Postprint: Development and Design of a Digital Spectrometer Based on Roach II

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Abstract

To achieve real-time measurement of wideband electromagnetic environments, a digital spectrometer was developed and designed based on the Roach II development platform, featuring a real-time bandwidth of 10 MHz–2 GHz and a dynamic range reaching 55 dB. First, the development and design philosophy of the digital spectrometer and considerations for module parameter configuration were analyzed, implementing test functions for fast sweep mode and pulse monitoring mode. Second, through measurement and analysis of key indicators such as frequency response, dynamic range, and linearity, and through comparison with measurement results from commercial spectrometers, it was determined that this digital spectrum analyzer possesses relatively accurate measurement precision and can be applied to wideband real-time spectrum monitoring and transient signal analysis at radio telescope stations.

Full Text

Development and Design of a Digital Spectrum Analyzer Based on the Roach II Platform

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Abstract: To achieve real-time measurement of broadband electromagnetic environments, a digital spectrum analyzer was developed and designed based on the Roach II platform, featuring a real-time bandwidth of 10 MHz–2 GHz and a dynamic range of 55 dB. First, by analyzing the development concepts and module parameter settings of the digital spectrum analyzer, we implemented testing functions for both fast-scan mode and pulse monitoring mode. Second, through measurement and analysis of key performance indicators—including frequency response, dynamic range, and linearity—and by comparing the results with those from commercial spectrum analyzers, we confirmed that the developed digital spectrum analyzer achieves relatively accurate measurement precision and can be applied to broadband real-time spectrum monitoring and transient signal analysis at radio telescope sites.

Keywords: digital spectrum analyzer; development and design; performance testing; signal monitoring

Introduction

With continuous advancements in science and technology, the utilization rate of frequency resources has increased dramatically. The 10 MHz–2 GHz band is widely used by commercial equipment, communication devices, radio and television broadcasting, aviation navigation, and public safety systems, making the electromagnetic environment in this band exceptionally complex. Due to the high sensitivity and wide operating frequency range of radio astronomy services, radio frequency interference (RFI) has an increasingly significant impact on radio telescope observations. Broadband and transient signals, particularly periodic transient signals, substantially affect pulsar observations and real-time searches for Fast Radio Bursts (FRBs). Similarly, broadband and transient interference sources also impact continuum observations because they cause relatively high integrated power within the bandwidth. Therefore, capturing broadband and transient signals is critically important in radio astronomy, as only by identifying and eliminating these signals can we ensure efficient scientific output from radio telescopes.

To mitigate the substantial impact of RFI on astronomical observations, RFI engineers have invested considerable effort in establishing radio quiet zones, monitoring electromagnetic interference, capturing interference signals, and performing spectrum analysis. The National Radio Astronomy Observatory installed two RFI monitoring systems at the Green Bank 100 m Telescope (GBT) site, with the monitoring system near the feed arm using the same local oscillator signal as the receiver for down-conversion and employing a 2×40 MHz broadband FFT spectrum analyzer. This system offers fast testing speed and high sensitivity, enabling effective monitoring of RFI at the site [1]. The Westerbork Synthesis Radio Telescope (WSRT) observatory developed a spectrum monitoring system covering 20 MHz–3000 MHz that integrates control and data analysis, creating a convenient radio environment monitoring system for data storage, analysis, searching, and mapping [2,3]. Both FAST and the Shanghai Tianma 65 m telescope have established electromagnetic environment monitoring systems tailored to their specific requirements [4]. To ensure effective monitoring of various electromagnetic interferences during the construction phase of the Xinjiang Qitai 110 m fully steerable radio telescope (QTT), the Xinjiang Astronomical Observatory independently designed and developed an automated, highly reliable electromagnetic environment monitoring system covering 0.1–12 GHz, enabling effective monitoring of various electromagnetic signals at the site [5].

However, the aforementioned electromagnetic environment monitoring systems have certain limitations in capturing broadband and transient electromagnetic interference signals. For instance, commercial spectrum analyzers employed in these systems typically have real-time bandwidths not exceeding 40 MHz and use sweep-frequency modes, resulting in low spectrum measurement efficiency. Therefore, this paper proposes to utilize the Roach II hardware development platform, which is widely applied in the astronomical field, to complete the development and design of a digital spectrum analyzer capable of fast-scan mode and pulse monitoring mode, providing a solution for broadband, real-time electromagnetic environment monitoring at radio astronomy sites.

