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The Signal Processing Firmware for the Low Frequency Aperture Array

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The signal processing firmware that has been developed for the Low Frequency Aperture Array component of the Square Kilometre Array is described. The firmware is implemented on a dual FPGA board, that is capable of processing the streams from 16 dual polarization antennas. Data processing includes channelization of the sampled data for each antenna, correction for instrumental response and for geometric delays and formation of one or more beams by combining the aligned streams. The channelizer uses an oversampling polyphase filterbank architecture, allowing a frequency continuous processing of the input signal without discontinuities between spectral channels. Each board processes the streams from 16 antennas, as part of larger beamforming system, linked by standard Ethernet interconnections. There are envisaged to be 8192 of these signal processing platforms in the first phase of the Square Kilometre array so particular attention has been devoted to ensure the design is low cost and low power.

Keywords: instrumentation: interferometers; instrumentation: radio astronomy; techniques: digital signal processing

1. Introduction

The Low Frequency Aperture Array (LFAA) (Faulkner & bij de Vaate, 2013) component of the Square Kilometre Array (SKA) will consist, in SKA Phase 1, of 2^{17} log-periodic dipole antennas (SKALA). The current architecture, shown in Figure 1, envisages the transport of the Radio-Frequency (RF) bandwidth of 300 MHz over fiber to a Central Processing Facility (CPF). Once inside the building these antenna signals are digitized, channelized and beamformed together to form logical stations which are an aggregation of 256 antennas. The LFAA is currently designed to produce 512 of these logical stations which can be flexibly configured by programming the signal processing platform to send its traffic across a highly configurable network.

The antennas are grouped in tiles of 16 antennas each. Each tile is processed in a Tile Processing Module (TPM), and 16 TPMs are connected together in a flexible way to form a station, using a general purpose high speed Ethernet interconnect. This distributed beamformer architecture allows to dynamically reconfigure the antennas composing each station.

Signal processing inside a LFAA station includes a first channelization stage, corrections for cable length mismatch, geometric delay, receiver amplitude and phase response, and atmospheric and polarization

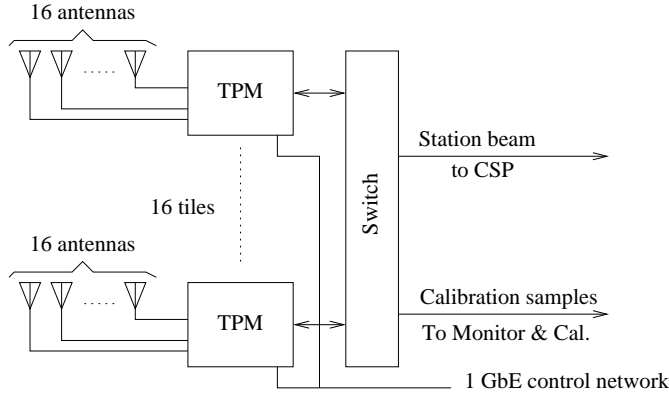


Fig. 1. Architecture of the Low Frequency Aperture Array station. Groups of 16 antennas form a telescope tile. 16 tiles form a station, that produce a station beam to be processed in the central signal processor

calibrations. Beamformed samples are then organized into frames and sent to the SKA Central Signal Processor (CSP). The CSP provides a second channelization stage, correlation, beamforming for pulsar search and timing.

The two stage oversampling filterbank architecture allows for a very large number of spectral channels, avoiding the spectral holes present in a conventional two stage channelizer. In previous instruments a "twice oversampled" architecture was sometimes used, at the cost of doubling the amount of data to be transferred between the two stages (Comoretto *et al.*, 2011), but this was not acceptable in an instrument as large as SKA. An oversampled filterbank has been used in the correlator for the ALMA interferometer (Escoffier *et al.*, 2007), implemented as a set of 32 tunable digital down-converters, but this approach is not scalable to the number of channels required here.

This paper describes the signal processing algorithms, procedures and instrumental effects, in the context of the SKA Low telescope signal processing chain, while the TPM hardware is described in detail elsewhere (Naldi *et al.*, 2017). Section 2 provides an overview of the LFAA signal processing, and subsequent sections describe in detail the ADC conversion and synchronization (section 3), the channelizer (section 4), the beamformer (section 5), the interface for data transport between tiles and towards the CSP (section 6), and diagnostic and calibration functions (section 7). Some tests and implementation details are shown in section 8.

2. LFAA signal processing

The LFAA signal processing subsystem is responsible for the formation of one or more beams from each station. Station beams are channelized to a resolution of 781.25 kHz, covering the frequency range of 50 to 350 MHz. Each beam is composed of the signals from 256 antennas, coherently added along one or more directions in the sky. Up to 8 beams may be formed, with a total aggregate bandwidth of 300 MHz (e.g. 6 beams of 50 MHz each). Beams must be capable of following a source moving in the sky at up to several times the sidereal rate.

Both the SKA Low and SKA Mid telescopes adopt a 2-stage channelization scheme, with a first stage oversampled polyphase filterbank followed by a second stage critically sampled filterbank implemented in the CSP. Oversampling must not exceed 20%, in order to limit the amount of data transferred to the CSP. The first stage LFAA channelizer provides a flat and alias free frequency response on a region equal to the channel separation. The slightly larger bandwidth (oversampling) is used to accommodate the portion of the band affected by the filter transition zone and aliasing of the adjacent channels. The alias free region in each frequency channel is further channelized in the CSP, with a variable resolution ranging from 226 Hz to about 5.4 kHz, while the portion affected by aliasing and filter edges is discarded. These *fine channels* are then stitched together to form a continuous uniform spectrum at the desired final frequency resolution. In-band ripple is limited to ± 0.2 dB, minimum stop-band rejection must exceed 60 dB, with more than 80 dB as a goal for most of the stop-band region.

The TPM must deal with several instrumental effects. Cable length mismatches among antennas must be corrected in a static way, for pointing to zenith. Receiver and antenna gain and phase frequency responses must be corrected with a frequency resolution of one spectral channel, and corrections are updated every 10 minutes during the observation, without stopping it. Polarization impurities and polarization rotation must be individually corrected for each beam. The signal must be equalized in frequency, to accommodate for the frequency dependence of the observed signal spectral density, in order to keep the amplitude of the signals sent to the CSP within ± 3 dB.

Beside the beamformed data, the TPM must produce some diagnostic quantities for the calibration subsystem. The station calibration algorithm requires a continuous stream of channelized samples from one selected spectral channel. The total power and a coarse frequency spectrum, computed over a limited integration time, must also be provided for each input signal.

The TPM is connected to the local monitor and control (LMC) subsystem via a 1Gb Ethernet interface. A control software framework has been developed (Magro *et al.*, 2017), including a low level communication layer that uses a symbol table embedded in the firmware, and higher level functions that interface to a TANGO control middleware (Tango Team, 2015). Most of the parameters are set before the actual observation, but all calibration quantities (including beamforming parameters) must be changed dynamically at predefined times, without stopping the observation.

Beamformed data are sent to the CSP using a 40 Gb high speed Ethernet interconnect. The same network is also used to send the channelized samples to the LFAA calibration subsystem.

The TPM is responsible of time stamping of the samples from the Analog to Digital Converter (ADC). Each TPM is synchronized to Universal Time Coordinated (UTC) using a peak-per-second (PPS) pulse and a reference high precision clock, with UTC time distributed via the control interface.

The LFAA antennas operate in a quiet Radio Frequency Interference (RFI) region, but the telescope is anyway very sensitive to RFI. The channelization subsystem must be able to cope with RFI, limiting the effects to the affected time and frequency regions.

2.1. Tile Processing Module architecture

The LFAA station beamformer structure is based on a frequency domain beamforming architecture. Data streams from the individual antennas are channelized with a channel spacing of 781.25 KHz, and delayed in the frequency domain by applying a dynamic phase correction to each individual channel. Each signal is also corrected using a static instrumental gain, phase and polarization calibrations, updated on a timescale of a few minutes. It is possible to select multiple regions in the processed band, and/or to generate multiple beams of the same or different spectral regions. The channelization process is used both to allow for frequency dependent calibration, for frequency domain beamforming, and to provide the first stage of a two-stage channelizer.

Processing is performed in groups (tiles) of 16 antennas in a TPM. TPMs are connected together in a flexible way using the 40 Gb high speed network, with non-blocking network switches. Stations can then be configured dynamically as arbitrary groups of tiles. The same network is used to transfer samples from individual antennas to the control, calibration and monitor subsystem, and beamformed samples to the Central Signal Processor. Data to be sent to the CSP is packed into frames of 2048 samples for one frequency channel, two polarizations. This requires a corner turner operation from the channelizer output (frames of one time sample, all channels) to the CSP frames (one channel, many consecutive time samples).

