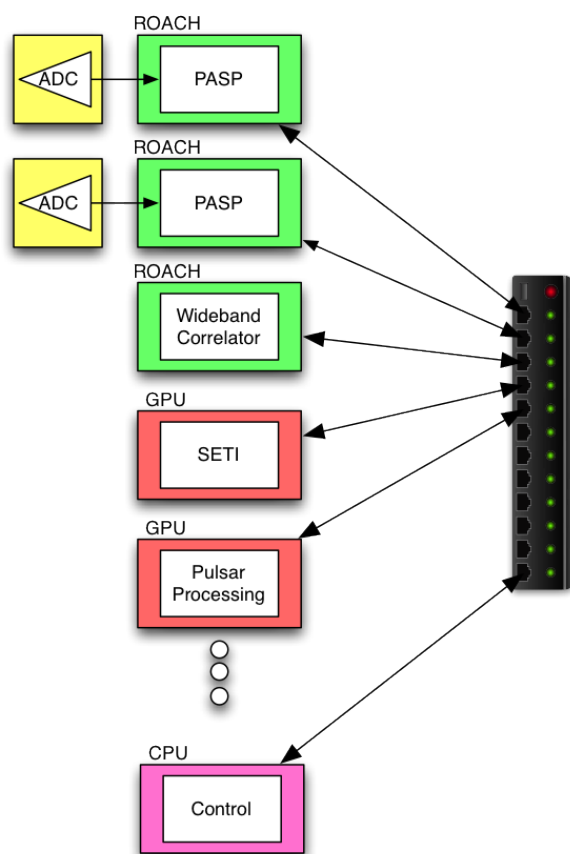


Figure 4.4: A potential architecture for multiple scientific instruments simultaneously processing data from the same telescope

## Chapter 5

# Algorithm Partitioning

5.1 Constraints

5.2 Cost

5.3 Optimization

5.4 Performance

## Chapter 6

### Analysis/Results

## Chapter 7

## Conclusions

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