1 System Design

The digital spectrum analyzer designed and developed in this paper is based on the Roach II platform and employs Nyquist sampling, polyphase digital filtering, and Fast Fourier Transform (FFT) theory. By adjusting the channel count design and scan time, we implemented both fast-scan mode and pulse monitoring mode. The Roach II development platform, widely used in the astronomical field, features a reconfigurable open computer architecture and independent programmable functions, with extensive modular designs that can meet diverse performance indicator requirements. The Roach II platform is primarily built around the Virtex-6 series FPGA chip, can run the Linux operating system, and includes two Z-DOK interfaces that can connect to various input/output interface cards, such as analog-to-digital conversion, digital-to-analog conversion, and other devices. In the digital spectrum analyzer design, it is mainly used to connect ADC boards, with currently available options including 3 GS/s-8 bit, 5 GS/s-8 bit, and 10 GS/s-4 bit ADC cards to meet different sampling bandwidth requirements [8].

[Figure 1: see original paper] shows the design process of the digital spectrum analyzer. The ADC performs Nyquist sampling, and the quantized digital signal first passes through a polyphase filter for filtering and channel division. The signal then undergoes Fast Fourier Transform for conversion from the time domain to the frequency domain. The resulting frequency-domain signal data is autocorrelated, followed by vector accumulation. After caching and integration, the data is stored.

1.1 ADC Sampling and Selection

As a critical component of digital sampling, the ADC' s performance indicators and proper setting of the sampling rate are key focuses of the entire digital spectrum analyzer design. According to the Nyquist sampling theorem, to ensure complete signal reconstruction after sampling, the sampling frequency must be greater than or equal to twice the highest frequency of the signal:

$$f_{\text{sample}} \geq 2f_{\max} \tag{1}$$

where f_{sample} is the sampling frequency and $f_{\max}$ is the highest frequency of the signal.

Following the Nyquist sampling theorem, designing a digital spectrum analyzer with 2 GHz bandwidth requires an ADC sampling frequency greater than or equal to 4 GHz. High sampling frequencies increase data volume, imposing stringent requirements on ADC selection. The hardware platform employs an ADC board model EV8AQ160, which integrates 1:1 and 1:2 data demultiplexers (DMUX) and LVDS output buffers to reduce output data rates, facilitating direct connection with various types of high-speed FPGAs for high-rate data storage and processing. The EV8AQ160 board integrates four ADC channels that can operate in three modes: a four-channel mode with 1.25 GSps sampling rate, a dual-channel mode with 2.5 GSps sampling rate, and a single-channel mode with 5 GSps sampling rate [9]. The digital spectrum analyzer development employs the single-channel mode with a 5 GSps sampling rate and 8-bit output data width. Additionally, to compensate for sampling data errors caused by device parameter dispersion and transmission path differences, the ADC board includes control and correction for integral nonlinearity, gain, offset, and phase for each ADC channel.

1.2 Polyphase Digital Filtering

Implementing digital filtering before decimation or after interpolation is a crucial issue in sampling rate conversion. To avoid aliasing during the sampling process, digital filter design is particularly important [10].

Assuming $x(m)$ is the signal input and $y(m)$ is the signal output, with $\delta(m)$ defined as the impulse function, the expression can be represented in convolution form:

$$y(m) = \sum \delta(k) \cdot x(m-k)$$

Based on digital filter principles, the polyphase digital filtering algorithm is applied in the digital spectrum analyzer development, with channel division shown in [Figure 2: see original paper].

Assuming the transfer function of the FIR filter [11] is:

$$H(z) = \sum_{m=0}^{N-1} \delta(m) z^{-m}$$

where N is the filter length. If the impulse response $\delta(m)$ is divided into D groups and N is an integer multiple of D (i.e., $N/D = j$), the polyphase representation of the transfer function becomes:

$$H(z) = \sum_{k=0}^{D-1} z^{-k} \sum_{m=0}^{j-1} \delta(mD+k)(z^D)^{-m}$$

Defining the polyphase components of $H(z)$ as:

$$E_k(z^D) = \sum_{m=0}^{j-1} \delta(mD+k)(z^D)^{-m}$$

The transfer function can be expressed as:

$$H(z) = \sum_{k=0}^{D-1} z^{-k} E_k(z^D) \tag{7}$$

The polyphase filter in the digital spectrum analyzer development design consists of a PFB module, a finite impulse response filter, and an FFT module. The PFB module sets the number of channels, which corresponds to half the number of FFT operation points because only real signal FFT operations are performed. In fast-scan mode, the PFB module is set to 16384, yielding a filter bank with 8192 channels, while in pulse monitoring mode, the PFB module is set to 2048, yielding a filter bank with 1024 channels. The primary advantages of polyphase digital filter design include suppressing adjacent channel interference through channel division, reducing data computation volume, and providing a pathway for efficient real-time signal acquisition.

