Research on Ultra-wide Bandwidth Low-frequency Signal Channelization for Xinjiang 110 m Radio Telescope Postprint

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Abstract

Aiming at the subband division of the ultra-wide bandwidth low-frequency (UWL) signal (frequency coverage range: 704–4032 MHz) of the Xinjiang 110 m QiTai radio Telescope (QTT), a scheme for ultra-wide bandwidth signal processing is designed. First, we analyze the effect of different window functions, such as the Hanning window, Hamming window, and Kaiser window, on the performance of finite impulse response (FIR) digital filters, and implement a critical sampling polyphase filter bank (CS-PFB) based on the Hamming window FIR digital filter. Second, we generate 3328 MHz simulation data of ultra-wideband pulsar baseband in the frequency range of 704–4032 MHz using the ultra-wide bandwidth pulsar baseband data generation algorithm based on the 400 MHz bandwidth pulsar baseband data obtained from Parkes CASPSR observations. Third, we obtain 26 subbands of 128 MHz based on CS-PFB and the simulation data, and the pulse profile of each subband by coherent dispersion, integration, and folding. Finally, the phase of each subband pulse profile is aligned by non-coherent dedispersion, and a broadband pulse profile is generated, which is basically the same as the pulse profile obtained from the original data using DSPSR. The experimental results show that the scheme for the QTT UWL receiving system is feasible, and the proposed channelization algorithm in this paper is effective.

Full Text

Preamble

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Research on Ultra-wide Bandwidth Low-frequency Signal Channelization for Xinjiang 110 m Radio Telescope

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Abstract

We present a channelization scheme for the ultra-wide bandwidth low-frequency (UWL) signal of the Xinjiang 110 m Qitai Radio Telescope (QTT), covering the frequency range of 704–4032 MHz. First, we analyze the effects of different window functions—including the Hanning, Hamming, and Kaiser windows—on the performance of finite impulse response (FIR) digital filters, and implement a critical sampling polyphase filter bank (CS-PFB) based on a Hamming-window FIR digital filter. Second, using the ultra-wide bandwidth pulsar baseband data generation algorithm, we produce 3328 MHz of simulated ultra-wideband pulsar baseband data spanning 704–4032 MHz, based on 400 MHz bandwidth pulsar baseband data from Parkes CASPSR observations. Third, we apply the CS-PFB to this simulation data to obtain 26 contiguous subbands of 128 MHz each, and derive the pulse profile for each subband through coherent dedispersion, integration, and folding. Finally, we align the phases of all subband pulse profiles using incoherent dedispersion to generate a broadband pulse profile that is essentially identical to that obtained from the original data using DSPSR. Our experimental results demonstrate that the proposed scheme for the QTT UWL receiving system is feasible and that the channelization algorithm is effective.

Key words: pulsars: general – methods: data analysis – techniques: miscellaneous

1. Introduction

Radio telescopes receive extremely weak cosmic radio signals, which are processed and analyzed to extract information about the position, velocity, temperature, density, and chemical composition of celestial sources. These instruments have broad applications in cosmology, astrophysics, and planetary science, and play a crucial role in investigating dark matter, dark energy, gravitational waves, and cosmic microwave background radiation \cite{Marr_{2015}}.

To maximize sensitivity, the bandwidth of front-end receiving systems has evolved toward wideband and ultra-wideband configurations. For example, the Australian 64 m Parkes radio telescope employs ultra-wideband receivers covering 0.7–4.0 GHz \cite{Johnston_{2021}}, the German Effelsberg 100 m telescope covers 0.6–3.0 GHz \cite{Lazarus_{2016}}, the U.S. Green Bank Telescope uses 0.5–3.0 GHz ultra-wideband receivers for pulsar timing \cite{MacMahon_{2018}}, and China's Five-hundred-meter Aperture Spherical Telescope (FAST) is equipped with ultra-wideband receivers spanning 500–3300 MHz \cite{Zhang_{2023a}}. Ultra-wide bandwidth enables coverage of broader frequency ranges and collection of more radio signals, thereby effectively improving telescope sensitivity. Such systems also provide higher frequency and time resolution, along with wider dynamic range to detect fainter celestial signals and transient events.

To meet the demands of high-precision radio astronomical observations, backend digital systems must process increasingly wide bandwidths in real time with higher temporal and spectral resolution. An ultra-wideband receiving system with 2 GHz bandwidth, dual polarization, and 16-bit quantization generates 128 Gb of data per second—far beyond the capacity of single-channel communication equipment for real-time transmission and processing. Channelization technology addresses this challenge by decomposing wideband signals into multiple adjacent subbands that can be processed in parallel, thereby reducing backend system pressure and improving signal processing efficiency \cite{Morrison_{2020}}.

