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A Single RFSoC-based 4-channel Wideband Digital Backend for Pulsar Observation

Chenye Zhou*(1), Qiao Meng(1), Chen Wang(2), Wei Liu(3), Congyan Chen(1), Shaocong Guo(1), Gaojing Li(1) and Jianxun Shao(1)

(1) Institute of RF- & OE-ICs, Southeast University, Nanjing, China

(2) National Astronomical Observatories, Chinese Academy of Sciences, Beijing, China

(3) Department of Astronomy, University of California Berkeley, Berkeley, California, USA

Abstract

Pulsar observation is a critical tool for exploring the universe, necessitating advanced digital backends to efficiently capture and process faint pulsar signals. This paper introduces a 4-channel wideband digital backend for pulsar observation, with each channel featuring dual polarization and a maximum bandwidth of 2 GHz. The system is capable of simultaneously processing multiple signal bands, with a total bandwidth up to 8 GHz, and employs Bartlett's method for power spectrum estimation. The design divides 8 high-speed data streams from ADCs into 32 low-speed data streams to reduce power, while a specialized combined Fast Fourier Transform (FFT) unit with bit-reversed order is utilized to minimize resource consumption. This approach yields a compact and power-efficient solution integrated into a single Radio Frequency System on Chip (RFSoC). The backend fully utilizes the hardware resources and supports multiple observation modes, offering flexible bandwidth and frequency resolution options. The system's performance has been validated through on-site telescope observations, confirming its capability to reliably acquire and process pulsar signals.

1 Introduction

Pulsar observation is essential for unraveling the mysteries of the universe, driving the development of numerous advanced digital backends designed to efficiently capture and process faint pulsar signals. A multitude of wideband FPGA-based backends have been developed. For instance, PDFB4 boasts a maximum bandwidth of 1024 MHz [1], and a digital backend with a 1.2 GHz bandwidth is detailed in [2]. However, these systems are customized to process signals from a single band. To encompass the entire bandwidth of a telescope, multiple digital backends may be necessary, leading to an unwieldy observation system and potential synchronization challenges between backends. Systems featuring a heterogeneous architecture, integrating an interconnected network of GPUs and FPGAs, have also been devised such as HIPSR [3] and UWLPIPE [4]. In these systems, FPGAs serve solely as polyphase filter banks (PFBs) to channelize the wide band of signal into multiple subbands, while GPUs are employed to process the subband data for pulsars. This method enables the processing of wider bandwidth and benefits from the flexibility of GPU programming. However, the power consumption of GPUs is exceedingly high. With the continuous advancements in integrated circuit technology, RFSoC offers the opportunity to design more compact and power-efficient systems with ADCs, programmable logic and embedded processors on a single chip. A pulsar digital backend based on RFSoC, featuring a 512 MHz bandwidth, is presented in [5]. It employs PFB followed by correlation and integration to derive the power spectrum of pulsar signals. Nevertheless, an RFSoC chip can accommodate eight RF inputs, yet the backend design processes only a single signal band, leaving the full potential of RFSoC untapped.

This paper introduces a 4-channel wideband digital backend for pulsar observation utilizing a single RFSoC chip. Capable of simultaneously processing multiple signal bands, it computes the power spectrum of pulsar signals using Bartlett's method. The resources of the RFSoC are fully harnessed, achieving optimal functionality while maintaining relatively low power consumption. Section 2 delineates the design of the digital backend. The 4-channel backend was tested on the Jiamusi 66 m telescope, and the observation results are presented in Section 3. The conclusion is drawn in Section 4.

2 Design of the Digital Backend

The block diagram of the pulsar observation system with the 4-channel wideband digital backend is depicted in Fig. 1. The telescope's signal is divided into four observation channels, each with distinct frequency ranges. Each channel encompasses signals from two polarizations. The digital backend is capable of processing all four channels simultaneously. The maximum bandwidth for each channel is 2 GHz, resulting in a total bandwidth up to 8 GHz. The channel bandwidth is determined by the ADC sampling rate and can be adjusted to meet specific requirements. The currently available observation modes are given in Table 1. The output from the digital backend is transmitted to the data recording server via optical fibers. The detailed design of the digital backend is presented in Fig. 2 and will be elaborated upon in the following sections with the 2000 MHz mode as an example.