1.3 Overall Architecture Design

Based on the aforementioned design process and theoretical foundation, we employed MATLAB/Simulink and the Casper Toolflow library with a modular design approach to implement both fast-scan mode and pulse monitoring mode. The overall architecture design is identical for both modes, with parameters adjusted for digital sampling, polyphase digital filtering, FFT points, vector accumulation modules, and Bram modules to meet the requirements of different measurement modes.

The overall architecture design of the digital spectrum analyzer, shown in [Figure 3: see original paper], primarily consists of digital sampling, polyphase digital filtering, Fast Fourier Transform, autocorrelation, Delay modules (blue), vector accumulation design, and Bram modules (yellow). The Delay module functions as a shift register that can be configured to delay by integer multiples of clock cycles. In the digital spectrum analyzer design, the Delay module aligns sampled data temporally. For example, in fast-scan mode with 2 GHz bandwidth divided into 8192 channels, the resolution bandwidth is 244 kHz. By setting Delay module parameters, frequency can be correctly mapped to corresponding channels, avoiding frequency offset phenomena. Therefore, Delay module configuration is a crucial aspect of the digital spectrum analyzer design.

The vector accumulation design employs the Vacc module, illustrated in [Figure 4: see original paper]. This module primarily performs vector sorting and accumulation while eliminating glitches that affect the spectrum. It has two input ports: new_acc and din. The new_acc input port receives a pulse signal indicating the start of a new accumulation—when a new pulse signal is received, accumulation begins. The din port is the data input port corresponding to an output port dout. By setting dout port parameters, the data length and bit width can be effectively controlled. When a complete vector accumulation is finished, the Valid port outputs a Boolean value of 1 and interacts with the Bram module; otherwise, it outputs 0.

The Vacc module has three parameter settings. The vector length parameter sets the length of input or output vectors. For fast-scan mode, FFT is set to 16384 points, outputting data for 8192 frequency channels divided into odd and even channels with four signal paths each, so the accumulation vector length is set to 1024. Correspondingly, the pulse monitoring mode vector length is set to 128. Note that accumulation involves overlapping signal addition without averaging, causing rapid data bit growth. To avoid overflow, accumulation count and time must be controlled. The Number of output bits parameter sets the bit width of the output signal, while the Binary point (output) parameter specifies how many bits in the total binary representation are fractional bits. The new_acc signal primarily marks the start of an integration period to prevent vector data misalignment.

The Bram module serves as an interface module primarily for storage functionality, implemented internally in the FPGA as an array. It has three input ports and one output port, as shown in [Figure 5: see original paper]. Data streams enter through the data_in port and exit through the data_out port. The addr address line controls storage at corresponding locations to maintain correct data ordering. Synchronization between the valid storage address input port and the data stream input port is controlled by pulse signals.

The Bram module’ s data read time should match the data vector accumulation time. If the read interval is too short, repeated readings of the same unupdated data will occur within a certain time period or during cyclic data reading. Conversely, if the read interval is too long, the storage will update multiple times while reading occurs only once, causing some spectrum data to be missed.

The compilation and operation process is illustrated in [Figure 6: see original paper]. First, the overall architecture design is completed in Simulink, with parameters set for each module to ensure consistent data flow. After clicking run, simulation is performed to verify no errors before compilation. Next, the casper_xps command is entered in MATLAB to start compilation, generating a binary bof file. Finally, the compiled binary bof file is copied to the corresponding directory on the Roach II development platform. With the Roach II platform connected to the computer via Gigabit Ethernet, a Python script is written in the Linux operating system to control the digital spectrum analyzer operation. Based on this Python script, the Roach II platform can be launched from the local computer for performance testing and spectrum signal testing.

2 Performance Testing

Python script control of the Roach II development platform is a crucial step in implementing digital spectrum analyzer testing functions. The process begins by clearing all variables in the buffer and connecting to the Roach II platform via IP address. After connection, the bof file to be executed is loaded into the Roach II platform. Then, values for software registers such as accumulation length and gain are written and configured. The system waits 10 seconds to filter out incorrect spectrum output values before reading data from eight BRAM modules and storing it in arrays. The eight arrays are interleaved and combined into a single array for output and storage.

2.1 Dynamic Range Measurement

The dynamic range of a digital spectrum analyzer refers to the ratio (in dB) between the maximum and minimum signals that can be simultaneously present at the input 端 while allowing the smaller signal to be measured within a given uncertainty. Therefore, dynamic range measurement is a critical indicator in digital spectrum analyzer development and design. A hardware test system was constructed using the Valon 5008 to provide the sampling clock, which offers excellent performance and high precision, while a signal generator provided an external 10 MHz signal for locking, as shown in [Figure 7: see original paper].