The firmware has been optimized for the Italian TPM, described in detail in (Naldi *et al.*, 2017). It includes 16 dual channel ADCs connected in groups of 8 to two separate Xilinx Kintex Ultrascale Field Programmable Gate Arrays (FPGA), each processes both polarizations for 8 antennas (Figure 2). The two FPGAs are interconnected by a parallel high speed bus, with an aggregate bandwidth of 22 Gbps in each direction. Each FPGA has an external memory bank, and a Quad Small Form-factor Pluggable (QSFP) connector for up to two 40 Gb Ethernet interfaces, but only one QSFP will be used in the full scale SKA system for cost and power considerations.

The structure is adapted to a time multiplexed data stream, with 4 samples processed in parallel at each FPGA clock cycle. After channelization and beamforming, odd and even frequency channels for the

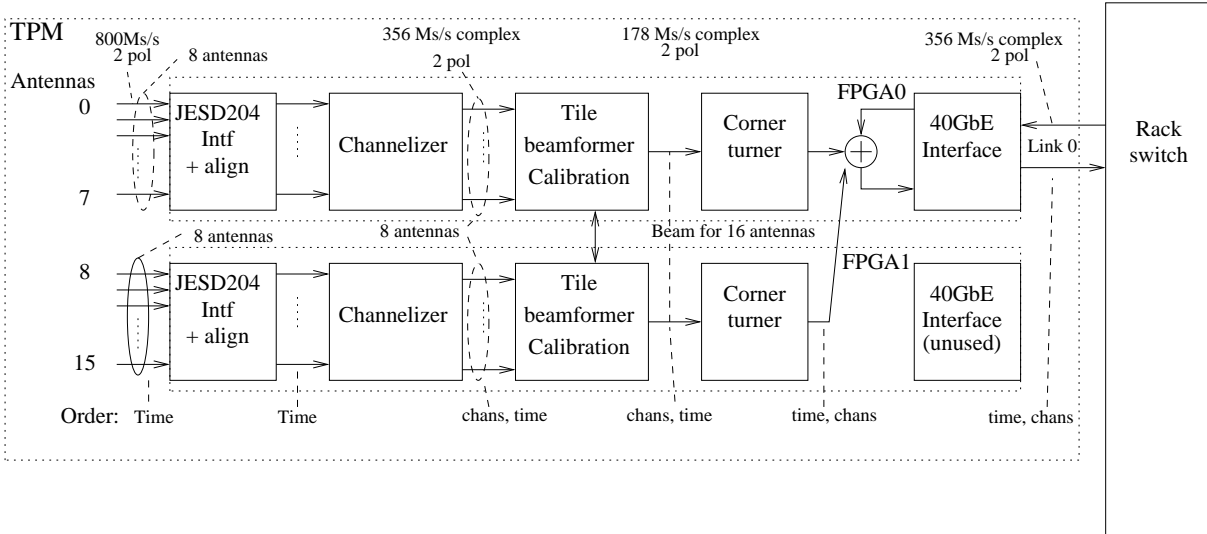


Fig. 2. Signal processing chain of a tile processing module

whole tile beam are processed separately in the two FPGAs. Channelized data is stored in an external local memory, that is used for the corner turner function. Station beamforming is performed by daisy-chaining the TPMs. The first TPM in the chain retrieves from memory the samples corresponding to a packet to be sent to the CSP, and sends it to the next one, that in turn retrieves the corresponding samples, adds them to the incoming packet and forwards it down the chain. The last TPM then reformats the packet and sends it to the CSP.

Data rates are also shown in figure 2. Each ADC generates 800 Mbyte/s of 8 bit samples, for an aggregate data rate of 204 Gbps. The channelizer selects a bandwidth of 300 MHz, oversampled to 356 Msample/s, with resolution increased to 12+12 bit complex samples. The aggregated data rate after the channelizer is then 274 Gbps, that is reduced by a factor of 16 (one beam every 16 antennas, 17 Gbps) in the tile beamformer. Half of this information is exchanged among the two FPGAs. The traveling sum on the 40 Gb interface uses 16+16 bit complex samples, for a data rate, including packet overhead, of 23.2 Gbps. The final beamformed data to the CSP is represented with 8+8 complex samples, with a data rate of 11.6 Gbps.

The calibration subsystem requires a subset of the channelized samples for one channel, all antennas and polarizations, represented with 8+8 bit complex samples. The corresponding aggregated data rate is about 0.5 Gbps.

3. ADC interface

The TPM hosts 16 dual-input AD9680 digitizers sampling 16 dual polarization antennas at 800 megasample/second (MSPS). Both the ADC and the signal processing chain can operate in the second Nyquist zone, and with slightly different digitization rates, but this possibility is not used in SKA1. Digitized data are transferred towards two Xilinx Kintex UltraScale XCKU040 FPGAs using fast serial interfaces exploiting JESD204B Subclass 1, which guarantees deterministic latency.

3.1. JESD interface synchronization

The synchronization process consists of 3 phases: Code Group Synchronization (CGS), Initial Lane Synchronization (ILAS) and data transmission phase. Two special purpose signals are required for JESD204B Subclass 1 (JEDEC, 2011) operation: SYSREF and SYNC.

SYSREF is synchronous to the device clock and it is used to synchronize an internal counter, named Local Multi Frame Counter (LMFC), in both the transmitters and the receivers. On the TPM board SYSREF and clocks are generated by a specialized AD9528 PLL and then distributed to all the devices

by means of ADCLK948 buffers. Clock and SYSREF PCB traces to the ADCs are length matched within 100 ps to each other, allowing the ADCs to sample the SYSREF on the falling edge of the device clock with ample setup and hold margin.

In the CGS phase the FPGA issues a synchronization request driving the SYNC signal low. When the ADCs sample SYNC low, they transmit a synchronization pattern consisting of /K28.5/ characters in the 8B10B encoding scheme. The FPGA is synchronized when all the transceivers receive at least four consecutive /K28.5/ symbols without error, at that point the FPGA drives SYNC high.

After sampling SYNC high the ADCs wait for the next LMFC counter wrap-to-0 event and then start the ILAS phase where they transmit a predefined pattern. At the subsequent LMFC counter wrap-to-0 event the ADCs enter the Data phase and transmit sampled data.

On the receiving side, in the ILAS phase the FPGA checks for the predefined pattern and it internally delays the lanes in order to match the delay of the slowest lane. After the ILAS phase, the core starts forwarding sampled data to the user logic at the next LMFC wrap-to-0 event. The whole process always takes a deterministic number of LMFC periods.

JESD204B operation is managed in the FPGAs by the Xilinx JESD204 proprietary core, which handles the synchronization autonomously and forwards ADC data towards user logic using a simple streaming interface. Since the Xilinx core supports up to 12 lanes, two cores sharing the same SYSREF signal are instantiated.

3.2. Framing and time stamping

After synchronization the JESD204 core streams sample aligned ADC data to the framer. The framer packetizes the incoming data in frames that are 864 samples long (1080 ns). At the beginning of the observation the framer aligns the first data in the first frame to a PPS rising edge and then it continuously streams framed data.

The FPGA manages two counters, *sync_time* and *time_stamp* counters. The *sync_time* counter represents UTC time, it is set before the observation is started and it is incremented by a PPS rising edge. The *time_stamp* counter is started when the framer streams the first ADC data and it represents the time in ns elapsed from the beginning of the observation. At the same time, the *sync_time* counter content is copied in a local *start_time* register. The combination of the two counters provides univocal time-stamping of each frame.

Processed frames correspond univocally to ADC frames. At the beginning of the observation the channelizer waits for a fixed amount of time, corresponding to the filter preload time, before outputting the first channelizer frame, and then produces one frame of channelized samples for each input ADC frame. The tile beamformer processes one channelizer frame at a time. Therefore the time associated to each processed frame t_f , up to the tile beamformer output, can be derived by simply counting the frames and is not explicitly specified with the frame itself:

$$t_f = t_0 + t_1 + N_f \Delta t \quad (1)$$

Here t_0 is the time for the start of the observation, stored in the *start_time* register, t_1 is the deterministic time needed to preload the channelizer filter ($t_1 = 7560$ ns in the current implementation), N_f is the frame number, that is reset before the beginning of observation, and $\Delta t = 1080$ ns is the frame length.

