Design of a 96 Element FX Correlator for the LOFAR-UK Station

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Abstract

A design for a 96 dual polarization FX correlator is under development for the LOFAR-UK station at the Chilbolton Observatory in the United Kingdom. This instrument will compute the auto and cross correlations of all 192 signal paths over 25 MHz of the LOFAR HBA band. The correlation products will form the basis of imaging the full sky overhead the LOFAR station on timescales of $\sim$ 100 ms in a search for fast radio transients. Using the FPGA based boards developed by various groups in the radio astronomy community we can significantly speed up the development time of this instrument. With a modification to the current LOFAR firmware it will be possible for commensal operation of this single station, full sky correlator with the normal operation of the international LOFAR array.

1 Introduction

A number of new low frequency dipole arrays, which have come online over the past few years, have opened up our ability to instantaneously access large sections of the radio sky. These arrays, made up of tens to hundreds of dipoles, require a significant amount of digital signal processing (DSP) in order to fully utilize them. The continued growth of computational power will allow us access a wider field of view and higher time resolution using a greater number of array elements. This will open up a new parameter space in the search for fast, rare radio transient events [1]. In order to accomplish this task a new class of correlators is required which can process hundreds of signals and output short timescale integrations. We are developing a new correlator to be deployed on the LOFAR station at Chilbolton Observatory to correlate all 96 dual polarization high band antenna elements to form complete sky images on short scales.

The low frequency array (LOFAR) is a radio telescope developed by ASTRON which consists of a number of core and international stations spread throughout Europe, centered in the Netherlands [2]. Each station is composed of a low band array (LBA) of dipoles optimized for the 30-80 MHz band and the high band array (HBA) which is sensitive to the 120-240 MHz band, the layout of the station can be seen in fig.1. Each of the elements in the HBA is made up of four subelements and a configurable beamformer to select between field of view and sensitivity. As of this writing there are 27 core stations and seven international stations, with another ten being deployed in the near future. The international station in the United Kingdom is located at Chilbolton Observatory. This station was completed in September 2010 and was verified for use in international observations in January 2011. The main mode of operation for each station is in the international observation mode where the station is beamformed and the beam products are transmitted to a correlator in Groningen, Netherlands. Each station can also be used as a standalone array. In this mode the beamforming can be bypassed to allow access to each individual signal. By accessing these signals we can develop a single station correlator with full access to the sky above.

2 Large-N FX Correlator

The first stage of an FX correlator is the fast Fourier transform (FFT), this operation is an $O(m \log m)$ operation where m is the size of the desired FFT. The number of operations scales linearly with the number of frequency channels. The main factor for fine channelization is the radio frequency interference (RFI)

