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Design and implementation of digital backend for a PAF prototype

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Abstract

Phased array feed (PAF) receiver system has become the cutting-edge technology for radio astronomy. The Joint Laboratory for Radio Astronomy Technology (JLRAT) team has been focusing on PAF development for Square Kilometre Array (SKA) and Five hundred meter Aperture Spherical Telescope (FAST). This paper is to present our work to design and implication of an experimental digital backend for a PAF prototype. The backend hardware adopts the ROACH2 boards from CASPER and High Performance Computing (HPC) servers with GPUs. The design and implementation of the framework are descried. The beamforming software development is also presented.

1 Introduction

Phased Array Feed (PAF) receiver system is to place antenna elements closely at the focal plane of a radio telescope, using phased array technology to sample the electromagnetic field across the focal plane of the telescope. The outputs of the receiver are then coherently combined by a beamformer with appropriate weights to synthesise several discrete beams.

PAF is one of three Advanced Instrumentation Programmes (AIP) within the Square Kilometre Array (SKA), aimed at developing the next generation of technology for radio astronomy[1]. The PAF consortium is seeking to develop cost effective wide-band, multi-pixel, wide field-of-view (FOV) receivers for the SKA. These receivers replace conventional single pixel feed receivers located at the focus of the offset parabolic dish antennas to provide a multi-pixel "camera" on the sky.

The world largest single dish radio telescope, Five hundred meter Aperture Spherical Telescope (FAST, see Figure 1), is built up in late 2016, and started fully operating in early 2020. Current a 19-beam L-band receiver is installed, making FAST an efficient survey machine [1]. A L-band PAF system is one of the key option of FAST future upgrade, since it can bring continuous sky coverage, possibly higher sensitivity, and anti-RFI capabilities.

[1] https://www.skatelescope.org/phased-array-feed/

Figure 1. Image of FAST

As one of the SKA PAF consortium members and one of the teams in the Key Laboratory of FAST, the Joint Laboratory for Radio Astronomy Technology (JLRAT) team has been focus on the PAF theoretical studies and technical development for the SKA and FAST. Based on the optics of FAST, a 19-elements L-band feed array (see Figure 2) has been designed and manufactured in order to develop a experimental PAF prototype.

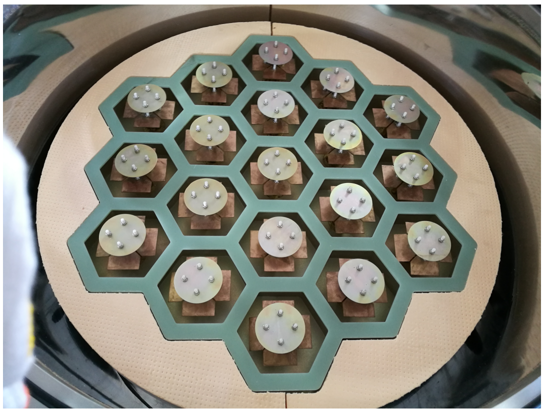

Figure 2. The System design

To assembled a fully functional PAF system, a digital backend is needed to combine with the feed array. This paper presents the design and development of such a digital backend based on the ROACH2 boards and GPU servers. Section 2 gives the overall system design including the framework and specifications. Section 3 shows the details of implementation. At last the work is concluded in Section 4.

2 System design

2.1 Framework

The 19 elements feed array will be connected to the digital backend through a warm frontend signal processing circuitry, including radio frequency (RF) and intermediate frequency (IF) electronic devices. The warm signal processing circuitry will be developed with a adjustable local oscillator (LO) frequency. The RF bandwidth is 400 MHz from 1.05 to 1.45 GHz and the IF output bandwidth is 100 MHz. By shifting the LO frequency from 1.05 to 1.35 GHz, the IF bandpass covers the entire RF range. The backend hardware adopts the ROACH2 boards provided by CASPER[2]and HPC servers with GPUs. Figure 3 shows the overall framework design of the system.

1) ADCs:

Two RJ45-16ADCs are mounted on each ROACH2 board. Each samples 16 signal paths with 204.8 MHz clock, given a depth of 8 bits. Two ROACH2 boards are used to digitize 38 signals. Each for 19 paths from one polarization.

