Architecture of C-band Phased Array Feed with RFSoC digital beamformer

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Abstract

We describe the architecture of a room-temperature C-band Phased Array Feed (PAF) demonstrator based on Radio Frequency System-on-Chip (RFSoC) for radio astronomy application. The instrument operates across the 4.75-6.00 GHz RF band (C-band). The RF section includes a compact module based on an 8×8 array of dual-polarization antennas integrated with MMIC (Monolithic Microwave Integrated Circuit) Low Noise Amplifiers (LNAs). A subset of 32 elements of one of the two polarization channels of the 128 antennas are connected to the LNAs, while the rest are terminated into internal loads. Following two stages of filtering and signal conditioning, the 32 RF signals are injected in two commercial RFSoC digital boards, each accepting 16 inputs with 1.25 GHz bandwidth, that will perform the frequency channelization, the partial and final beamforming of four independent beams with 1.25 GHz instantaneous bandwidth.

1. Introduction

High-sensitivity large-scale surveys are an essential tool for new discoveries in radio astronomy. A PAF placed at the focal plane of an antenna can increase the Field-of-View (FoV) and the mapping efficiency by fully sampling the sky [1]-[2]-[3]. A PAF consists of closely packed antenna elements with about half wavelength element separation that, by spatially sampling the focal plane, can synthesize multiple independent beams and be set to Nyquist-sample the sky. Multiple beams are formed by electronically adding the signals from different groups of radiating elements of the array. An antenna element can contribute to form multiple beams. The properties of the beams can be optimized over a wide range of frequencies by electronically controlling each element phase and amplitude (complex weights) leading to high aperture efficiency and low spillover.

We are building on our successful experience with the development of the PHAROS (PHased Arrays for Reflector Observing Systems) cryogenically cooled C-band PAF demonstrator with analogue beamformer [4]-[5] (Fig. 1) and on its upgrade, PHAROS2 [6]-[7], utilizing a Warm Section (WS) multi-element downconverter [8]

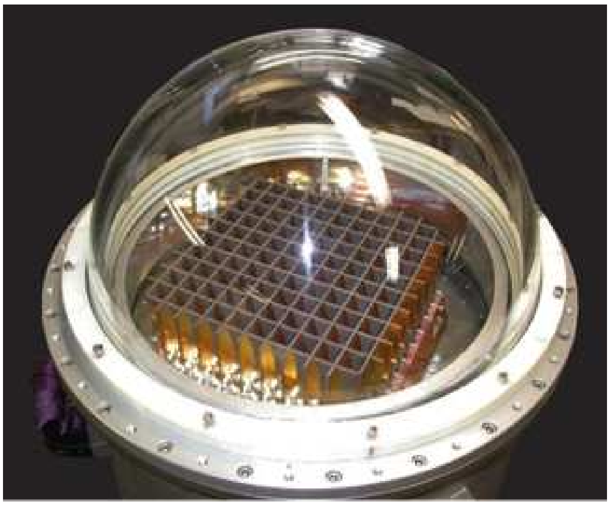

Figure 1. C-band PHAROS array showing the 10×11 dual polarization Vivaldi antennas through half-dome Plexiglas vacuum window.

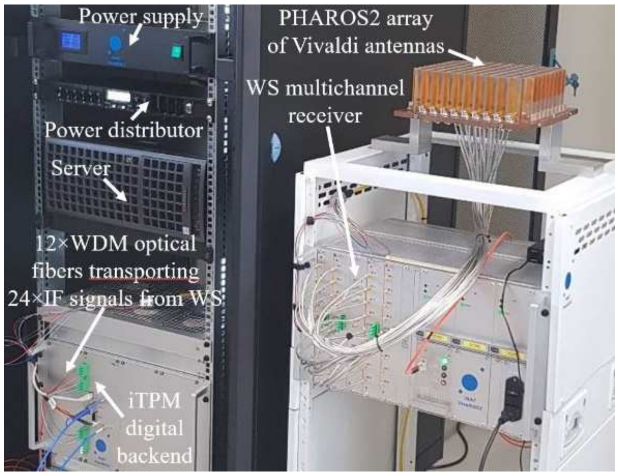

Figure 2. PHAROS2 hardware used for analog signal treatment (C-band array of Vivaldi antennas, Warm Section multichannel receiver and pre-Analogue to Digital Unit) and digital beamforming by the iTPM backend, based on Field Programmable Gate Arrays (FPGAs).

and a 275 MHz bandwidth digital beamfomer [9]-[10] based on the iTPM Italian Tile Processing Module [11] (Fig. 2), to design a new PAF demonstrator with digital beamformer capable of delivering an instantaneous bandwidth of 1.25 GHz. The design takes advantage of the performance of the Xilinx Zynq UltraScale+ RFSoC technology, which currently allows signal digitization and processing with maximum input frequency up to 6 GHz. Unlike PHAROS2, which adopts a Warm Section, the new PAF architecture allows direct sampling of the RF signals, thus eliminating the need of a downconversion stage, with great benefits in terms of engineering complexity, mechanical compactness and costs.

We describe our plans and the architecture for the new C-band PAF demonstrator we are designing for 4.75-6.00 GHz. The instrument will be placed at the focal plane of a large radio telescope. The prototype instrument will be based on RFSoC and will deliver four independent digitally formed beams with 1.25 GHz bandwidth. The PAF architecture is scalable in terms of number of array elements, number of beams and instantaneous bandwidth. The demonstrator will operate at room temperature. However, the design will consider aspects related to cryogenic operation, in view of designing a broadband 3.0-7.7 GHz low-noise PAF with >30 beams per polarization and >1 GHz bandwidth for the 64 m diameter Sardinia Radio Telescope [12], as required to perform high-sensitivity large scale radio astronomy surveys [13]-[14]. The PAF will also be employed for space debris studies [15]. The adopted technologies could find application in the Square Kilometer Array project [16].