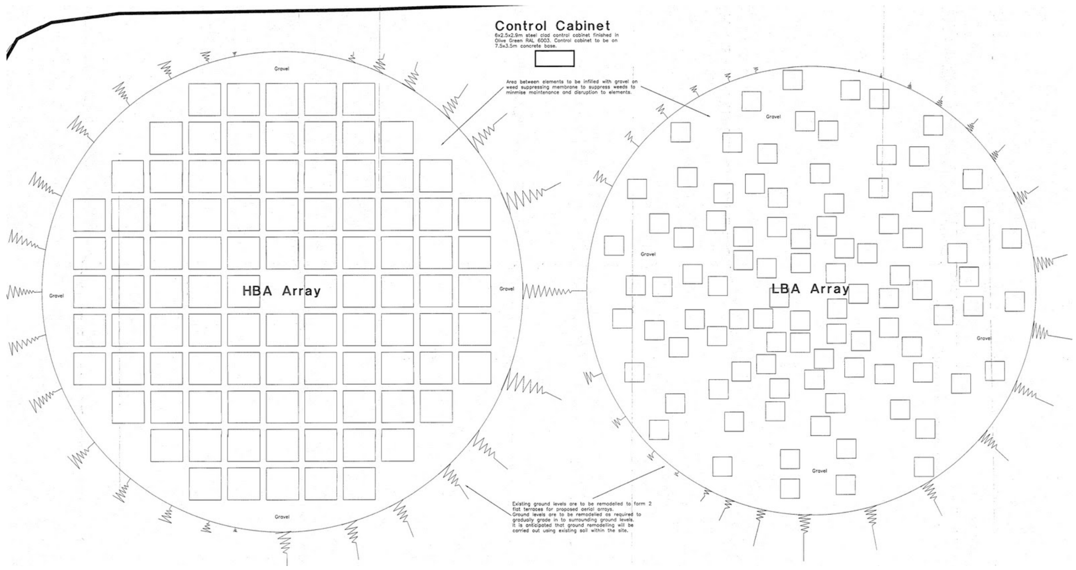

Figure 1: Groundplan of the LOFAR-UK station, the single station correlator will be used with the HBA.

environment surrounding the array. A channel resolution of $\sim$ 30 kHz is sufficient to localize the RFI, which will require a 1024 point FFT for 25 MHz of bandwidth.

The second stage is the correlation performed with a complex multiply of each pair of antennas. The dominant computation cost of the correlator is the large number of relatively simple CMACs in the second stage. The operation of an FX correlator scales as $O(n^2)$, where n is the number of antenna elements, and has been shown to be an efficient solution to the large-N correlation problem [3]. To correlate all 96 elements of the HBA array, with their polarization components (192 signal paths), requires 18624 complex multiply-accumulates (CMACs) per data clock. Correlation of a sufficient number of bits is required to cope with the dynamic sky and high RFI environment at low frequencies. With proper band equalization 4 bit correlation will be sufficient.

Between the first and second stage a cornerturn is required to parallelize the serial data from each streaming FFT. This groups the same frequency channels of each antenna so that the correlation can be performed efficiently using a pipelined architecture [4]. To reduce the output data rate a programmable accumulator will be incorporated to control the integration time. For 18624 baselines with 1024 frequency channels there are $\sim$ million complex values per integration. A complete integration will be $\sim$75 MB, using 16 bit representation for each value. The minimum integration time will then be limited by the data rates an imager can process in real time.

Field programmable gate arrays (FPGAs) provide an efficient way to perform the FFT and correlation stages. The newest FPGAs produced by Xilinx and Altera include an number of DSP cores which can be used as fast multipliers and second stage accumulators. Each new generation of FPGAs have significant increases in IO banks, logic blocks and on chip RAM while maintaining low power consumption. The newest lines of FPGAs can run firmware designs at many hundreds of MHz. We can take advantage of this by running the FPGA at an integer number of clocks faster than the data clock, 50 MHz. The multipliers can then be efficiently used on multiple streams, reducing the total number of multipliers required. By interconnecting multiple FPGAs a correlator design can be spread over many chips.

