Digital Backend Strategies for RFI Mitigation in Radio-astronomy Receivers

R2 – Reconfigurable Digital Signal Processing Systems

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Abstract

This research explores real-time mitigation strategies for radio frequency interference (RFI) in radio astronomy receivers. Utilizing Modified-LMS and multiscale Wavelet transformations, the study seeks to develop an adaptive filtering model across L to S frequency bands. The primary goal is to create a mathematical framework that ensures timely convergence of algorithms for spectral coefficient estimation while identifying transient interference instances with low MSE and high SNR. The study also aims to minimize computational complexity and optimize data processing time. Hardware validation involves RFSoC and GPU for processing acceleration.

Problem Statement

The problem addressed in this study involves eliminating low-power spectral density deep space RFI sources, that can lead to data loss, system lockup, and signal saturation caused by delay accumulation during real-time digital data processing.

Hypothesis

We hypothesize the feasibility of identifying and reducing delay accumulation in the data correlation process with low computational burden, enabling real-time RFI mitigation and enhancing the convergence speed using Wavelet transform (WLT) alongside modified least mean squares algorithm (Modified-LMS) [4].

General and Specific Objectives

Developing a mathematical model predicting spectral coefficient estimator complexity in adaptive filters targeting for a MSE lower than 0.1 and a SNR greater than 10dB with low computational load within the frequency bands from L to S.

- Assessing the performance of RFI cancellation using multiscale signal Wavelet transform and evaluate its impact on time convergence
- Studying algorithmic solutions for assessing spectral coefficient estimator complexity in adaptive RFI filtering.
- Developing a platform facilitating the validation of various RFI mitigation algorithms over multi-port Ethernet from a remote CPU.

Data Specifications and Parameters

The proposed methodology involves simultaneous observations with the main telescope and a reference antenna. Radio receiver channel configuration characteristics for RFI analysis are detailed in Table 1.

Table 1. Radio Astronomy Receiver Specifications and Parameters

Channel Resolution	Delay Errors	Frequency Ranges	Bandwidth (MHz)	Data Format	Pointing Range
4096 Full Stokes	L – band: > 0.2 ns/2 cm	L – band: (1.22 –1.44) GHz	1 to 10	CSV 16/32 bits/pixel (bpp)	Azimuth [120°, 240°]
8192 for AUDS	S – band > 0.2 ns/1.2 cm	S – band: (2.22 – 2.75) GHz	10 to 100	FITS Standard Real 16/32 bpp	Elevation [30°, 90°]

Methodology

Research on RFI Mitigation Methods → Fourier and Wavelet Transform Set → Modified Adaptive Filter Algorithm Set → Synthetic Data Generation → Testbed Architectural Design & Implementation → Verification and validation → Develop Dynamic Software for Data Collection and Analysis

Method involves identifying factors causing delays in adaptive filter convergence. Utilizes Wavelet and Fourier transform [1][2] alongside modified LMS filtering for real-time RFI mitigation [3], as shown in Figure 1.

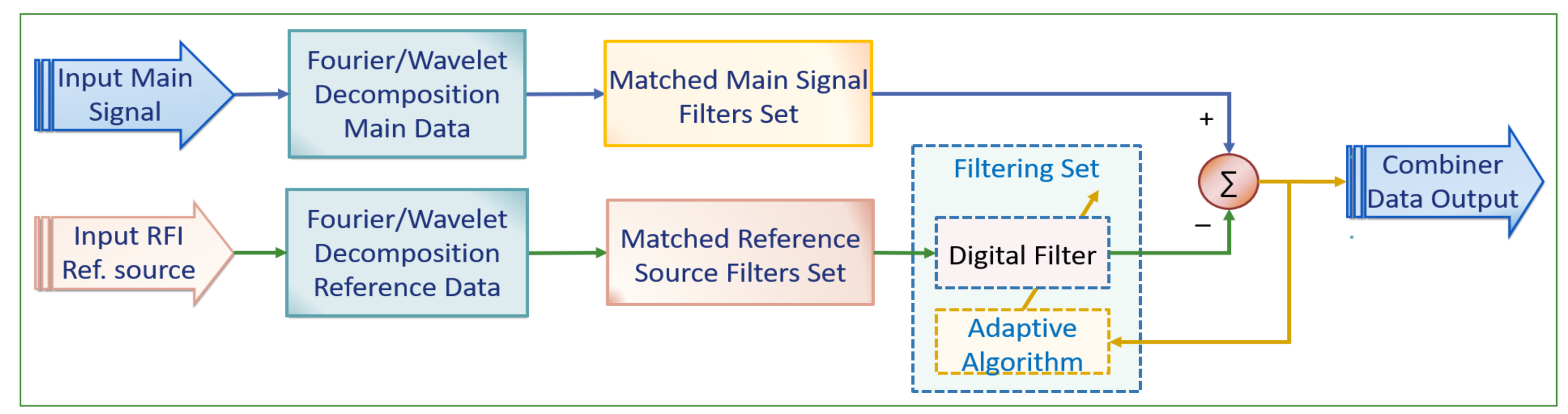

Fig. 1. Overview for the proposed methodology in digital receiver Back-End

The architectural design facilitating cross-device interaction is depicted in Figure 2. A testbed ensures enough GPU-RFSoC bandwidth and low-latency communication via optical fiber, facilitating bidirectional interaction with the CPU remotely.