The station beamformer packs together groups of 256 consecutive samples, in the packets propagated through the station beamforming chain, and 2048 samples in the packets sent to the CSP. These packets include a frame header, in the SPEAD format, that explicitly contains the observation *start_time* and the relative time for the first sample in the packet. The header format is described in section 6.

Particular care has been taken in synchronizing with the external PPS. As the PPS signal has an arbitrary phase with respect to the system clock, it is sampled multiple times in a clock period, and a clock phase which does not create ambiguities is chosen. This ensures that the internal time reference has a fixed time delay with respect to the system time. This has been verified by providing the same signal, locked to the system time, to multiple boards, and checking the repetibility and stability of the sampled

signal phases across boards.

3.3. Correction for cable mismatches

The data stream from each antenna can be delayed by an integer number of samples, to correct for mismatches in the length of the cables connecting each antenna to the TPM. The correction is almost static, i.e. it is computed only when the cable length is explicitly measured, and corresponds to aligning all antennas to a source at the zenith. It is not changed during normal operations, or for sidereal tracking.

The correction range is ± 512 samples, corresponding to about ± 120 meters of optical fiber, and is applied together to both polarizations for each antenna. The residual sub-sample delay is corrected in the frequency domain, in the beamforming process.

4. Polyphase channelizer

The channelizer divides the sampled bandwidth of 400 MHz into 512 equispaced spectral channels, with a spacing of 781.25 kHz and a channel bandwidth of 925.926 kHz. The channels overlap by a factor of 5/32 (oversampling of 32/27). The extra bandwidth allows for a channel shape that is flat in the central region, kept in the subsequent processing, leaving the filter transition region in the overlapping channel edges, discarded in the CSP. After correction for the deterministic pass-band ripple, this produces a residual flatness in the correlated signal of less than ± 0.01 dB, without discontinuities near the edges of the channels. To achieve the requirements for in-band flatness and out-of-band rejection, listed in section 2, a filter order of 14336 has been used.

The channelizer is based on the oversampling polyphase concept (Harris *et al.*, 2003), optimized for a real valued, time multiplexed signal, and to minimize the number of FPGA resources required. A polyphase filter implements a Weight-Overlap-Add operation (WOLA) on the input samples using a prototype low-pass filter, producing a vector of size N . This vector is then Fourier transformed, producing N equispaced channels ($N/2$ for a real valued signal) corresponding to the center time of the input sample segment. The Fast Fourier Transform (FFT) effectively translates the prototype filter response to each channel center frequency. For critically sampled filterbanks, the filter and the FFT is computed for times which are multiples of N samples, but reducing this spacing to a value $M < N$, larger output bandwidths can be obtained. In our case $N = 1024$ and $M = 864$.

4.1. Polyphase filter

The WOLA filter architecture is shown in Figure 3. A first dual port memory block produces blocks of N contiguous samples for every frame of M input samples. The output port runs at a higher clock frequency, and repeats the last $(N - M)$ samples of the previous block at the beginning of each frame. Successive delay blocks introduce a delay of N samples, again repeating $(N - M)$ samples at the beginning of each frame.

The structure is adapted to a time multiplexed data stream, with 4 consecutive samples produced at each clock cycle. The whole filter also produces 4 consecutive values at each clock cycle. To optimize memory usage, a single memory 4 times wider is used for the parallel samples in each block. The filter tap coefficients are identical for all the antennas, and a single memory is used for all parallel instances of the filterbank. As the filter is symmetric, a single dual port read-only memory is used to generate two symmetric sections of the filter. The total number of WOLA blocks is related to the filter specifications. In our design we used 14 blocks.

For oversampled polyphase filters, the oversampling introduces a cyclic phase rotation in each spectral channel that is corrected by rotating the filtered frame before the FFT.

4.2. FFT block

The FFT of the real sequence is performed packing two consecutive samples as the real and imaginary part of a single complex value, computing a complex valued FFT of size $N/2$, and then separating channels

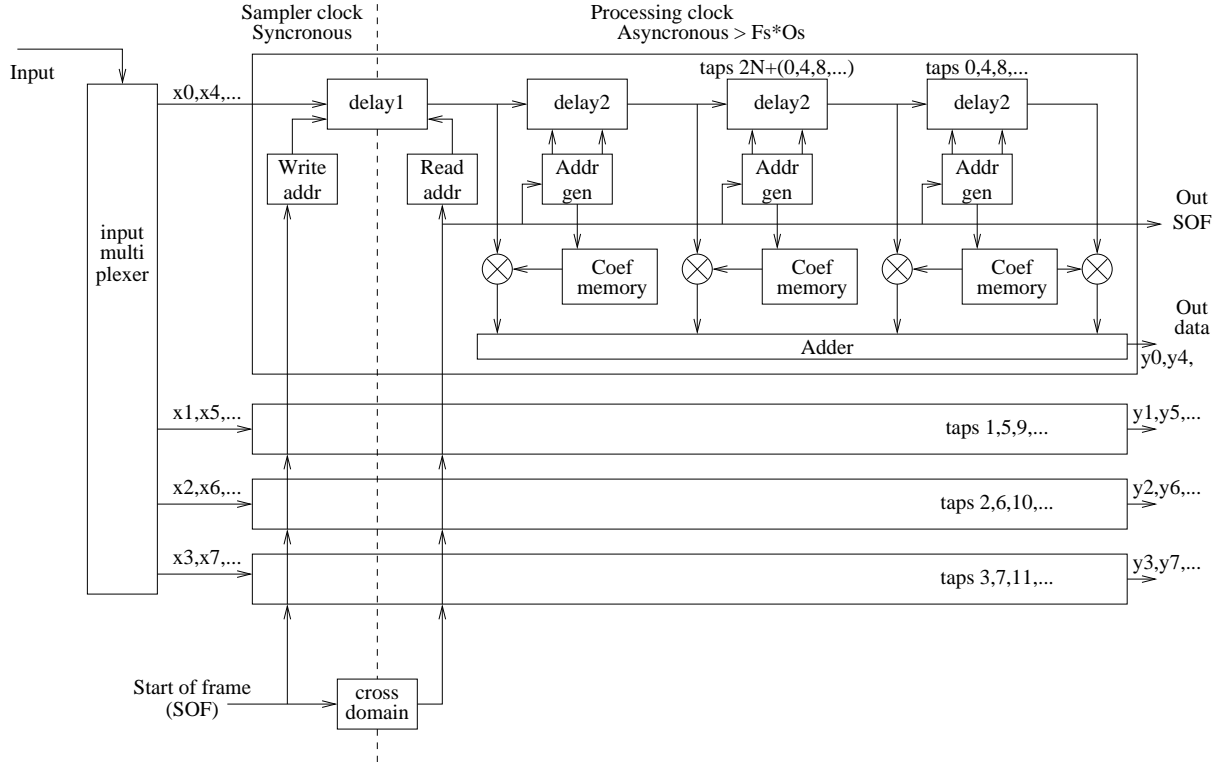


Fig. 3. Architecture for the time multiplexed, oversampling polyphase filter

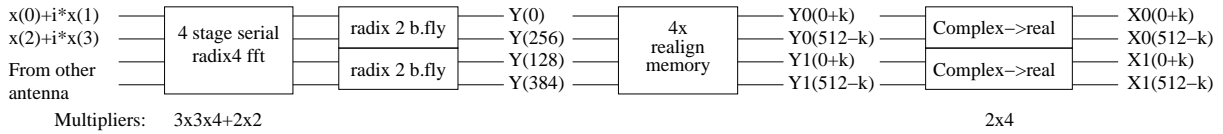


Fig. 4. 1024 point FFT core for two 4x time multiplexed real valued signals

k and $(N/2 - k)$ using the technique described in (Press *et al.*, 2007). FPGA implementation is shown in Figure 4. The FFT is composed of a serial Decimation-in-Frequency (DIF) radix-4 FFT block, that processes simultaneously two signals (two polarizations for a single antenna), followed by a parallel radix-2 butterfly stage and by the final real channels separation stage.

The core is optimized for a signal consisting of Gaussian noise. Overflow is possible in the last stages in the presence of monochromatic (RFI) signals, and the affected channels are properly flagged, but does not occur for normal radioastronomic signals or non monochromatic RFIs. The structure is very efficient, using just 48 multipliers for two parallel FFTs of 1024 points each, sampled at 4 times the FPGA clock frequency.

We analyzed several commercial or public domain firmware cores, but the resource usage was significantly higher. The custom core is also vendor independent and can be easily tailored to specific SKA requirements.