2) The F-engine:

The digitized signals are then poly-phase filtered, producing 1024 frequency channels per polarization with 0.1 MHz bandwidth of the beamformer stage. On each ROACH2, the signals will be send to a "corner turn" module to covert 19 digital streams each with 1024 channels to 4 streams each with 256 "channels" needed for the input to the X-engine beamformer and the correlator.

3) X-engine beamformer and the correlator:

The baseline design utilizes 2 HPC servers each with 2 GPUs to produce the 7 beams per polarization for each frequency channel. During a calibration operation prior to the observation, the correlator will compute the complex weights needed by the beamformer.

4) Data storage:

We will record the raw data for calibration experiment. Also for "time domain" observations, data storage will be a significant issue. 1 server will be configured as data storage server with 64 TB hard disk drive.

2.2 Specifications

- Number of elements: 19
- Polarization: 2
- Number of dual polarization formed beams: 7
- RF coverage: 1050 to 1450 MHz;
- IF Bandwidth: 100 MHz
- ADC sampling rate: 204.8 MHz;
- Beamformer processing BW: 102.4 MHz
- Number of coarse channels per polarization: 1024
- Channel frequency resolution: 0.1 MHz
- Sampling rate for beam formed Channels: 10 μsec

[2]https://casper.ssl.berkeley.edu/

3 Implementation

3.1 Firmware on ROACH2

We adopted the RJ45-ADC 16×250-8 card and ROACH2 boards provided by CASPER for digitization and channelization. Each ADC has four HMCAD1151 chips, enabling 8-bit sampling for 16 signals at speed up to 250 Msps. Two ROACH2 with four ADCs could handle 64 signal paths in total.

Figure 4 shows the firmware layout developed using the CASPER environment. The 32 data streams are collected from two ADCs. They are then send to 16 "PFB" modules, connected with a single core 32 path FFT module for channelization. Then a channel equalization is applied before the signals are processed by a "corner turn" module, which is to covert 19 digital streams each with 1024 channels to 4 streams each with 256 "channels".

3.2 Beamformer on Server

After being transposed, the data is send to HPC servers through 40 Gbps Ethernet card. Two servers are used, each for one polarization. Meanwhile, the raw data is recorded to the data storage server.

1) Correlation:

At current stage, we only apply "offline" calibration mode. That is to store the raw data when observing the calibrator. Then to load the data to the correlator to calculate the weights for each formed beam. As for calibration, with the temporary recorded channelized data, we apply Max-SNR algorithm implement with CUDA package. From the ON/OFF observation towards a point radio source, we obtain the weights from Equation 1 and 2 (see [2, 3] for details):

$$\mathrm{SNR} = \frac{\mathbf{w}^{\mathrm{H}}\mathbf{R}_{\mathrm{s}}\mathbf{w}^{\mathrm{H}}}{\mathbf{w}^{\mathrm{H}}\mathbf{R}_{\mathrm{n}}\mathbf{w}} \tag{1}$$