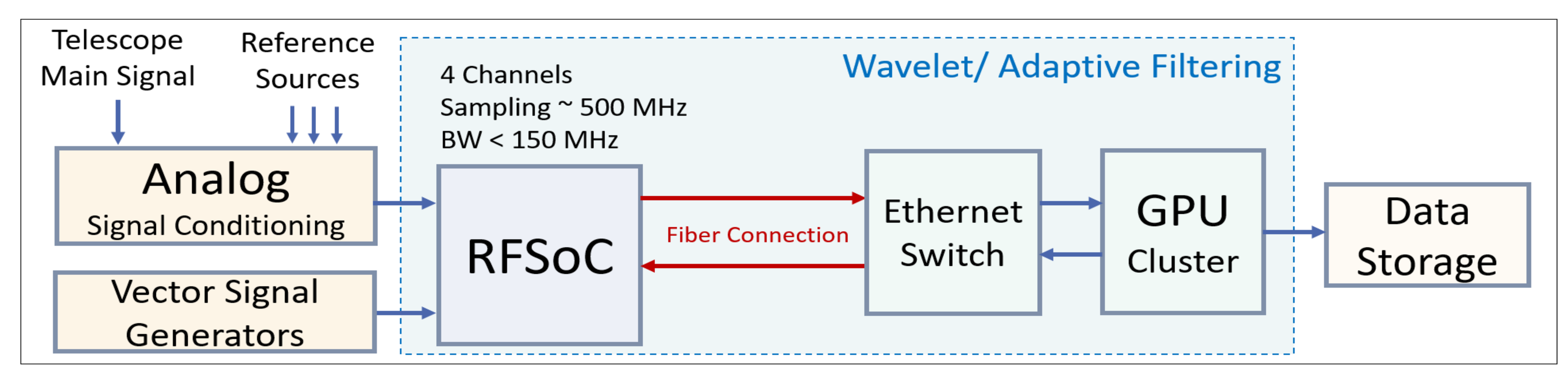

Fig. 2. Reconfigurable architectural design testbed

Adaptive filters are tuned for computational complexity, adaptivity, and linearity, with mean square error (MSE) and signal-to-noise ratio (SNR) as evaluation metrics [4].

A Full factorial experimental design analysis estimates variance and reliability based on data processing delays, as depicted in Figure 3.

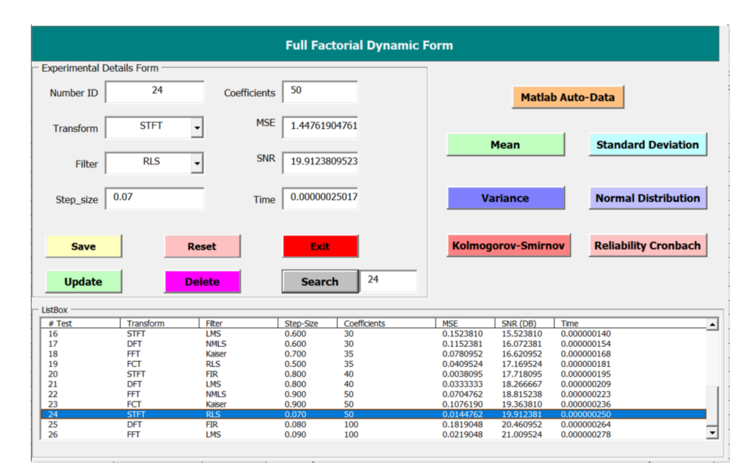

Fig. *3* Previous Reliability Analysis

The laboratory test model involves synthesizing both main astronomical signals and reference RFI using two vector signal generators. High-performance GPU-RFSoC data communication will be achieved through mixed programming involving Xilinx Vitis HLS, PYNQ, and Matlab [5].

Input and output signals will be monitored using a spectrum analyzer and a remote Control channels.