4.3. Filter design

The filter block, being repeated for each signal, is the most resource intensive structure in the design. Therefore filter design has required particular care, in order to minimize filter size for given specifications. Common design techniques for filters of this size usually involve windowing of an ideal passband filter. This produce very high stop-band rejection, above what is effectively needed, at the expense of a larger size.

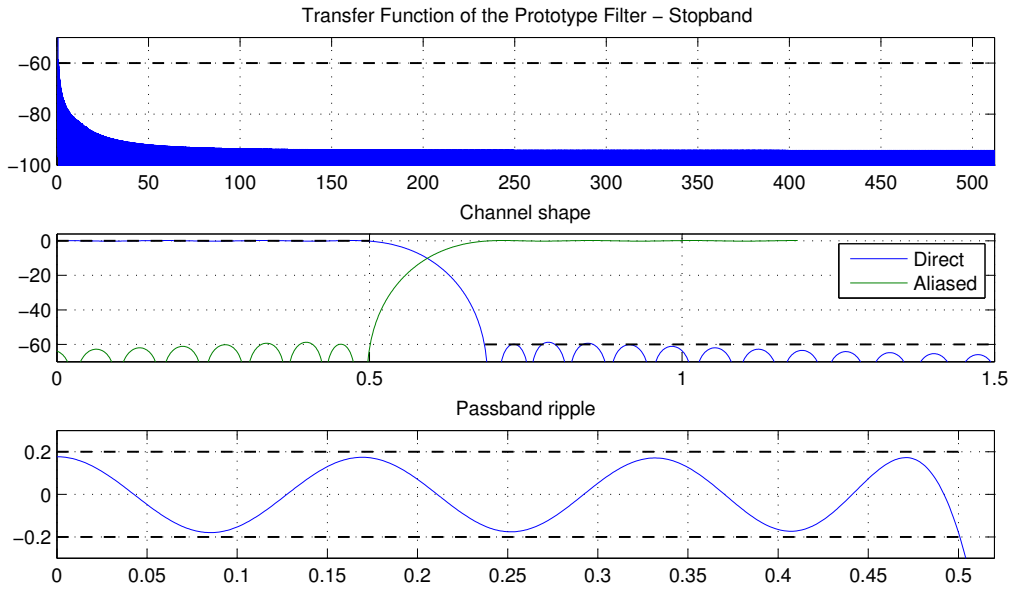


Fig. 5. Prototype channel filter response. Frequency scale is expressed in units of channel-to-channel separation, vertical scale in dB

Equiripple design techniques, like the Remez-mcClellan algorithm (Parks & mcClellan, 1972), usually do not converge for filters of order beyond a few hundreds. We adopted the technique of designing a relatively short (1/16 of the final size) equiripple filter using the Remez-mcClellan algorithm, and interpolating the result using a FFT based interpolator (Comoretto, 2012). The discontinuity present at the edges of the equiripple filter has been deleted before interpolation, and reintroduced in the interpolated result. We used a custom C implementation of the algorithm, which has been proved more robust than the one in the Matlab filter package.

The resulting filter shape is shown in Figure 5. The passband ripple has been set to ± 0.17 dB, the stop-band attenuation is greater than 60 dB at the beginning of the aliased region and drops to 86 dB for most of the stop-band. A total of $14N$ (14336) filter taps are required for a polyphase filter with the required oversampling factor of 1.185. For comparison, a filter with the same performances designed with conventional techniques has a size of at least $18N$.

5. Beamformer and calibration

Station beamforming is performed in the frequency domain, by phase referencing each antenna to a common station phase center and summing together the 256 antennas composing the station. Receiver, atmospheric and polarization calibrations are also applied to each signal before summing them together. The sum is performed hierarchically: the 8 stations in each FPGA are summed together, then odd and even channels for the whole tile are exchanged among FPGAs and summed in a tile partial beam, and finally each partial beam is summed to a traveling packet that runs across the tiles composing the station.

5.1. Tile beamformer and calibration

The tile beamformer is described in more detail in (Comoretto, 2015). SKA-low specifications require the beamformer to produce up to up to 8 independent beams, placed anywhere in the sky, and up to 16 independently tunable frequency regions (sub-bands), placed anywhere in the digitized band, for a total bandwidth of 300 MHz (384 channels). Each sub-band can be assigned to any beam, and can repeat the same frequency region (e.g. 8 identical sub-bands for 8 beams at the same frequency). Due to hardware

limitations, the sub-band width is constrained to a multiple of 8 spectral channels (6.25 MHz), and its position can be set with a granularity of 2 spectral channels (1.5625 MHz).

The selected channels are then multiplied by a phase proportional to the sample frequency and antenna geometric delay. The delay is dynamically computed using an initial delay value and a delay rate.

Before beamforming, the signals from each antenna are corrected for amplitude and phase instrumental response, for atmospheric propagation effects, and for beamforming tapering. The correction is expressed by a complex polarization matrix for each frequency channel, antenna and beam. Signals are also equalized in amplitude, to allow for requantization with 8+8 bits/sample without significant quantization losses.

Thus the beamformed signals $S(t, \nu, b)$ for one station, two polarizations, for the frequency channel ν and beam b is given by:

$$\begin{pmatrix} S_h(t, \nu, b) \\ S_v(t, \nu, b) \end{pmatrix} = \sum_a \exp(2\pi j \nu \tau(t, a, b)) \begin{pmatrix} C_{hh}(\nu, a, b) & C_{hv}(\nu, a, b) \\ C_{vh}(\nu, a, b) & C_{vv}(\nu, a, b) \end{pmatrix} \begin{pmatrix} A_h(t, \nu, a) \\ A_v(t, \nu, a) \end{pmatrix} \quad (2)$$

$$\tau(t, a, b) = \tau_0(a, b) + t \dot{\tau}(a, b)$$

where $C(t, \nu, b)$ is the beamformed signal for beam b , $A(t, \nu, a)$ is the channelized signal for antenna a , $\tau(t, a, b)$ is a linear approximation for the geometric delay of antenna a relative to beam direction b , and $C(\nu, a, b)$ is a correction matrix. Subscripts h, v refer to the two linear polarizations. All quantities, except the delay, are complex, and specified for the 384 selected combinations of frequency and beam directions. The corrections are referred to the center of each frequency channel and decimated sample interval. The phase error increases towards the channel edges. For a channel width of 781.25 kHz, an uniform circular station with a diameter of 35 meters, and pointing up to 45 degrees from the zenith, the maximum phase error is 0.1 radians and the corresponding beam decorrelation for a uniform circular station is 0.25%, or -0.01 dB. This has been test using a simulated linear array, with results in figure 9.

The correction matrix C is composed of several terms:

- the correction for the (complex) antenna/receiver frequency response, including the subsample cable length mismatch
- the inverse of the Jones matrix relating the polarization in the sky to the measured fields at the two antenna polarization ports, including the parallactic rotation
- the desired antenna tapering amplitude for beamforming
- an equalization term, common to all antennas and polarizations in the station, to provide the CSP with a signal of constant amplitude.

All quantities are calculated externally to the TPM, and expressed as integer values. Linear delay is updated every 1024 channelized samples (1105.92 μ s). Phase is expressed with a resolution of 4096 steps/turn, delay with a resolution of 153 fs in a range of ± 80 ns (± 24 m), and delay rate with a resolution of 8.4 fs/s and a range of ± 17 ns/s. For a source moving at a sidereal rate, delay and delay rates can be updated every 2 minutes before the phase error becomes significant.

Matrix C is expressed as a complex mantissa, with 16 + 16 bits of accuracy, and a 3 bit exponent specified every 8 frequency channels for each antenna. The mantissa is updated at the calibration cycle interval, currently specified as 10 minutes.

Operations in equation (2) is performed in the following order:

- Channelized samples (18 bit values) are scaled by the exponent of $C(\nu)$ and requantized to 12 bit accuracy;
- Samples are multiplied by the complex exponential for the geometric delay;
- Samples are multiplied by the mantissa of the matrix $C(\nu)$, and requantized to 8 bit accuracy;
- The sum for beamforming is performed using 16 bits, and the 16 bit result is rescaled and requantized to 8 bit accuracy for the CSP.

5.2. Station beamformer

The tile beamformer produces partial sums of 16 antennas, organized in frames of one time sample and 150 MHz of frequency channels. These partial beams are stored in local memory, in blocks of up to about 0.23 seconds, and retrieved as contiguous frames of 128 time samples for 8 channels and 2 polarizations. Each sample is represented as a $16 + 16$ bit complex value.