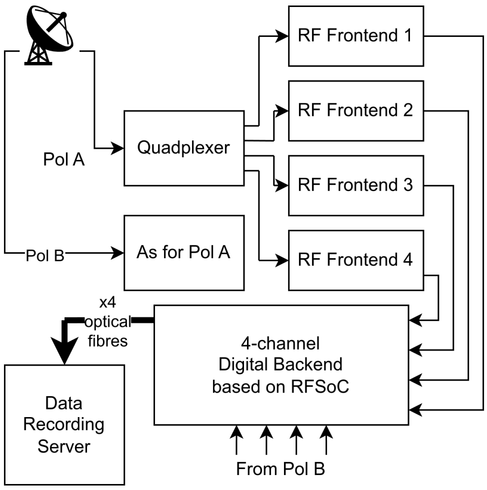

Figure 1. The pulsar observation system.

Table 1. Available observation modes

Single channel Bandwidth (MHz)	Frequency Channels	Highest Time Resolution (us)	Frequency Resolution (MHz)
1200	512	6.827	2.344
	1024	13.653	1.172
	2048	27.307	0.586
2000	512	4.096	3.906
	1024	8.192	1.953
	2048	16.384	0.977

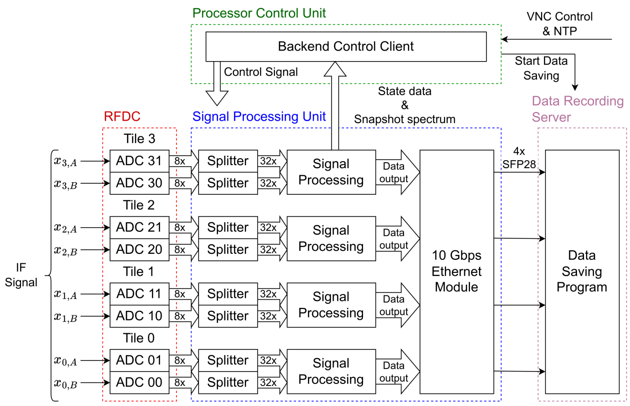

Figure 2. The structure of the entire digital backend system.

2.1 RF Data Converter

Prior to further signal processing, the signal must first undergo digitisation, a task traditionally requiring an external ADC. The adoption of RFSoC eliminates the necessity for external ADCs and circumvents FPGA input port timing issues. Within the RFSoC, eight ADCs are available, which we utilize to digitize the signals of four observation channels, each with two polarizations. As illustrated in Fig. 2, the RF data converter (RFDC) internally transforms the signals into a parallel output of 8 data streams at 500 MSps with 12-bit resolution, achieving a total sampling rate of 4 GSps. The data are then fed into the signal processing unit.

2.2 Signal Processing Unit

The signal processing unit is implemented on the programmable logic (PL) of RFSoC. If the data streams from RFDC are processed directly, the PL must operate at a clock rate of 500 MHz which will cause power consumption and timing issues. The core power supply voltage for PL is 0.85 V, with a maximum current limit of 50 A, as specified by the Power Design Manager. This imposes a power limit of 42.5 W and makes the 4-channel design unattainable. Reducing the clock rate can substantially decrease the dynamic power consumption. As a result, the signal processing unit first divides the 8 parallel data streams from the RFDC into 32 data streams at 125 MSps using a splitter. This adjustment allows the PL to operate at a lower clock rate of 125 MHz, which significantly reduces the dynamic power. The on-chip power consumption for the 2000 MHz bandwidth mode is detailed in Table 2. As evident, the reduced clock rate results in relatively low power consumption, remaining below 30 W to reserve sufficient design margin.

Table 2. On-Chip Power Consumption

Bandwidth (MHz)	Freq. Channels	Power (W)
2000	512	21.291
	1024	23.387
	2048	27.044

However, the reduced clock rate requires parallel signal processing of more data streams which can consume more resources. As a result, the signal processing procedure is carefully designed to save resources. The block diagram of the single-channel signal processing procedure is presented in Fig. 3. The initial step involves applying a Hanning window to mitigate spectral leakage of FFT with 32 real-valued data streams. The second step is a parallel complex FFT. Here, the two polarization signals $x_A(n)$ and $x_B(n)$ are treated as the real and imaginary components of a complex signal $x(n)$, respectively. Suppose the N-point FFT results of these three signals are $X_A(k)$, $X_B(k)$ and $X(k)$. Due to the conjugate symmetry of $X_A(k)$ and $X_B(k)$, we can derive the following relationship:

$$\begin{cases} X_A(k) = \frac{1}{2}(X(k) + X^*(N-k)) \\ X_B(k) = -\frac{j}{2}(X(k) - X^*(N-k)) \end{cases} \tag{1}$$