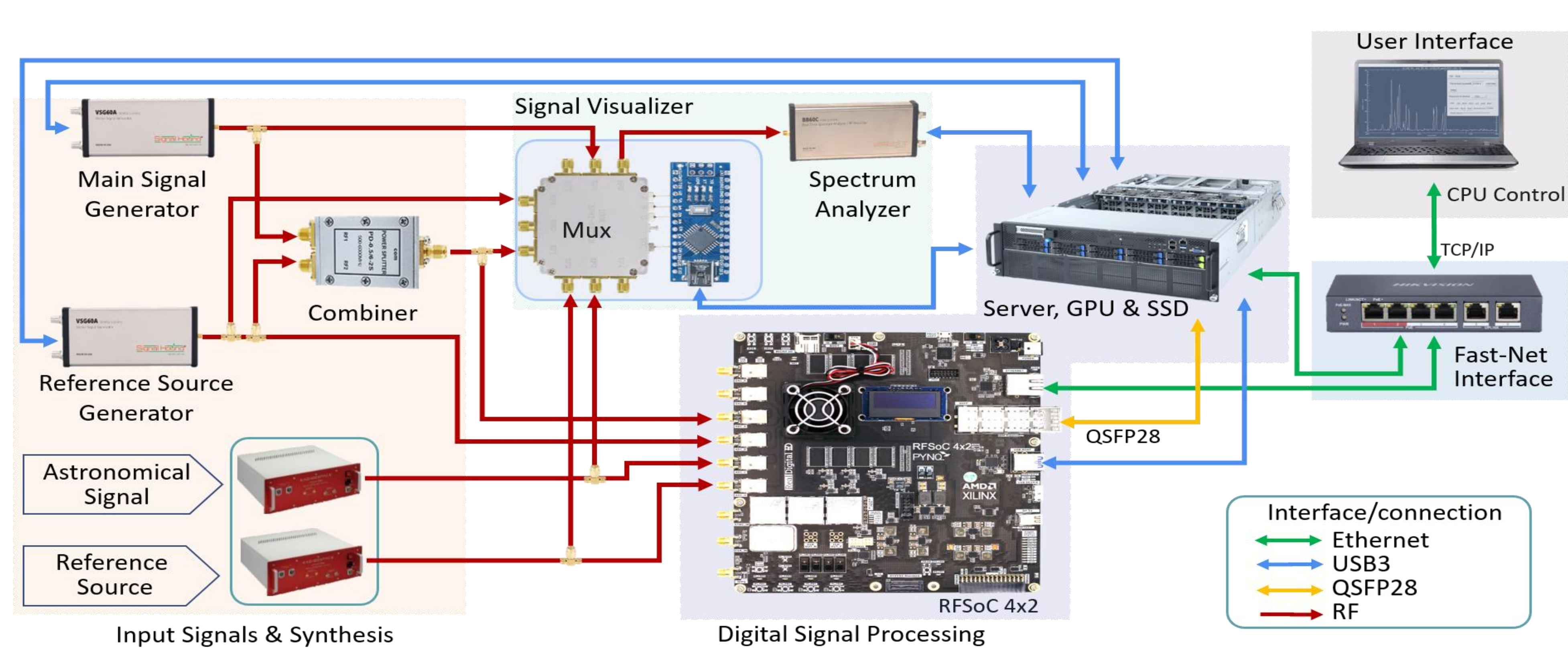

Fig. 4. Testbed Architectural Design Real-Connection

Preliminary Results

The cross-correlation analysis between Fourier and wavelet transforms, alongside a finite impulse response filter, demonstrates superior behavior of discrete wavelet transform (DWT) over discrete Fourier transform (DFT), as illustrated in Figure 5.