The TPMs composing a station are logically organized in a network chain, with each TPM sending frames for the partial beam to the next one in the chain. By changing the address of the next TPM, it is possible to define the tiles composing each station. The first TPM in the chain retrieves sequentially the frames for the same channels and for the whole time block, then send them to the next one. Every other TPM, upon receiving a frame, retrieves from memory the corresponding frame and adds it to the traveling partial sum. The last TPM in the station chain accumulates 16 frames, forming 8 frames with 2048 samples and a single frequency channel, and sends each frame to a separate section of the CSP. Samples sent to the CSP are represented as $8 + 8$ bit complex values. In this way each section of the CSP receives from each station a contiguous stream of samples for a single channel at a time.

Each frame, in both formats, has an associated header in the format specified in section 6.

6. SPEAD formatter

Beamformer and channelizer data is transferred between TPMs using SPEAD (Manley *et al.*, 2010), an application-layer protocol developed for the CASPER (Collaboration for Astronomy Signal Processing and Electronics Research)¹ and widely adopted by the radio astronomy community. Data is streamed in and out of the SPEAD formatter using the AXI4-Streaming Protocol (ARM, 2013). In addition AXI4-Stream t_{USER} side channels and additional ports are used to populate and construct the SPEAD header and the total length of the data payload is configured via AXI4-Lite Memory-Mapped (ARM, 2013) registers and is expected to be a 2^N value. Incoming t_{DATA} is expected to be equal in size to, or a multiple in size of the 2^N value in the configuration register. Incoming SPEAD payload data is valid when t_{VALID} is asserted and the final value is determined when t_{VALID} and t_{LAST} are both asserted. There is no internal error checking of the size of incoming t_{DATA} streams.

The SPEAD formatter uses two First In First Out (FIFO) memories on the slave side of the AXI4-Stream Interface. The first FIFO is dedicated to the payload data and has two functions; the first function is to allow the crossing of clock domains and to handle changes in incoming t_{DATA} data width to match the clock/data width of the up-stream component(s) generating the data; second function is to act as a shallow buffer for the incoming payload data while the header fields are being assembled. The second FIFO is used to hold the header fields as they are constructed. Once the header is complete an internal controller State-Machine places the header followed by the payload data into a third FIFO to present the combined, complete SPEAD packet to the output AXI4-Stream master interface. This final FIFO allows the crossing of clock domains and to handle width changes between the internal t_{DATA} width of 64 bits, defined by the SPEAD Specification (Manley *et al.*, 2010), and to match the clock/data width of the down-stream component(s) connected to the SPEAD formatter.

Using additional firmware components data can be transferred FPGA-to-FPGA or FPGA-to-Network Interface, either via a network switch or directly to a server's network interface. This is achieved by encapsulating the SPEAD application-layer stream data into single or multiple User Datagram Protocol (UDP) packets, where each packet contains its own SPEAD header; in this example the maximum data payload stream is limited to 8192 bytes plus the header, an additional 72 bytes. This due to the custom 10Gb Ethernet UDP Media Access Control (MAC) firmware used on the TPM FPGAs which is not discussed in this paper.

The formatter firmware is capable of implementing SPEAD Version 4, SPEAD-64-40 and SPEAD-64-48 implementation of SPEAD set at compilation time via Very-high-speed-integrated-circuits Hardware Description Language (VHDL) generics and is capable of generating four header types which are set at

¹<https://casper.berkeley.edu/>

compilation via VHDL generics depending on the source of the data stream to be transmitted and its required destination. To fully utilize the customized *immediate*² item fields SPEAD-64-48 is used in all implementations of the formatter used on the TPMs.

6.1. SPEAD header

In order to differentiate between the different types of streaming data generated by the TPMs a unique SPEAD header of 72 bytes is generated and transmitted with the data. The header format loosely follows the recommended practices (Manley *et al.*, 2012). The required Heap offset (item ID 0x0003), (Manley *et al.*, 2010), has been omitted and some item IDs are recommended to use *absolute* address references to the corresponding location in the payload data. Instead the *immediate* method has been used in order to reduce the header size and its effect on the overall bandwidth of the system.

Regardless of source of the incoming data-stream, the first five header fields following the header identifier field are common in all SPEAD formatter implementations and deviation from the SPEAD recommended practices are shown in Table 1.³

Table 1. First five SPEAD formatter header fields

a Field Index	Item ID	Hex Code	Item Field(s)
1	Heap Counter	0x0001	Logical Channel ID ^a , Packet Counter ^b
2	Packet Length	0x0004	Packet Payload Length ^c
3	Reference Time	0x1027	Unix Format Reference Time (s) ^d
4	Timestamp	0x1600	Timestamp (ns) ^e
5	Center Frequency	0x1011	Frequency (Hz) ^f

^a 2 bytes

^b 4 bytes

^c 6 bytes

^d Unix Time is 4 bytes but resized to 6 bytes to fill this field

^e No corresponding Time-Stamp scale (item ID 0x1027) used for Time-Stamp value as defined in (Manley *et al.*, 2012). Always assumed to be nano-second.

^f Immediate, integer value of Center Frequency - not an absolute addressed IEEE float 64 as defined in (Manley *et al.*, 2012)

Upon receiving the first t_{VALID} signal the formatter registers each of the header field/sub-field values required to complete the header. The source of these field values differ and can originate from:

- (i) VHDL generics configured at compile time;
- (ii) AXI-4 Stream side-channels (t_{USER} , 4 bytes wide);
- (iii) dedicated inputs to the SPEAD formatter VHDL component.

The sources for each field/sub-field are shown in Table 2. In order to simplify the memory addressing in software, all header input sources, regardless of source, are resized by the SPEAD formatter to fit the number of bytes allocated in the header item fields.

In addition to using t_{USER} , t_{ID} (1 byte wide) is used to connect to down-stream UDP MAC components and is used as an index to a preconfigured, via the AXI4-Lite Memory Mapped interface, Look Up Table (LUT) containing a list of MAC Addresses; Internet Protocol (IP) Addresses; and UDP Destination Ports. This allows TPMs to target specific destinations through network switches to:

²In the context of SPEAD the terms *immediate* and *absolute* refer to using the Most Significant bit (MSb) of the 64 bit wide header field as an indicator to flag whether the item field contains the data defined by the item ID (*immediate*, $MSb = 1$) or the offset address of the location within the payload data (*absolute*, $MSb = 0$).

³If the SPEAD recommended practices were followed the SPEAD header would have a total size of 88 bytes, plus the addition of a further 16 bytes of corresponding data embedded into the payload data, a total overhead of 104 bytes/packet regardless of the size of the payload data. Hence the non-standard optimizations made.

- (i) create the beamforming ring;
- (ii) send data to the CSP or the calibration subsystem of the Local Monitor and Control system;
- (iii) connect to station correlation hardware.

Table 2. SPEAD header field sources

Field	Sub-Field	Source
SPEAD Header	Magic Number ^a	VHDL Generic
SPEAD Header	SPEAD Version ^a	VHDL Generic
SPEAD Header	Item Identifier Width ^a	VHDL Generic
SPEAD Header	Heap Address Width ^a	VHDL Generic
SPEAD Header	<i>Reserved</i> ^b	VHDL Generic
SPEAD Header	No. of Header Items ^a	VHDL Generic
Heap Counter	Logical Frequency Channel ID ^b	$t_{USER}[28..13]$
Heap Counter	Packet Counter ^c	Dedicated Input
Packet Length	Packet Length ^d	Dedicated Input
Reference Time	Reference Time ^d	Dedicated Input
Timestamp	Timestamp ^d	Dedicated Input
Center Frequency	Center Frequency ^d	Calculated using Physical Frequency Channel ID ($t_{USER}[8..0]$)
CSP Channel Info	Beam ID ^b	$t_{USER}[12..9]$
CSP Channel Info	Physical Frequency ID ^b	$t_{USER}[8..0]$
CSP Antenna Info	Sub-Array ID ^a	Dedicated Input
CSP Antenna Info	Station ID ^b	Dedicated Input
CSP Antenna Info	No. of Contributing Antenna ^b	Dedicated Input

^a 1 byte^b 2 bytes^c 4 bytes^d 6 bytes

The Heap counter field (item ID 0x0001) is constructed using the logical channel ID, 2 bytes wide, and an externally incremented 4 byte wide packet counter. The logical channel ID is the identifier of the channel in one beam, which may contain a range of physical channels. The packet counter should be incremented for each packet being generated by the SPEAD formatter. This gives each packet a unique identity and can be used by the receiving logic on network connected systems, either FPGAs or server hardware, to handle out-of-order receiving of data and to determine the loss of packets.