As a result, only a single combined FFT unit is required, followed by a decomposition unit to obtain the FFT results of two polarizations in one channel. Also, the output of FFT IP core is set to bit-reversed mode in order to save additional RAM resources. This design eventually results in

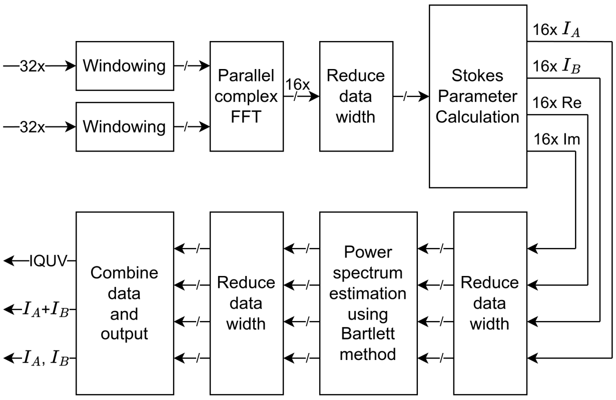

Figure 3. Block diagram of the single-channel signal processing procedure.

a reduction of approximately 40% LUT resources and 45% BRAM resources. Due to the conjugate symmetry characteristic of FFT, only half of the data streams are retained in this step, and the data are complex-valued. The third step involves the calculation of Stokes parameters. The following four parameters are computed:

$$\begin{cases} I_A = |X_A|^2 \\ I_B = |X_B|^2 \\ Re = Real(X_A^* \times X_B) \\ Im = Imag(X_A^* \times X_B) \end{cases} \quad (2)$$

where X_A and X_B represent the FFT results of the two polarizations. The actual Stokes parameters, regardless of the coordinate system used, can be accurately derived from these values. The fourth step is power spectrum estimation, achieved using Bartlett's method. The number of sequences to average is configurable, allowing for adjustable time resolution in pulsar observations. The final step involves combining the data and generating the output. A buffer RAM is required to prepare the data for Ethernet transfer at this step, and the bit-reversed FFT output order is resolved within this process. As depicted in Fig. 3, three output modes are available and the data width can be selected with 8 or 16 bits. After each processing step, the data width may increase, impacting both power consumption and hardware resources. To address this, a data width reduction unit is incorporated to ensure that the input for each step remains 16-bit. The data scale is dynamically controlled by the processor control unit. The resource utilization is demonstrated in Table 3. The design of the digital backend fully leverage the available resources, reaching 96.25% utilization of DSPs with 2048 frequency channels. Following the signal processing unit, the data is transmitted to the data recording server via a 10 Gbps Ethernet module. The comparison with existing FPGA-based backend is shown in Table. 4.

2.3 Processor Control Unit

The processing system (PS) of the RFSoC functions as a processor control unit. The digital backend control client is designed to operate directly on the PS, utilizing an embedded Ubuntu system. The client can be accessed remotely via VNC, and an NTP server is connected to the PS to ensure accurate time synchronization. The user interface of the client is illustrated in Fig. 4. The first function of the client is to configure the telescope characteristics and select the observation mode. The PL is dynamically reconfigured for different observation modes. Another critical function of the client is to monitor the operational status of the PL. In addition to basic temperature and voltage information, the data scale at each step depicted in Fig. 3 is also monitored. This enables the user to control the data width reduction process effectively. The third function of the client is to display the real-time power spectrum. The spectrum is refreshed every second by capturing a snapshot of the data in the PL. A histogram plot is also provided to illustrate the distribution of signal amplitude, allowing the user to verify the proper functioning of the digital backend. The final function of the client is to set the parameters of the pulsar under observation and manage the data-saving process. The client utilizes SSH to instruct the data save control server to initiate data saving.

