Signal Transport and Digital Signal Processing for the ALPACA L band Array Feed

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***Abstract*—The Advanced L band Phased Array Camera for Arecibo (ALPACA) will rely on RF-over-fiber signal transport and hybrid FPGA/GPU signal processing hardware for calibration, beamforming, and imaging. We report on signal transport system development, phase and gain stability requirements, and array signal processing algorithm development.**

***Index Terms*—antennas, electromagnetics, propagation, measurements.**

I. Introduction

Compared to traditional single-pixel astronomical receivers, the ALPACA L band array feed will enable faster wide-field survey observations, pulsar searches, and detection of fast transient radio sources. The array consists of 69 dual polarized wideband dipoles optimized for noise matching and sensitivity [1]. With the front end antennas and amplifier designs completed and in the process of fabrication, attention is turning to development of RF over fiber signal handling and transport and digital receiver back end systems.

Design requirements for signal transport include minimal contribution to the system noise budget, sufficient dynamic range to accomodate both signals of interest well below the noise floor and powerful radar signals and other interference in the Arecibo signal environment, and gain and phase stability sufficient to permit calibrated array beamformer coefficients to be reused in the digital signal processing back end for observations over many days or weeks. To meet the performance requirements of the wideband ALPACA receiver, a new implementation of the core channelization algorithm has been developed for the digital beamformer and correlator system.

II. ALPACA Signal Transport

The analog signal from each antenna must be transmitted from the receiver front end at the optical focus of the telescope to the back end digital signal processing system, while maintaining an overall system noise temperature at or below the design goal of 25 K. To accomplish this, we have designed an RF-over-fiber (RFoF) link based on the system designed at McGill University for the Canadian Hydrogen Intensity Mapping Experiment (CHIME) [2], and adapted to meet the specific requirements for ALPACA. We have implemented designs and verified functionality for single-channel signal transport versions, and the implementation and testing of the multi-channel design are underway.

The multi-channel RF transmitter (TX) board supports four channels and has been modularized to increase production yield. This is done using separate PCB sub-assemblies, or modules, for each channel, which connect to the main carrier board using castellated vias. The carrier board provides power to the TX modules, along with a calibration injection port and an SMP connection to the flexible stripline cable exiting the cryostat. The TX modules use directly modulated 1310 nm laser diodes coupled to single-mode fiber. To reduce the noise contribution from the laser diode while maintaining as much dynamic range as possible, we have included preamplification followed by adjustable attenuation. The bandpass filter we are using was specified to have sharp roll-off below 1300 MHz to attenuate strong radar interference just outside of the band, and provides more than 10 dB of attenuation at 1261 MHz. A four-channel TX carrier board is shown in Figure 1.

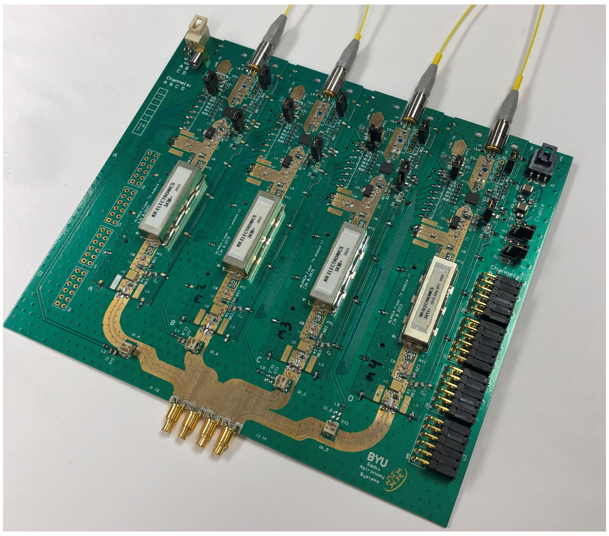

Fig. 1. A four-channel RF-over-fiber transmitter board for ALPACA signal transport.

At the other end of the optical fiber signal link is the signal transport receiver (RX) board, which will be housed in the Arecibo Lab complex. The multi-channel RX board supports up to 16 channels. It too has been modularized to increase production yield, although the modules attach to the main carrier board using connectors, and are removable. Each RX module uses a photodiode to collect the incoming signal from the optical fiber, which is then amplified and filtered. On the carrier board, a calibration signal is coupled in prior to baluns. The ADCs on the ZCU216 board are fed by differential pairs through a high density connector. Figure 2 shows a rendering

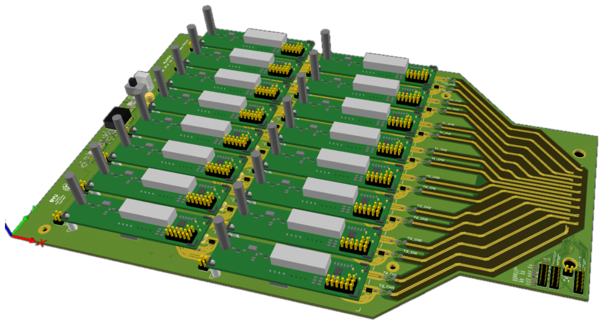

Fig. 2. A rendering of the 16-channel RF-over-fiber receiver board for ALPACA signal transport.