2. Architecture of the C-band PAF with RFSoC

Figures 3 and 4 show a simplified schematic of the array and the full architecture of the PAF, respectively. The PAF architecture adopts 32 identical RF signal chains, each of which is composed of an antenna integrated with a MMIC LNA and with a 4.75-6.00 GHz filter cascaded with an analog signal conditioning module. The signals are injected in two Xilinx ZCU216 RFSoC boards for digitization and beamforming. The two digital boards communicate through a network switch. Data are stored in a PC.

3. PAF digital signal processing with RFSoC

Each Xilinx ZCU216 RFSoC (Fig. 5) is capable of acquiring and processing up to ≈1.25 GHz bandwidth RF streams from 16 single-polarization antennas, using a 2.5 GS/sec sampling rate. Each sample is coded with 14 bits.

Therefore, each board manages 560 Gbps and process the signals to accommodate its maximum I/O throughput of 100 Gbps, available through 4 x 25 Gbps Ethernet interfaces (QSFP). Data processing will include channelization of the sampled data for each antenna based on an oversampling polyphaser filterbank architecture and beamforming. Each ZCU216 produces four beams that are added in one of the two boards (for example #1 of Fig. 2). The four complete beams are formed and retrieved from the second ZCU216 (#2 of Fig. 2). The 100 Gbps switch is not needed if only the integrated beams are of interest.

The digital processing architecture is similar to the one of PHAROS2, described in [9].

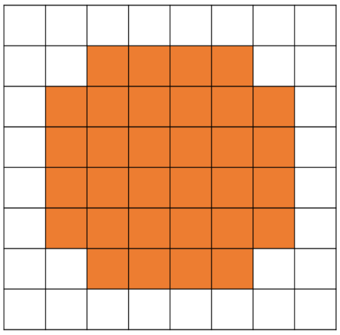

Figure 3. Simplified schematic of the 8×8 array of antennas to be placed at the focal plane of a large radio telescope. Each element will be sensitive to two orthogonal linear polarization signals. The inner 32 antenna elements (in orange) are active, i.e. cascaded with MMIC LNAs. The outer elements (in white) are dummy.

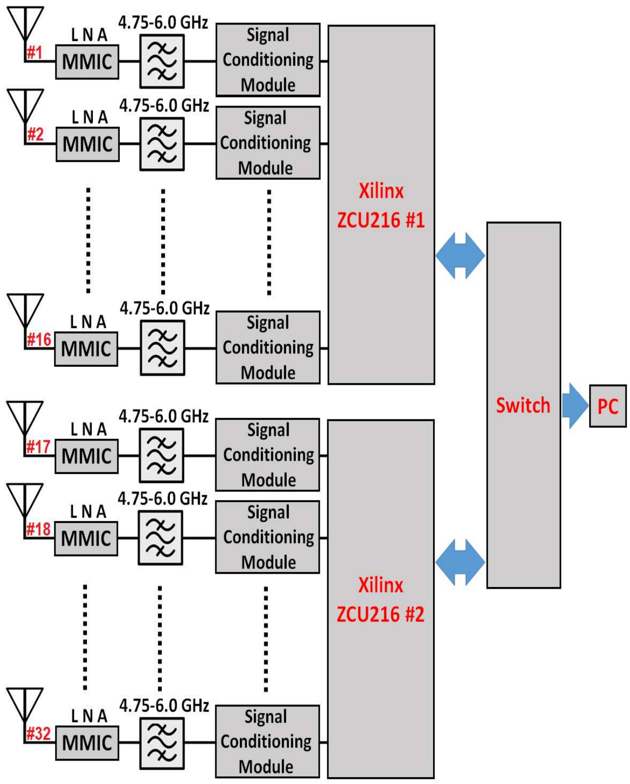

Figure 4. Block diagram of the 4.75-6.00 GHz PAF showing the 32 RF signal chains and the two digital RFSoC boards connected to a 100 Gbps network switch and a PC.

4. Conclusions

We described the architecture of a C-band PAF demonstrator with digital beamformer based on RFSoC. The demonstrator will be capable of forming four independent RF beams over an instantaneous bandwidth of 1.25 GHz.

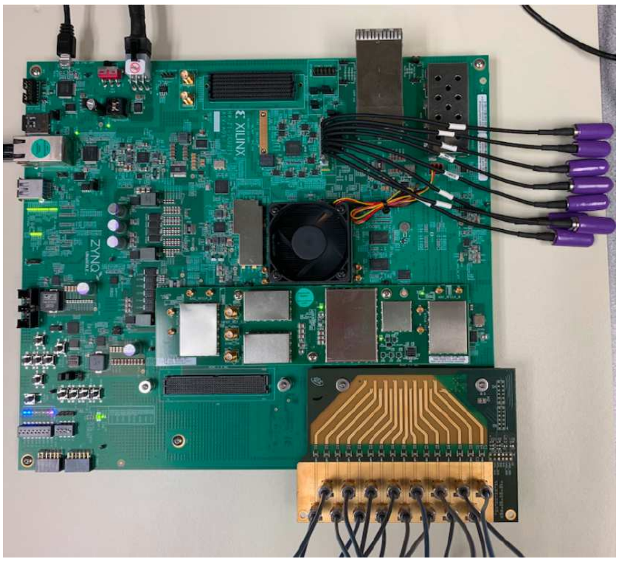

Figure 5. Picture of one Xilinx ZCU216 RFSoC evaluation kit. A mezzanine board, shown on the lower right side, will be used to connect the ZCU216 with the RF module (outputs of the signal conditioning modules).

5. Acknowledgements

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