Table 3. Resource Utilization

Freq. Channels	512	1024	2048
LUT%	60.11	68.31	82.22
LUTRAM%	16.72	21.53	28.26
FF%	51.70	58.01	69.34
BRAM%	45.92	45.93	51.85
DSP%	82.77	84.27	96.25

Table 4. Comparison with existing FPGA-based backends

Backend	Maximum Bandwidth (MHz)	Maximum Freq. Channels
PDFB [1]	1024	8192
Liu's work [2]	1200	2048
Ergesh's work [5]	512	512
This work	8000	8192

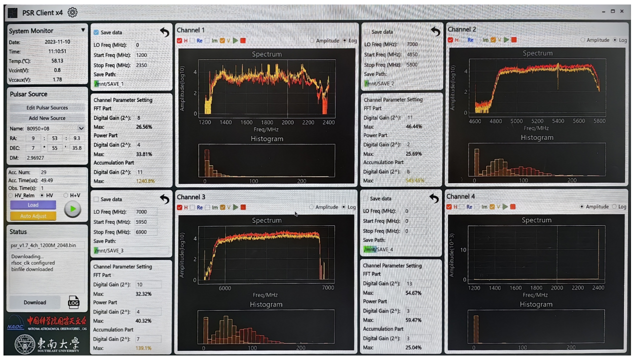

Figure 4. Client user interface of the digital backend.

2.4 Data Recording Server

The maximum data transfer rate from the programmable logic (PL) exceeds 8 Gbps, necessitating high-performance network packet processing. To meet this requirement, we employ the Data Plane Development Kit (DPDK) to develop the data-saving program. DPDK provides a user-space driver for the network interface card (NIC) with zero-copy capability, enabling efficient handling of the data transfer demands. Once the control client on the processing system (PS) selects an observation mode, four data-saving programs are initiated remotely in the background via SSH. The DPDK data-saving programs launched on the PS are illustrated in Fig. 5. These programs remain in a listening state, awaiting the start signal from the control client. The observation data are saved in the standard FITS format.

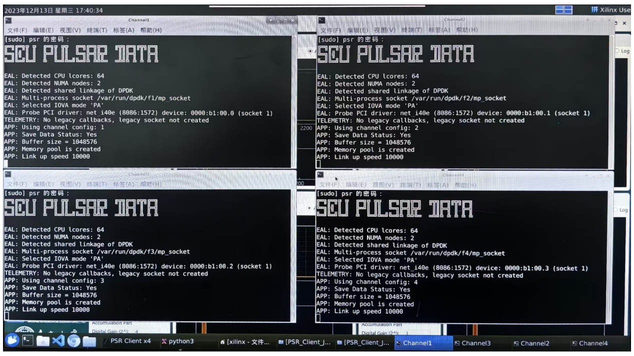

Figure 5. DPDK data-saving program for the 4 channels.

3 The Observation Result

The 4-channel wideband digital backend has been successfully installed on the Jiamusi 66 m telescope. Three channels of the digital backend are utilized, corresponding to the frequency ranges of 1.20–2.35 GHz, 4.85–5.80 GHz, and 5.95–6.90 GHz. The real-time signal spectrum is displayed in Fig. 4. To validate the functionality of the digital backend, a pulsar observation experiment was conducted on November 11, 2024. The pulsar B0329+54 was observed, and the recorded data were processed using the DSPSR software. The observation results for the first channel are illustrated in Fig. 6. The successful detection of pulsars confirms the operational efficacy of the digital backend.

4 Conclusion

In this paper, we have successfully implemented a 4-channel wideband digital backend for pulsar observation fully utilizing the resources of a single RFSoC chip. The system achieves simultaneous processing of four signal bands with dual polarization and a total bandwidth of up to 8 GHz. It offers flexible observation modes and efficient power spectrum estimation. The Stokes parameters are also calculated. The single-chip design adopts combined FFT units to save resources and splits high-speed data streams to achieve an on-chip power below 30 W. This offers a scalable and highly efficient solution for pulsar observation.

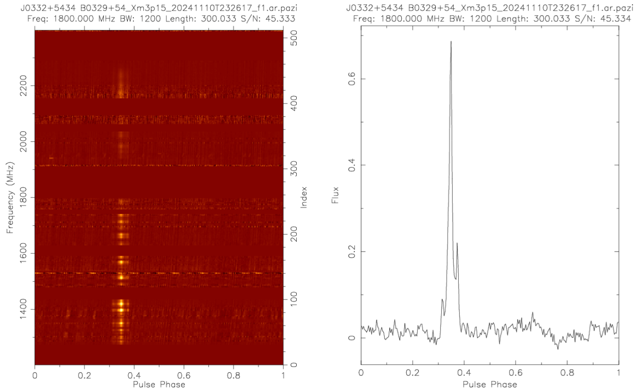

Figure 6. Observation result of B0329+54 on channel 1.

The successful execution of observation experiments has validated the system's functionality and performance, representing a notable advancement in the field of wideband pulsar signal processing.

5 Acknowledgements

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