$$\mathbf{R}_{\mathrm{s}}\mathbf{w} = \lambda\mathbf{w} \tag{2}$$

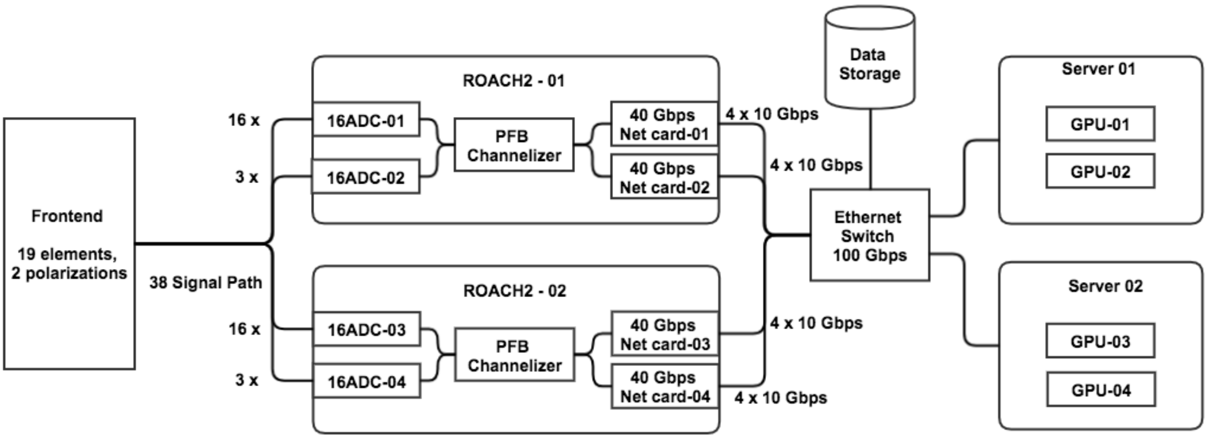

Figure 3. The Framework design

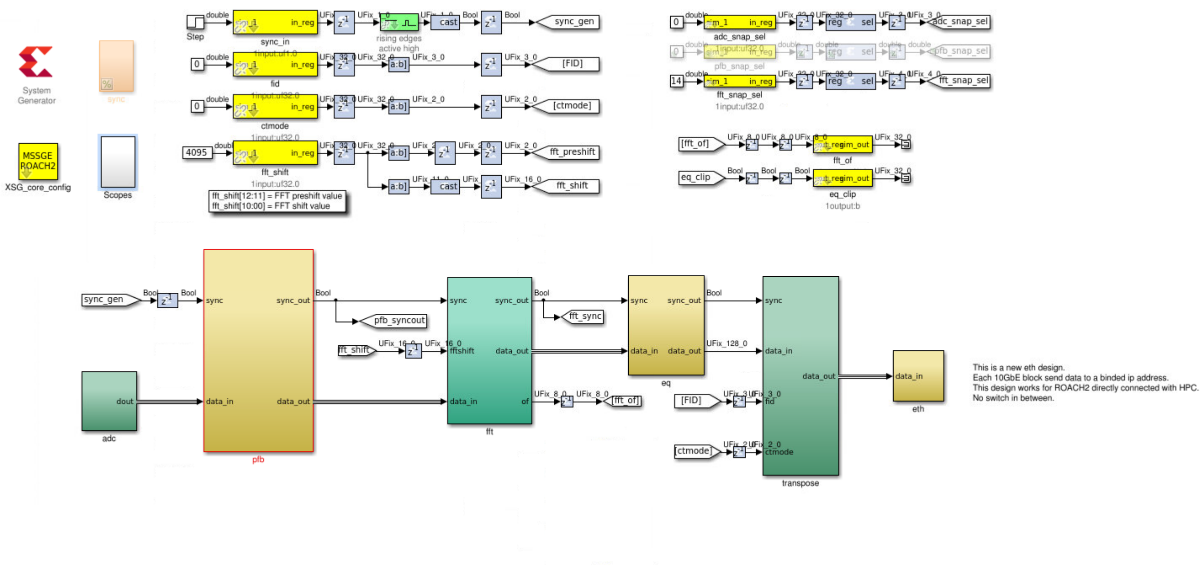

Figure 4. The Firmware layout design on ROACH2

The outputs are the weights of each elements for each formed beam at a certain telescope pointing. A database of weights is established and kept updated for the beamformer.

2) Beamformer:

The software of beamformer has been developed using Python and QT5 on Linux system. The beamformer can run in "online" or "offline" mode. The difference is whether the server to receive raw data from the Ethernet card or from the HDD. Ether way, the raw data is then load to the memory of GPU with the weights, where the calculation is performed. The output will be base-band data of the formed beam, which will be further processed according to the astronomical purpose.

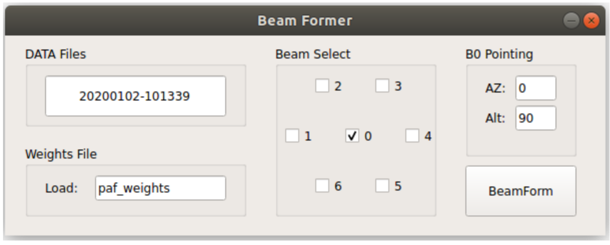

Figure 5. The software for the beamformer module

4 Conclusion

The framework design and implement are finished. The beamforming software and calibration algorithms are also developed. We will setup lab experiment for the backend system and run a long term test. After the functional debugging in the lab, it will be installed to small radio telescope for astronomical calibration test and observations.

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