Digital channelization is theoretically based on filtering algorithms. Traditional methods rely on discrete Fourier transform (DFT) filters, typically implemented using fast Fourier transform (FFT) algorithms. However, DFTs suffer from spectral leakage and cannot achieve high-precision channelization \cite{Ghandour_{2020}}. Polyphase filter bank (PFB) channelization has become the mainstream approach due to its flexibility and efficient implementation on field-programmable gate array (FPGA) platforms. In recent years, with the deployment of ultra-wideband receiving systems, PFB-based channelization has emerged as a key research area.

The Parkes ultra-wideband low-frequency (UWL) project divides the 704–4032 MHz signal into three RF bands, which are further split into 26 contiguous 128 MHz subbands using FPGA-based processing. The preprocessing stage employs a critical sampling polyphase filter bank (CS-PFB) for subband division, removing 5 MHz from each subband boundary to eliminate edge aliasing. Parkes UWL plans to adopt an oversampled polyphase filter bank (OS-PFB) in the future to solve inter-subband aliasing, though this technology remains under development \cite{Hobbs_{2020}}. Burnett et al. \cite{Burnett_{2020}} described the Arecibo digital backend design, which planned to use 18 ZCU111 boards with 2048-point oversampling PFBs for subband division and spectral leakage suppression, but no further progress has been reported. The Australian Square Kilometre Array Pathfinder digital backend employs a two-stage PFB: signals from 188 PAF receivers at 384 MHz bandwidth are processed first by an OS-PFB with a 32/27 sampling rate, then by a CS-PFB \cite{Tuthill_{2015}}. The Murchison Widefield Array uses two-stage channelization with CS-PFBs for its 80–300 MHz band, resolving aliasing by discarding some bands \cite{Ord_{2015}}.

The Qitai Radio Telescope (QTT) will adopt world-leading technologies to address major scientific challenges such as gravitational wave detection, the molecular origins of life, dark matter, and black hole research, establishing a world-class platform for breakthroughs in radio astronomy while supporting national strategic needs in defense and space exploration \cite{Wang_{2023}}.

Achieving QTT's multi-science objectives requires continuous advances in ultra-wideband reception and multifunctional digital backend technologies, guided by QTT's operational needs and future data processing directions. The QTT UWL receiving system is planned to cover 704–4032 MHz with 12-bit ADC sampling and dual polarization. Like other systems, it will face significant challenges, including radio frequency interference and the real-time transmission and processing of massive data streams generated by ultra-wideband signals.

In this paper, we analyze the ultra-wideband scheme for the QTT UWL receiving system, planning to divide the ultra-wideband signal into three contiguous analog bands that are further split into 26 narrow bands of 128 MHz using the channelization algorithm presented herein.

2. QTT UWL Digital Backend Sampling and Frequency-banding Scheme

The data transmission flow of the QTT UWL digital backend system is illustrated in Figure 1 [Figure 1: see original paper]. The ultra-wideband receiver and reference antenna data streams are divided into three segments for transmission. The three segments cover RF analog signals of 704–1344 MHz, 1344–2368 MHz, and 2368–4032 MHz, which are sent to three RFSoC boards for sampling and preprocessing. After channelization, the data are transmitted via 100 Gb Ethernet to a GPU cluster for parallel processing, with the final preprocessed astronomical signals stored in a disk array.

The channel division scheme for the QTT UWL receiving system is shown in Figure 2 [Figure 2: see original paper]. Following the Parkes UWL design, the first band (704–1344 MHz) is sampled at 4096 MHz in the first Nyquist zone, processed by the channelization algorithm, and yields five 128 MHz subbands (SB1–SB5) in the 704–1344 MHz range, shown as red horizontal lines on the left side of Figure 2.

For the second band (1280–2560 MHz RF analog signal), we sample at 2560 MHz in the second Nyquist zone, preserving eight 128 MHz subbands (SB6–SB13) in the 1344–2368 MHz range, displayed as blue horizontal lines in the middle of Figure 2. Note that spectral information in the second Nyquist zone is inverted relative to the first, so subbands are labeled in reverse order.

For the third band (2048–4032 MHz RF analog signal), we again sample at 4096 MHz but in the second Nyquist zone, using the channelization algorithm to process the signal and retain 13 subbands of 128 MHz bandwidth (SB14–SB26) in the 2368–4032 MHz range. The output band is shown as red horizontal lines on the right side of Figure 2, with reversed spectral marking due to the second Nyquist zone inversion.

The final output from PFB processing at both sampling rates is complex data with 128 MHz bandwidth per subband.