The Center Frequency field (item ID 0x1011) is calculated by the SPEAD formatter by multiplying the channel spacing of 781.25 kHz, described in section 4, with the Physical Frequency channel ID taken from $t_{USER}[8..0]$. The calculated value is placed in the Center Frequency field as an integer value.

6.1.1. Additional SPEAD formatter header fields

In order to fulfill complete TPM functionality there are currently seven header field IDs which are used for transferring data:

- (i) between TPMs;
- (ii) to CSP;
- (iii) to LMC;
- (iv) to local station correlation hardware.

The SPEAD header item IDs, and their corresponding positions in the header, denoted by the Field Index, are shown in Table 3.

Table 3. Additional SPEAD formatter header fields

Field Index	Item ID	Hex Code	Item Field(s)
6	LMC Raw Data Info	0x2000	<i>Reserved</i> ^c ; Antenna Start ID ^a ; No. of Included Antenna ^a
7	LMC TPM Info	0x2001	TPM ID ^b ; Antenna Station ID ^b ; <i>Reserved</i> ^b
6	LMC Channel Info	0x2002	Start Channel ID ^c ; No. of Included Channels ^a ; Antenna Start ID ^a
7	LMC Antenna Info	0x2003	TPM ID ^b ; Antenna Station ID ^b ; No. of Contributing Antenna ^b
6	CSP Channel Info	0x3000	<i>Reserved</i> ^b ; Beam ID ^b ; Physical Frequency ID ^b
7	CSP Antenna Info	0x3001	<i>Reserved</i> ^a ; Sub-Array ID ^a ; Station ID ^b ; No. of Contributing Antenna ^b
8	CSP Sample Vector	0x3300	Payload Offset ^d

^a 1 byte^b 2 bytes^c 4 bytes^d 6 bytes - Fixed Value 0x000000

6.1.2. SPEAD formatter payload

For CSP sample vectors (item ID 0x3300), the payload data is presented in 8 byte words to the formatter. Starting from the Least Significant Byte (LSB), 1 byte time samples for each of the two polarities and the real and complex parts are transferred in the order shown in Table 4.

Table 4. SPEAD formatter payload fields for CSP Sample Vector (item ID 0x3300)

Word Index	MSB Byte 7	Byte 6	Byte 5	Byte 4	Byte 3	Byte 2	Byte 1	LSB Byte 0
0	$V_{POL}\Re_{[1]}$	$V_{POL}\Im_{[1]}$	$H_{POL}\Re_{[1]}$	$H_{POL}\Im_{[1]}$	$V_{POL}\Re_{[0]}$	$V_{POL}\Im_{[0]}$	$H_{POL}\Re_{[0]}$	$H_{POL}\Im_{[0]}$
1	$V_{POL}\Re_{[3]}$	$V_{POL}\Im_{[3]}$	$H_{POL}\Re_{[3]}$	$H_{POL}\Im_{[3]}$	$V_{POL}\Re_{[2]}$	$V_{POL}\Im_{[2]}$	$H_{POL}\Re_{[2]}$	$H_{POL}\Im_{[2]}$
2	$V_{POL}\Re_{[5]}$	$V_{POL}\Im_{[5]}$	$H_{POL}\Re_{[5]}$	$H_{POL}\Im_{[5]}$	$V_{POL}\Re_{[4]}$	$V_{POL}\Im_{[4]}$	$H_{POL}\Re_{[4]}$	$H_{POL}\Im_{[4]}$
...
1023	$V_{POL}\Re_{[2047]}$	$V_{POL}\Im_{[2047]}$	$H_{POL}\Re_{[2047]}$	$H_{POL}\Im_{[2047]}$	$V_{POL}\Re_{[2046]}$	$V_{POL}\Im_{[2046]}$	$H_{POL}\Re_{[2046]}$	$H_{POL}\Im_{[2046]}$

A total of 2048 time samples, representing the real and imaginary parts of a complex number for two polarizations, are streamed per SPEAD packet.

6.2. SPEAD receiver

To accommodate FPGA-to-FPGA connectivity a SPEAD receiver component has been developed. There is only one version of this component and it is able to determine the source of the incoming data-stream by examining the SPEAD header fields before outputting the payload data on the AXI4-Streaming master interface. SPEAD header field items are placed into the equivalent source locations defined by the SPEAD formatter. That is, the AXI4-Stream master t_{USER} is regenerated and the equivalent dedicated outputs are used. These master side outputs for header elements are registered on the first t_{VALID} assertion and held for the duration of the expected streaming data payload length, determined from the corresponding header field, which is delimited by the final t_{VALID} and t_{LAST} assertion. FIFOs are used on the AXI4-Streaming slave and master side interfaces to allow the crossing of clock domains and to handle changes in the internal t_{DATA} width of 64 bits, again defined by the SPEAD Specification (Manley *et al.*, 2010), to make the output width wider or narrower to match the clock/data width of the up-stream/down-stream component(s) connected to the SPEAD receiver.

7. Diagnostic and calibration functions

The TPM provides some diagnostic and calibration features. These features are used to set the appropriate gain in various points across the signal path, and to aid the station calibration algorithm.

More sophisticated features, including a test pattern generator, long frame ADC data capture, or a simple correlator, are present in dedicated personalities, that can be loaded in the FPGAs in maintenance mode.

7.1. ADC total power

The signal sampled from the ADC must remain in a definite range, with a Root Mean Square (RMS) amplitude comprised from 15 to 30 ADC units, in order to guarantee proper operations. Lower amplitude levels result in excess quantization noise at the high end of the spectrum, while higher amplitudes introduce nonlinearities due to clipping of the noise-like signal. Considering the possibilities of a sudden variation of the input signal due to RFI, it is advisable to keep the signal level around 19 ADC units. Therefore an almost continuous monitoring of the digitized total power is necessary.

Each ADC input has a dedicated total power detector, that integrates the digital power over a predefined number of input frames. The results are read by the monitor and control subsystem. The integration time can be configured from about 1 ms to a few seconds.

7.2. Coarse spectrum

The channelizer output from each antenna can be used to compute a coarse resolution spectrum, with a resolution of one spectral channel (781.25 kHz). At each time it is possible to compute the autocorrelation (total power) spectrum of one arbitrary antenna, or the cross spectrum between two arbitrary antennas. The coarse spectrum is used as an aid in the calibration procedure, while the cross correlation is used for diagnostic purposes.

7.3. Channelized data capture

Station level calibration is performed by cross correlating channelized samples from all antennas, and comparing the results with the expected results from a sky model. Details of the proposed calibration techniques are presented elsewhere, and the final calibration algorithm is still under study, but all these techniques rely on samples captured after the coarse channelization. Calibration is performed on a single spectral channel at a time, over a representative subset of the total observed channels. Calibration curves for each antenna are then derived by interpolating the calibration solution for the observed channels.

The channelized data capture module extracts samples for all antennas and polarizations for a single channel, and frames them in a SPEAD block for 128 8+8 bit complex samples, 32 signals. The resulting packets can be sent both on the control interface or on the high speed optical link. The average data rate is 0.5 Gbps, i.e. about 50% of the bandwidth of the control interconnection, or 1.3% of the bandwidth of the high speed link.

Captured data can be received using a fast UDP data capture library. Data format has been initially checked using the program *wireshark*, to confirm that the header format, data payload and size was conform to the expectations.

8. Firmware testing, implementation and performance

The firmware is composed of individual library modules, Each module is tested separately using a VHDL simulation engine with a specific testbench. The testbench generates a stimulus signal, that is either a tone, a set of tones, or a pseudo-random white noise. The control interface is simulated using a VHDL Axi4lite master emulator, that reads and writes data to disk files, Both input and output signals are recorded on files. A Matlab code then reads the input signals, process them in a functional model and compares the results to the VHDL simulation outputs. We use both a "golden standard" model, with floating point accuracy, and a fixed point model with requantization of the signal in a few critical points. The model is

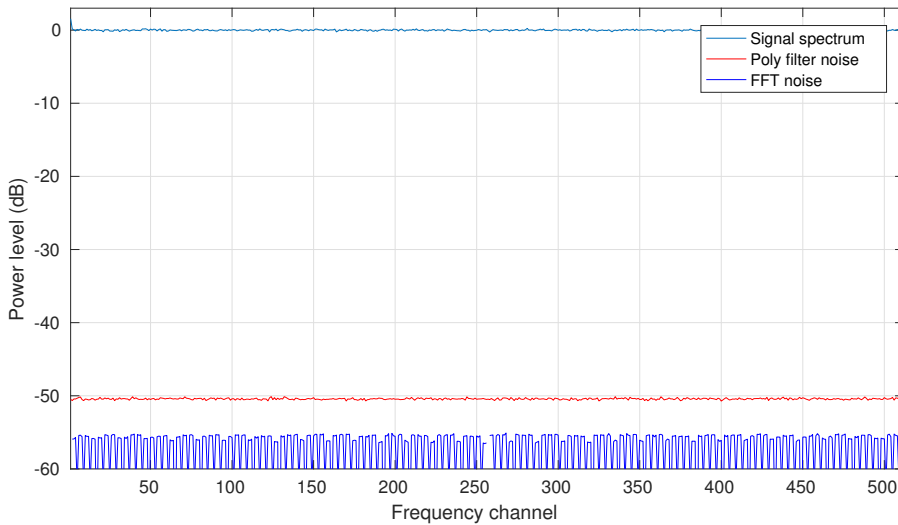


Fig. 6. VHDL simulation results for the polyphase channelizer. From top: channelized power, quantization noise power due to requantization in the polyphase filter and in the FFT. Power scale in dB with respect to the average power

not exact at the bit level, but differences are limited to details in the actual rounding. Noise performance is then analyzed statistically, comparing model and simulations with different quantization stages turned on and off.