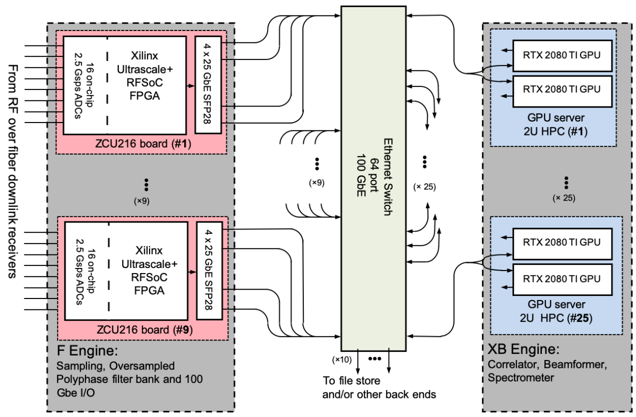

Fig. 3. Signal processing is distributed over two stages. Antenna voltage signals are digitized and channelized in the first stage by 9 ZCU216 RFSoC boards. These data products are transported over 100 GbE for beamforming by a cluster of 25 HPCs each with two NVIDIA GPUs.

of the RX carrier board with all 16 modules attached.

The BYU signal transport system will provide 22-28 dB gain across the band with an equivalent noise temperature below 950 K, to keep the overall Tsys contribution below 1 K after the cryo-LNA. With the transmitter board in 90° F ambient conditions (the highest expected ambient temperature in the AO receiver dome), the noise temperature remains below the required level.

III. Digital Signal Processing Algorithm Development

The digital back end is a heterogeneous architecture consisting of RF system on a chip (RFSoC which includes digitizers, FPGA, and CPU processor) and a cluster of GPU processing nodes networked by 100 GbE. This system will be capable of producing 40 simultaneous dual-polarized beams with approximately 305 MHz of instantaneous bandwidth centered at 1.4 GHz [3]. A system level block diagram of this architecture is shown in Figure 3. Array calibration is done by the GPUs in addition to the production of beamformed data products for various observational modes such as coarse and fine channel spectrometers capable of targeting broadband continuum sources or spectral line observations, respectively.

The capability to provide both coarse and narrow band spectra is realized by a two-stage channelizer implementation. The first stage (called the "F-Engine") is implemented in the Xilinx ZCU216 RFSoC board where array antenna voltages are sampled directly at L-band, channelized into coarse frequency bins (hundreds of kHz wide), packetized for ethernet transport, and switched via 100 GbE to the GPU processors (called the"XB-Engine") for second-stage processing, including array cross correlation and beamforming. In fine spectrometer mode the F-Engine coarse channel outputs are again channelized by the XB-Engine to obtain finer "zoom" frequency resolution (5.1 kHz wide).

Both stages of processing use polyphase filter banks (PFBs) for computationally efficient channelization. For radio astronomical instrumentation, the purpose of the channelizer is to perform spectral analysis, which for a single-stage channelizer is usually implemented with a conventional design approach where attenuation at the crossover point between adjacent channels is $-3\,\mathrm{dB}$. This results in a uniform power spread for spectra across the full bandwidth of the instrument. The PFB which accomplishes this is called a critically sampled (or maximally decimated) PFB because the channelizer output sample rate is equal to the channel spacing [4].

For the ALPACA design, in order to avoid spectral corruptions which can occur in a two-stage channelizer, the first stage is not a conventional critically sampled PFB. In fine spectrometer mode with a second PFB following a critically sampled PFB, gain variations, aliasing, and other unwanted artifacts are introduced into adjacent channels near coarse channel boundaries. To eliminate these issues the ALPACA first stage channelizer is an oversampled PFB.

The decimation rate of the first stage channelizer is decreased and the channel passband shape is designed to allow for a slight overlap between adjacent channels in their crossover region. Following the output of the second stage critically sampled PFB, the fine channels in the overlapped region are discarded to eliminate all unwanted artifacts. With proper prototype filter design only a few channels of overlap are required. This results in an oversampled PFB design with a slight increase in the channelizer output sampling rate (compared to the critically sampled case) that is easily managed by the FPGA and 100 GbE network.

Figure 4 shows an example simulation result comparing the output of fine spectrometer mode following a critically sampled or oversampled PFB as the first stage channelizer. A signal of interested is placed between adjacent channels within the passband of the instrument. Using an oversampled PFB for the first stage removes the aliased signal and gain scalloping.

IV. Conclusion

Stable and reliable signal transport is required to achieve performance goals for the ALPACA phased array feed system. Digital signal processing algorithms allow the formation of

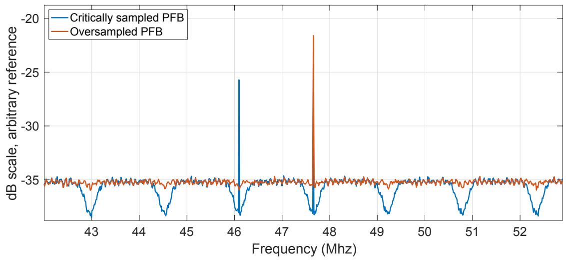

Fig. 4. Simulation comparing fine spectrometer mode output following either an oversampled or critically sampled PFB. When the first-stage channelizer is an oversampled PFB undesired spectral processing artifacts are removed.

beams and radio sky images with sufficient sensitivity and tolerance to RFI to realize the science goals for the ALPACA system. In view of the recent failure of the Arecibo telescope structure, we are currently assessing the options for repurposing the ALPACA wide-field receiver for an alternative large telescope.

ACKNOWLEDGMENT

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