3.1. Prototype Low-pass FIR Filter Design Based on Window Function

Finite impulse response (FIR) digital filters have a finite-length unit impulse response h(n) and represent a stable system. The expression for an N-tap FIR filter is given in Equation (1), where the system output y(n) is the linear convolution of the input sequence x(n) with h(n) in the time domain, corresponding to multiplication in the frequency domain.

The FIR digital filter comprises digital multipliers, adders, and delay units, essentially performing delayed and weighted operations on a sequence of input signals. As shown in Figure 3 [Figure 3: see original paper], x(n) is the input signal, h(n) are the FIR filter coefficients, y(n) is the filtered output, and N denotes the number of taps (with filter order N−1). Each filtering operation requires N multiplications and N−1 additions; for large orders, the delay becomes prohibitive for high-speed processing.

Commonly used window functions include the Rectangular, Bartlett, Hamming, Hanning, Blackman, and Kaiser windows \cite{Kumar_{2014}}. When designing FIR filters using the window method, performance depends on both filter order and window type. For comparison, we designed a 64-tap FIR low-pass filter with 100 Hz cutoff frequency and 800 Hz sampling frequency using different windows. As shown in Figure 4 [Figure 4: see original paper], the Blackman window provides the greatest first sidelobe attenuation, while the Hamming window offers a steeper transition band for the same filter order. Considering these characteristics, we selected the Hamming window method to design the prototype low-pass FIR filter.

3.2. Design of CS-PFB

The PFB structure is illustrated in Figure 5 [Figure 5: see original paper], which decomposes the input sequence and prototype filter coefficients into multiple "phases" or "branches" for efficient implementation. The PFB algorithm requires fewer multiplications and additions per unit time than conventional implementations. For an N-order filter with M-level polyphase decomposition, only (N+1)/M multiplications and N/M additions are needed per unit time, enabling parallel processing at much lower sampling rates.

For polyphase decomposition of the input sequence, the input data x(m) can be decimated by factor D to generate D grouped samples x_D(m), with each branch processed separately through convolution. Figure 6 [Figure 6: see original paper] visualizes polyphase decomposition for D=3, splitting the input signal (a) into three branches (b), (c), and (d).

We design the prototype low-pass FIR filter h_{LP}(n) with length N, where each sub-filter has length Q. We require N/D = Q to be integer; if not, zero-padding is applied to the filter coefficients. Figure 7 [Figure 7: see original paper] shows how 15 prototype filter coefficients are polyphase-decomposed into three branches of five coefficients each.

After polyphase decomposition, the filter coefficients and input data are rearranged by flipping the input data matrix and filter coefficient matrix vertically. Following convolution on each sub-channel's rearranged data and coefficients, FFT or inverse FFT (IFFT) is applied to obtain the channelized subband data. For D-point real input data, the output contains D/2 valid points due to FFT/IFFT conjugate symmetry, yielding D/2 valid channels; for D-point complex input, D valid channels are produced.

4. UBPB Algorithm

To verify the feasibility of our QTT UWL signal scheme, we designed the Ultra-wide Bandwidth Pulsar Baseband (UBPB) data generation algorithm to simulate UBPB data. The algorithm uses existing wideband pulsar baseband data to generate UBPB data through resampling and dispersion addition. The process is diagrammed in Figure 8 [Figure 8: see original paper]. Pulsar baseband data are processed in blocks for efficiency, transformed to the frequency domain via FFT for coherent dedispersion \cite{Zhang_{2023b}} using center frequency, bandwidth, and dispersion measure (DM) information. After setting the center frequency, bandwidth, and DM for the new UBPB data, dispersion is added (the inverse of coherent dedispersion), converted back to the time domain via IFFT, and stored as baseband data.

During UBPB generation, constraints on block size and parameters must be satisfied. Let the existing pulsar baseband data have bandwidth B, frequency range f_l to f_h, dispersion DM, observation time t seconds, and block size K per processing step. For the generated ultra-wideband pulsar baseband data with bandwidth B , frequency range f_l to f_h , dispersion DM , and observation time t seconds, the constraints are given by Equation (2). For pulsar baseband data, the sampling rate f_s = 2 × B. The dispersion delays Δt and Δt at the highest and lowest frequencies for both the original and generated UBPB data are shown in Figure 9 [Figure 9: see original paper] and calculated as expressed in Equation (3). These constraints ensure each processing block contains complete full-bandwidth pulse information while not exceeding the baseband data length.