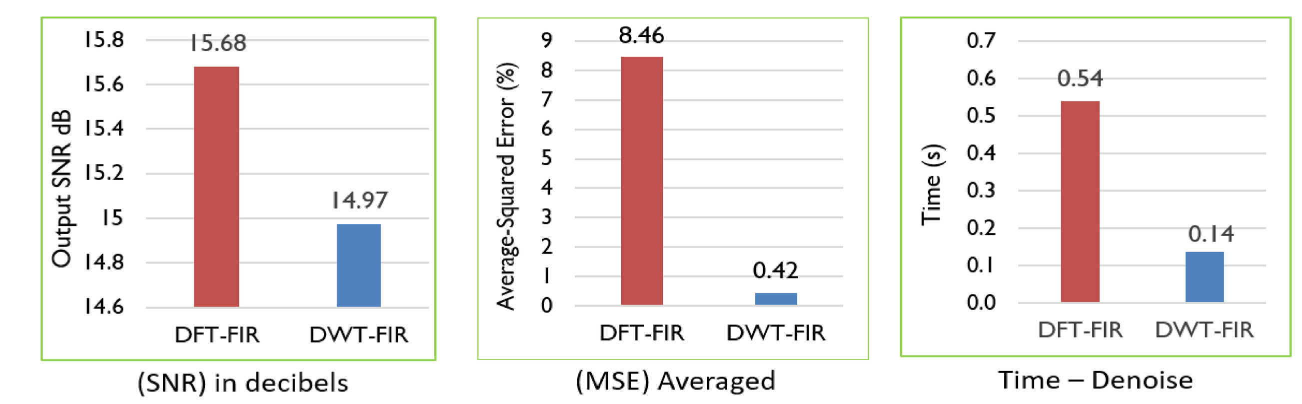

Fig.5 DWT, DFT and FIR filter performance analysis

Figures 6 and 7 depict the statistically analyzed average MSE and SNR performance of simulated RFI filter algorithms favor adaptive filtering.

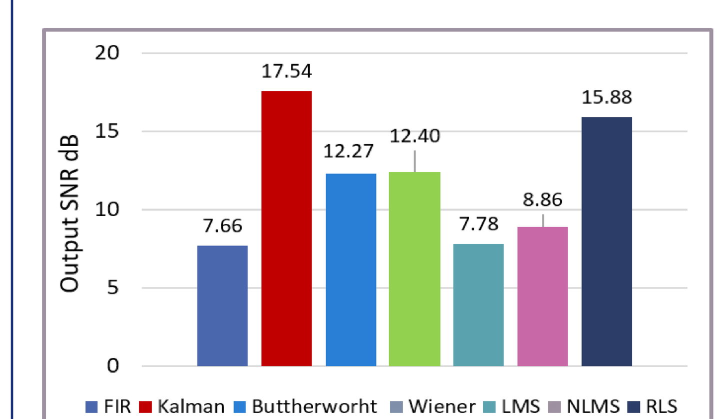

Fig.6 Adaptive Filter SNR performance

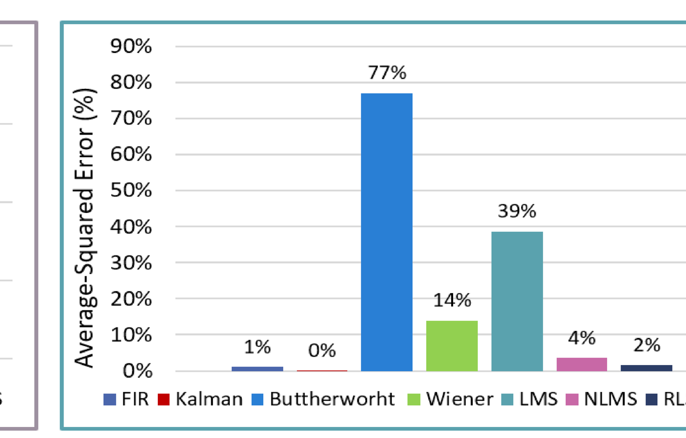

Fig.7 Adaptive Filter MSE averages

A Digital Back-end (DBE) testbed was designed, with its performance pre-evaluated, and upgrades implemented.

Conclusions

- Wavelet and Fourier transforms, alongside adaptable digital filter models, were selected for analysis and testing.
- The instrument configuration model was validated, and the DBE testbed was acquired, assembled, and assessed.
- Ongoing efforts focus on implementing upgrades and conducting control software testing for real and synthetic data in real-time.

References

[1] G. F. Forte, J. Querol, A. Camps, and M. Vall-Llossera, “Real-time RFI detection and mitigation system for microwave radiometers,” IEEE transactions on geoscience and remote sensing, vol. 51, no. 10, pp. 4928–4935, 2013.

[2] S. Liu, W. He, and X. Chen, “Research on multiscale wavelet transform in adaptive filtering,” in Journal of Physics: Conference Series, vol. 1650, No. 3. IOP Publishing, 2020, p. 032044.

[3] Z. A. Khezzar, R. Benzid, L. Saidi, and M. K. Smail, “Envelope detection by Shannon energy calculation in DCT domain and DFS-based notch filter for interference mitigation in GNSS receivers,” Treatment du Signal, vol. 39, no. 3, p. 835, 2022.

[4] D. Kong and I. Galton. “MSE analysis of a multi-loop LMS pseudo-random noise canceler for mixed-signal circuit calibration”. IEEE Transactions on Circuits and Systems I: pp. 679: 3084–3098, 2020.

[5] J. P. Smith, J. Bailey, J. Tuthill, L. Stefanazzi, G. Cancelo, K. Treptow, and B. A. Mazin, “A high-throughput oversampled polyphase filter bank using Vivado HLS and PYNQ on a RFSoC,” IEEE Open Journal of Circuits and Systems, vol. 2, pp. 241–252, 2021.

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