An example of a simulation result, for the polyphase filterbank, is shown in figure 6. A pseudo-random white Gaussian noise, with a RMS level of 26 ADC units, has been used as the input signal. The measured power level in each spectral channel is shown in the top curve, both for the VHDL simulation and for the Matlab model (they are nearly identical). The quantization noise due to the polyphase filter and to the FFT stage has been derived by comparing the simulation and the model, and the noise power for these has been plotted respectively in the remaining two curves, about -51 dB and -55 dB with respect to the signal level.

8.1. Implementation results

A complete model for the firmware has also been generated, using a socket VHDL interface to control it from the actual control software.

Once all the modules have been validated at the functional level, the firmware has been implemented in a Xilinx XCKU040. Most of the synthesis has been performed using the Xilinx Vivado tool, but for some critical module an external synthesis tool (Synplify) has been used.

Resource utilization is summarized in table 5, and refers for 8 antennas (16 ADC channels), beamforming, and high speed Ethernet interface.

Resource	LUTs	Registers	Block RAM	DSP48
Channelizer	54k	91k	279	1343
Tile beamformer	21k	45k	97	400
Station beamformer	2k	2k	62	5
Other	73k	100k	97	0
Total	150k	238k	535	1748
% of available	62%	49%	89%	91%

Table 5. Resource utilization for one FPGA

The channelizer uses 81.5 multipliers per signal (163 every two signals), 56 for the polyphase filter, and 25.5 for the FFT. The synthesis tool has used some extra resources in the arithmetic blocks to improve the FFT closure time, for a total of 28 DSP blocks per FFT. The polyphase filter uses 151 RAM blocks, and the FFT 128, 8 (16 Kbyte total) per signal.

The beamformer uses 50 multipliers per signal. 2 are used to compute the current phase adjustment, 32 (8 complex) for the Jones matrix calibration and 16 (4 complex) for the phase adjustment.

Although individual components could be clocked at higher speed, e.g. the channelizer works for sample frequency up to 240 MHz, the whole design runs just above the required 200 MHz input frequency (800 MHz ADC sampling rate). A better placement is under study to increase the maximum clock speed.

8.2. *Channelizer performance*

The TPM has not yet been used in the field, and all tests have been performed using simulated signals in the laboratory, either an internal digital sinewave generator or external analog signals.

The channelizer filter shape have been analyzed using the internal sinewave generator, that produces a sinewave at full 8 bit scale with an arbitrary frequency. The signal frequency has been swept across three output channels, and the results compared with the filter bandpass of figure 5. The results are visible in figure 7.

The correspondence is very good, up to -75 dB. Below this level the quantization noise of the 8 bit digitized sinusoid produces a uniform spectral background noise, and a different signal must be used to assess larger filter attenuations.

A monochromatic tone from a good quality signal generator, with a frequency of 150 MHz and amplitude of 60 ADC units RMS has been used, added to a white noise with a RMS level of 0.72 ADC units. In this way the ADC operates in a noise-like regime, and the quantization process is very linear. The resulting channelized signal has been integrated for 4 seconds, using the on-board spectrometer, and the spectrum of the noise has then been subtracted. The resulting spectrum is shown in figure 8, both before and after the subtraction of the white noise spectrum, measured separately. The difference spectrum shows harmonics of the original tone, due to distortion in the analog amplifier, but not other spurious signal up to about -88 dB. No strong harmonics are present with low level input signals, or with the internal digital sinewave generator. The resulting noise floor is still dominated by compression in the analog amplifier, that prevents an accurate subtraction of the noise, and by the limited dynamic range (32 bits) in the spectrometer read-out. Further tests, with higher noise level, lower tone amplitude and much longer integration times, will be used to validate the expected -95 dB stopband rejection.

Quantization noise introduced by the design has been estimated using a VHDL simulation of the actual design. The simulation test signal is a Gaussian white noise of 26 ADC units RMS, and produces a flat channelized signal with a uniform RMS amplitude of 766 units. The VHDL model output has then been compared to an ideal floating point model of the filterbank. The total quantization noise has a RMS value of 5.2 units, i.e. an excess noise power of $4.5 \cdot 10^{-5}$. 80% of the noise power is due to the polyphase filter and 20% to the FFT. Considering an input RMS signal level comprised between 5 and 32 ADC units (the range required for a good linearity of the digitization process), the excess noise introduced by the channelizer is at most 0.12% of the signal intrinsic noise, and about 1/3 of the added noise in the 8 bit ADC converter.

8.3. *Beamformer performance*

The beamformer performance has been evaluated using a digital sinewave generator. The same sinewave is sent in parallel to all the tile inputs, using the input delay compensation stage to simulate a range of physical delays in the antenna signals and correcting them in the frequency domain. The resulting beamformed sinewave is compared to the sinewave produced by a single antenna, multiplied by the number of beamformed inputs. Simulated delays are in the range of ± 40 ADC samples, corresponding to a 38m diameter station observing at an elevation of 40 degrees, i.e. somewhat larger than those expected for a LFAA station. The simulation result is shown in figure 9. The graph shows the beamforming loss as a function of the frequency offset of the tone with respect to the frequency channel center. Frequency domain