Four frequency points were selected within the 10 MHz–2 GHz range: 200 MHz, 600 MHz, 1400 MHz, and 1800 MHz. The signal generator output fixed power levels starting from -3 dBm and decreasing by -3 dBm increments to test the digital spectrum analyzer’ s dynamic range. Assuming the power value output by the signal generator is the nth value and the corresponding dimensionless value collected by the digital spectrum analyzer is $y(n)$, the collected signal is considered a valid, undistorted signal if it satisfies equation (8):

$$y(n) \tag{8}$$

The test results are shown in [Figure 8: see original paper]. Both fast-scan mode and pulse monitoring mode satisfy equation (8) for power values from -9 dBm to -64 dBm, demonstrating that the digital spectrum analyzer achieves a dynamic range of 55 dB, meeting the requirements for general broadband and transient electromagnetic interference signal measurements.

2.2 Linearity Test

Linearity testing effectively verifies whether the power response of the digital spectrum analyzer is accurate during signal monitoring, representing another critical indicator in development and design. With the signal generator outputting fixed power values, the linearity of the digital spectrum analyzer can be measured by varying the frequency. Since the collected data is dimensionless, equation (9) is used to quantify the measured data into power values in dBm. Using the test result at -20 dBm from the signal generator as a reference, other measured power values are quantified accordingly, as shown in [Figure 9: see original paper]. The results indicate that 1000 MHz is a bad point due to design flaws in the ADC board itself, while linearity at other frequency points is good, confirming that the digital spectrum analyzer design basically meets requirements.

$$P_m = 10\log_{10}(c) + b \tag{9}$$

where P_m is the quantized power value in dBm, c is the raw collected data (dimensionless), and b is the calibration coefficient.

2.3 Comparison Test

To verify the accuracy of the developed digital spectrum analyzer, a measurement platform based on both the digital spectrum analyzer and a commercial spectrum analyzer was built, with the system link shown in [Figure 10: see original paper]. The signal first passes through a dual-polarized log-periodic antenna XSLP9142, then undergoes filtering through a bandpass filter to effectively suppress signals, interference, and noise above 2000 MHz. The signal then passes through a BBV9743 preamplifier, attenuator, and combiner to connect to both the developed digital spectrum analyzer and an N9030A commercial spectrum analyzer. Finally, test data is stored and plotted separately. The signal generator in the system link primarily provides a 10 MHz reference signal for the digital spectrum analyzer.

During testing, the integration time of the digital spectrum analyzer was set to 50 ms, and the sweep time of the N9030A spectrum analyzer was set to 50 ms for the 10–2000 MHz frequency range. Additionally, different thresholds could be set for the Roach II development platform to compare matching performance with the N9030A spectrum analyzer. The device parameters and technical specifications of the test system are listed in .

Based on the test link shown in [Figure 10: see original paper], different filters and attenuators were first used for exploratory testing to effectively suppress out-of-band interference effects on the system link. Then, different thresholds were set for system performance testing to find the optimal critical threshold. [Figure 11: see original paper] shows comparison results for power thresholds of

-64 dBm, -60 dBm, -55 dBm, and -50 dBm, using a 500–3200 MHz filter and a 15 dB attenuator.

The test results demonstrate good overall agreement between the digital spectrum analyzer and commercial spectrum analyzer. However, when thresholds are set to -64 dBm and -60 dBm, the digital spectrum analyzer can capture signals at 1406–1422 MHz and 1976–1984 MHz that are not detected by the N9030A commercial spectrum analyzer, as these are internal signals of the digital spectrum analyzer. By increasing the threshold, -55 dBm is identified as the optimal critical threshold, where power responses between the digital spectrum analyzer and commercial spectrum analyzer show high agreement and frequency responses are consistent.

This paper developed and designed a digital spectrum analyzer with real-time bandwidth of 10 MHz–2 GHz based on the Roach II platform, completing development, design, and performance testing for both fast-scan and pulse monitoring modes. Test results show that the digital spectrum analyzer achieves a dynamic range of 55 dB and demonstrates good agreement with commercial spectrum analyzers, providing relatively accurate measurement precision. It can be applied to broadband real-time spectrum monitoring and transient signal monitoring, providing support for electromagnetic interference analysis, spectrum management strategy formulation, and receiver design at radio astronomy sites.

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Note: Figure translations are in progress. See original paper for figures.