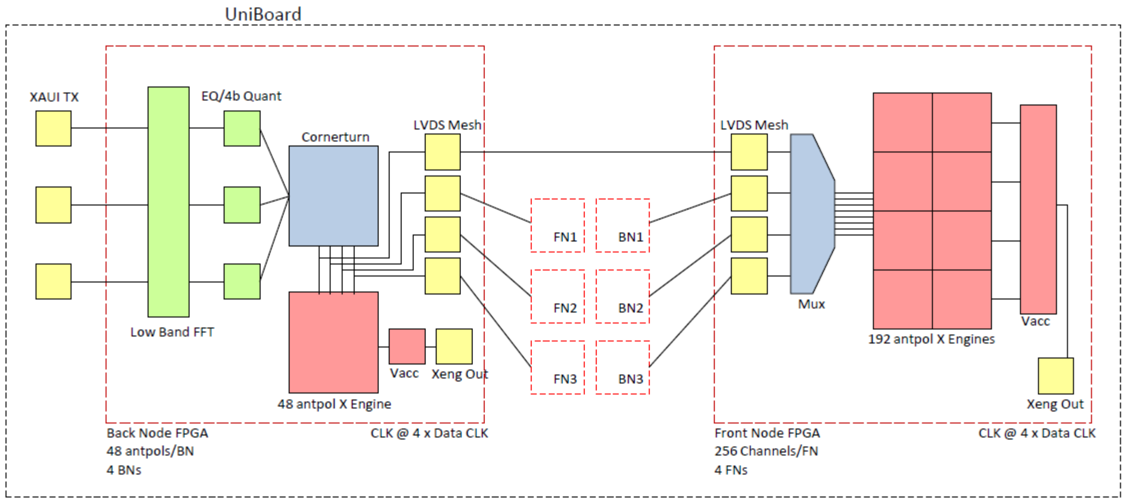

Figure 2: A UniBoard based design for a full-Stokes 96 element FX correlator at 25 MHz of bandwidth.

3 FPGA based Boards for Radio Astronomy

Instruments designed with FPGAs have proven to be very successful in radio astronomy. The Moore's law growth in FPGAs and the continued maturation of development tools have made these instruments easier to design. There has been a formation of collaborative groups which develop general purpose FPGA based boards for radio astronomy. The Collaboration for Astronomy Signal Processing and Electronics Research (CASPER) have been producing open source single Xilinx FPGA based boards for a number of years [5]. CASPER has developed a set of graphical tools which makes development of new instruments very fast and with a reduced learning curve by creating reusable DSP modules. ASTRON, in collaboration with a number of universities, has developed the UniBoard, a board with 8 Altera FPGAs [6]. They have taken a more traditional approach of using HDL for instrument development; they also have a set of reusable modules that greatly decrease development time. These groups have reduced the overall cost of radio astronomy instrument designs by taking a community based approach to board development.

Development is progressing for a UniBoard based correlator design. For the LOFAR station correlator, the input data rate will be 76.8 Gbps for 192 signals of 8 bit data at 50 Msps. The UniBoard uses Altera Stratix IV FPGAs which have 1288 multipliers, on the UniBoard there is up to 40 Gbps of IO and a 40 Gbps interboard low voltage differential signal (LVDS) communication network per FPGA. The four backnode FPGAs will be utilized to perform the FFT, cornerturn and a correlation for the local signals. These backnodes will compute 25% of the total correlation product. Using the backnode to frontnode interconnect the frontnodes will each be used to correlate 25% of the remaining baselines (fig.2). By clocking the UniBoard at four times the data clock 6984 CMACs are required per clock which can be accomplished using a single UniBoard.

4 Interface to Current LOFAR Backend

The current LOFAR station digital backend is made up of 24 remote station processing boards (RSPs) which are connected in a ring via XAUI to form the station beam. The RSP applies an initial polyphase filterbank (PFB) to the voltage data to make band selection with the beamformer possible. There is also a single channel correlator on the RSP which is used to generate the beamformer coefficients. The beamforming and correlating uses 6.025 Gbps of the 10 Gbps XAUI interface. Each XAUI interface is made up of 4 2.5 Gbps lanes which are not fully being utilized. With a modification to the RSP firmware the ring data rate can be further reduced to below 5 Gbps. This would free up two of the XAUI lanes which can be used for correlation. By adding a passive interface to the CX-4 connecter on the RSP board two lanes from each RSP can be used to send samples from each signal chain to the station correlator. The total bandwidth data rate from the antenna elements would be 19.2 Gbps per RSP for 12 bit data. This limits the total accessible bandwidth to ~ 25 MHz.

5 Status

This correlator is part of a new class of FPGA based correlators that will be developed over the next few years to accommodate the rapid growth in small antenna, large-N arrays being used in epoch of reionization experiments, and the SKA. The instrument backend will also provide an interface for a real time imager to be used to open up the parameter space of rare, fast radio transients. The development run of UniBoard is currently under way and the production run is expected in the third quarter of 2011. Meanwhile an agnostic approach is being taken to the firmware design where the main components can be developed in general HDL and optimized for the selected architecture. This allows us to test components of the firmware on other architectures in preparation for the final design.

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