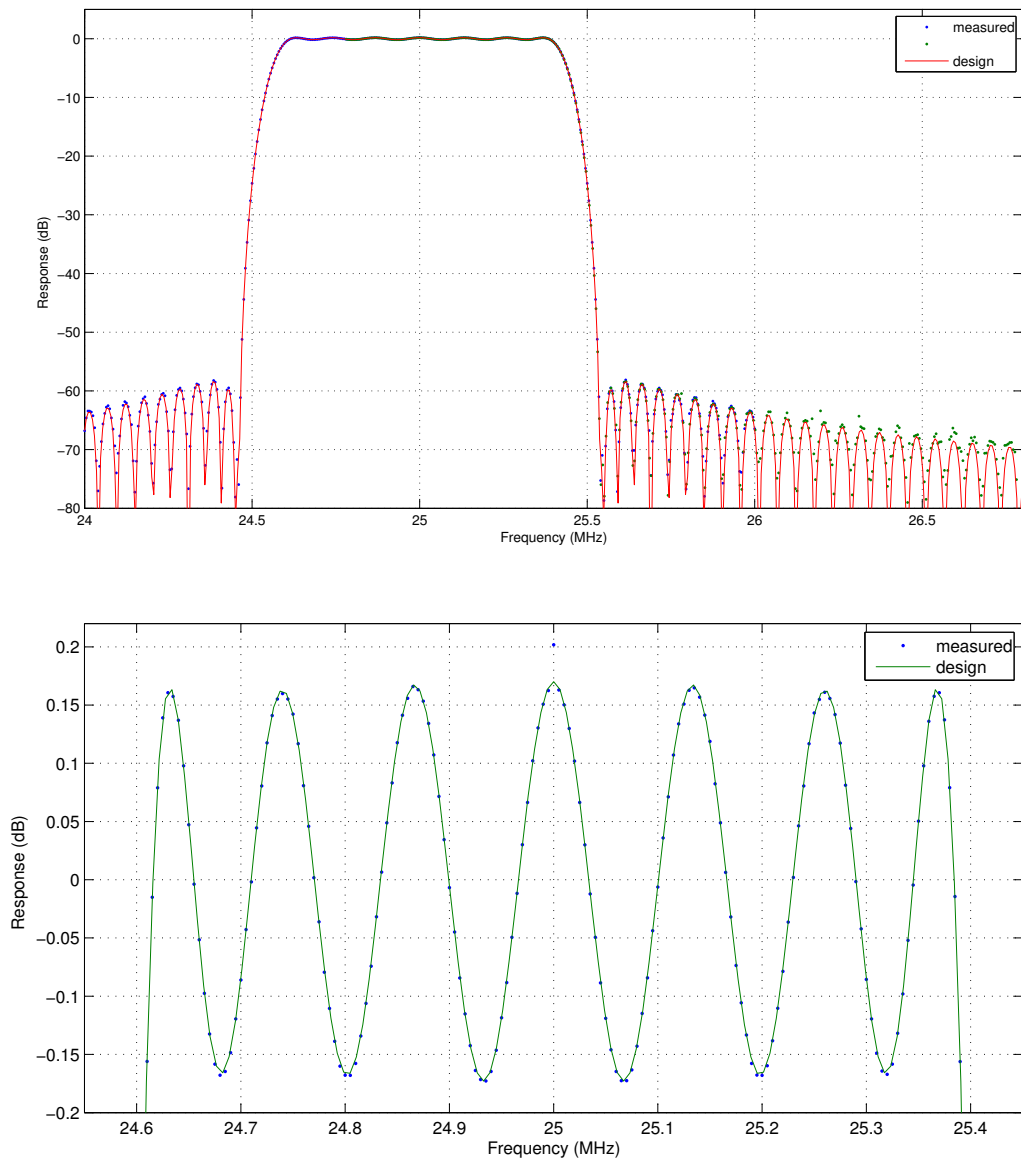


Fig. 7. Measured channel filter response. Lower figure is a zoom over the passband region. The continuous line represents the computed filter response, the points the measured values. Vertical scale in dB

beamforming is correct only for that frequency, and beamforming losses increase quadratically up to 0.033 dB at the channel edges. For comparison, the theoretic loss for this architecture is also shown.

The station beamformer has been verified using data patterns. When the same data pattern is generated in all the TPM belonging to a station, the resulting pattern at the end of the TPM chain consists of the starting pattern multiplied by the number of TPMs in the chain. The station data stream can be directed to a workstation where it can be acquired and verified. Alternatively, it can be transmitted back to the first TPM where a checker verifies the consistency of the data against the same pattern generated locally and multiplied by the number of TPM in the chain. In this way, using different types of patterns, it is possible to verify the operation of the station beamformer continuously for long period of time.

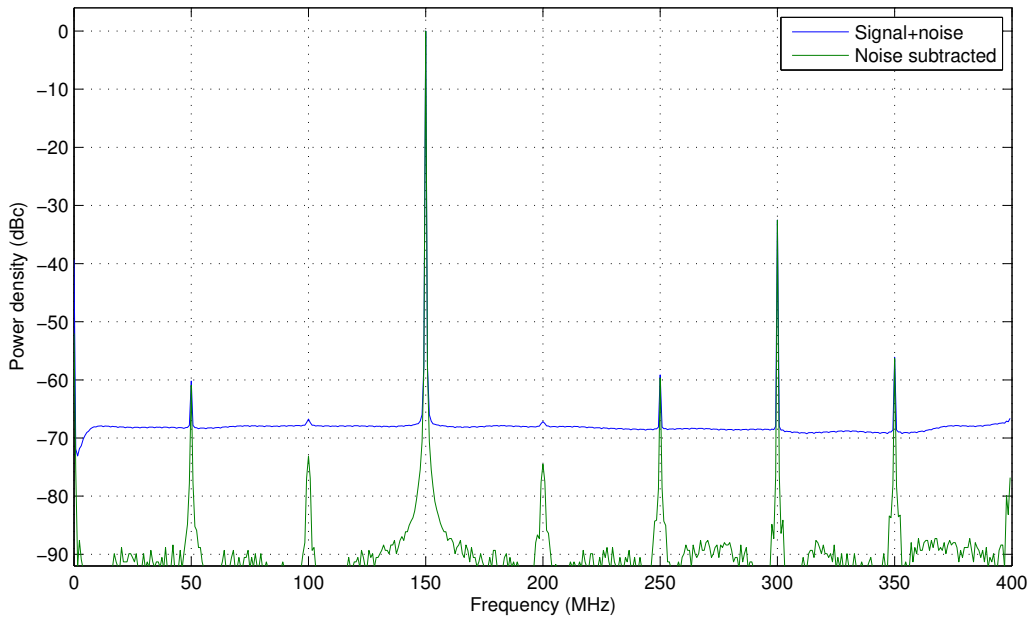


Fig. 8. Channelized power spectrum of an analog tone signal plus noise, with and without subtraction of the noise power

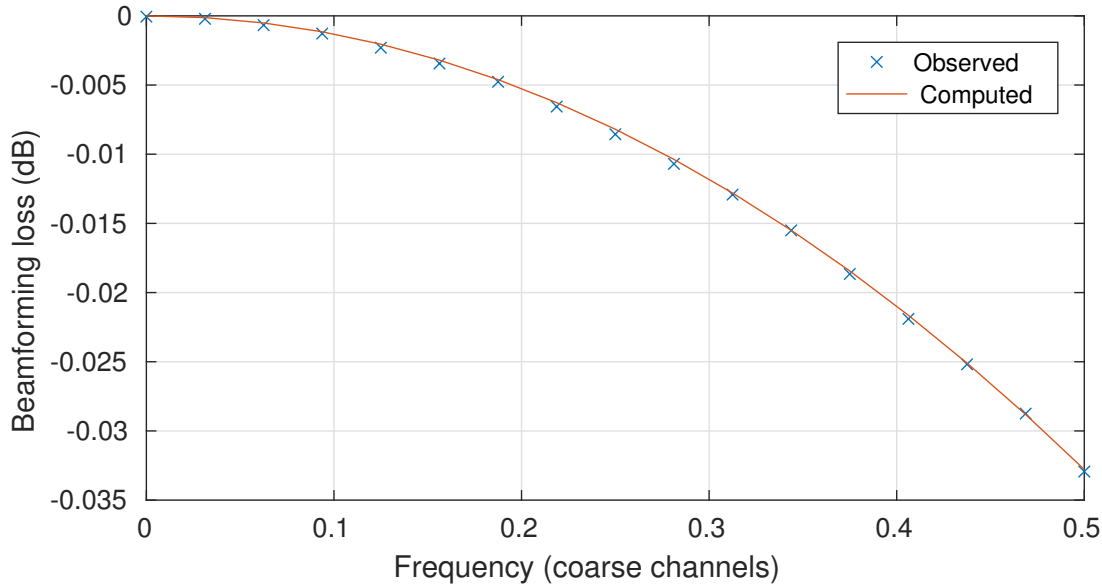


Fig. 9. Measured beamforming loss with respect to an ideal beamformer, as a function of the offset from the channel center

9. Conclusions

The firmware in the Tile Processing Module for the SKA Low Frequency Aperture Array implements a frequency domain beamformer, and the first stage of a high resolution spectroscopic channelizer. It allows for up to 8 independent simultaneous beams, with a total bandwidth of 300 MHz. Its innovative design for an oversampling channelizer allows for a seamless reconstruction of the observed band, and can be easily adopted in any channelization system with a very large (up to 10^7) number of channels. The distributed beamformer architecture allows for a dynamic reconfiguration of the antennas composing each station.

The design has been optimized for resource usage. In particular the filter performance is limited by the number of available hard multipliers in the adopted FPGA (Xilinx Kintex Ultrascale XCKU040). Fine tuning of the design will be required to reduce the power usage, a critical resource for the SKA telescope. We are looking to an alternative FPGA with more usable resources, reduced power consumption, or both.

The design has been tested by simulations, with the ADC, channelizer and tile beamformer already tested in the hardware. A first version of the complete design will be used as part of the Aperture Array Verification System demonstrator, in the first half of 2017 which will see the deployment of 400 antennas on the LFAA site.

Testing of the beamformer and digital firmware design will be carried out on both astronomical and artificial sources in order to validate the electromagnetic models of the station beam patterns. Should these tests be successful we envisage that the firmware will be deployed in the SKA-1 LOW system which will see the installation of 8192 of these digital boards capable of beamforming a total of 131072 antennas into 512 stations, before being correlated in a Central Signal Processing building.

The system will also be used at Sardinia Radio Telescope (SRT) site (Cagliari, Italy) as a channelizer/beamformer for the Sardinia Array Demonstrator (SAD) telescope, a system composed of 128 dual polarization Vivaldi antennas operating between 270 and 420 MHz, and in a beamformer for a phased array feed.

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