5.1. Simulation of Ultra-wide Bandwidth Pulsar Base-band Data

We apply the UBPB algorithm from Section 4 to original baseband pulsar data with 400 MHz bandwidth, 1382 MHz center frequency, and DM = 2.64476 cm^{-3} pc, generating simulated UBPB data with 3328 MHz bandwidth, 2368 MHz center frequency, and the same DM. Table 1 compares the basic parameters. Since the number of pulses per data length is equivalent, the folding period P_2 of the generated UBPB data is calculated via Equation (4), where $P_1 = 0.00575730363767324$ s and $P_2 = 0.0006919836102972644$ s.

The 400 MHz dual-polarization baseband data spectrum is shown in Figure 10 Figure 10: see original paper, with bandpass range 1182–1582 MHz. The phase spectrum obtained using DSPSR/PSRCHIVE \cite{Hotan_{2004}, van_{{{Straten}}_{{2012}}}} is depicted in Figure 11 Figure 11: see original paper, with the folded pulse profile in Figure 11(b). After dedispersion, the phase spectrum appears in Figure 12 Figure 12: see original paper, with the collapsed pulse profile in Figure 12(b).

The 3328 MHz dual-polarization simulated data spectrum is shown in Figure 10(b), covering 704–4032 MHz. The phase spectrum from DSPSR/PSRCHIVE is in Figure 13 Figure 13: see original paper, with the folded pulse profile in Figure 13(b). After coherent dedispersion, the phase spectrum appears in Figure 14 Figure 14: see original paper, with the folded pulse profile in Figure 14(b). These simulations successfully recover dual-polarization spectral information and pulse profiles through folding.

5.2. Ultra-wide Bandwidth Data Channelization

We channelize the simulated ultra-wideband data using CS-PFB, dividing it into 26 subbands. Each sub-filter uses 64 coefficients, with two channelization structures for different sampling rates: Scheme 1 with 16 output subbands and 1024 coefficients, and Scheme 2 with 10 output subbands and 640 coefficients.

The first band (0–2048 MHz) uses Scheme 1 to retain five subbands in the 704–1344 MHz range. The second band (1280–2560 MHz) uses Scheme 2 to reserve eight subbands in the 1344–2368 MHz range. The third band (2048–4096 MHz) uses Scheme 1 to reserve 13 subbands in the 2368–4032 MHz range.

Pulse profiles are obtained by folding each subband. The five subbands in 704–1344 MHz are shown in Figure 15 [Figure 15: see original paper], where the 1st, 2nd, and 3rd subbands contain only noise. The eight subbands in 1344–2368 MHz appear in Figure 16 [Figure 16: see original paper], and the 13 subbands in 2368–4032 MHz are presented in Figure 17 [Figure 17: see original paper].

The frequency-phase diagram of all 26 subbands after channelization is shown in Figure 18 Figure 18: see original paper, with phase on the horizontal axis and channel number/frequency on the vertical axis. Each subband exhibits phase delay, which can be corrected through non-coherent dedispersion to align pulses across subbands. The arrival time difference Δt between the i-th channel (center frequency f_i) and the reference channel (center frequency f_{ref}, typically the band center) is given by Equation (5), which can be expressed as Equation (6). The number of time-delay points to shift each subband pulse signal is calculated from Δt, where p_{fold} is the number of pulse periods and n_{bin} is the number of points per subband after folding.

After phase alignment, the frequency-phase diagram of the 26 subbands appears in Figure 18(b). The subbands are recombined to form an ultra-wideband profile, folded as shown in Figure 19 [Figure 19: see original paper]. Comparing with Figure 14(a) using 100 on-pulse and off-pulse samples, the standard deviation after subtraction is 0.02094 for on-pulse and 0.01191 for off-pulse. The consistent distributions and nearly identical profiles confirm the correctness of this channelization method.

6. Conclusion

Drawing from the Parkes ultra-wideband signal receiving and preprocessing scheme, this paper proposes a signal processing architecture for the QTT UWL receiving system. The FIR digital filter is designed as a prototype low-pass filter using the Hamming window, polyphase-decomposed into sub-filters with 64 coefficients to form the CS-PFB. Based on 400 MHz pulsar baseband data from Parkes CASPSR observations, we generate a 3328 MHz ultra-wideband pulsar signal via the UBPB algorithm. Using our CS-PFB design, this signal is divided into 26 subbands of 128 MHz, with each subband's pulse profile obtained through coherent dedispersion, integration, and folding. Incoherent dedispersion aligns the phases across subbands, yielding a recombined broadband pulse profile that matches—both in phase and amplitude—the profile obtained from the original ultra-wideband data using DSPSR. This work experimentally verifies the feasibility of the QTT UWL signal scheme and the effectiveness of the channelization algorithm, demonstrating its readiness for future real-time implementation in the QTT UWL system.

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