Digital Backend Strategies for RFI Mitigation in Radio-astronomy Receivers

R2 – Reconfigurable Digital Signal Processing Systems
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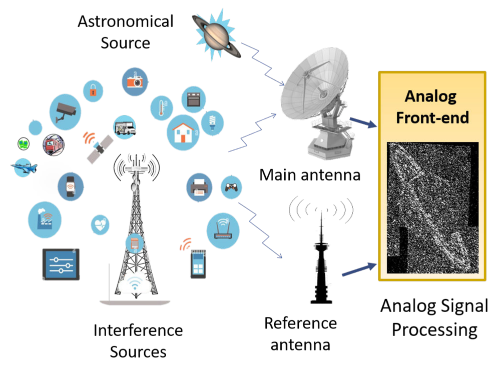
Abstract

This research focuses on achieving real-time radio frequency interference (RFI) mitigation in astronomy signals. The study explores the use of Modified-LMS and Wavelet transformations for adaptive filtering across L to S frequency bands. Our aim is to develop a mathematical model that assesses the impact of algorithmic changes while detecting transient interference events with a low mean square error (MSE) and a high signal-to-noise ratio (SNR). The evaluation focuses on examining the effects of algorithmic variations on spectral coefficient estimation and transient interference recognition within the digital backend of radio astronomy receivers. Hardware validation will be use a processing system with a radio frequency system-on-chip (RFSoC) and a graphics processing unit (GPU) as hardware accelerators.

Problem Statement

The problem addressed in this work is the removal of low-power spectral density deep space RFI sources that can lead to data loss, system lockup, or signal saturation caused by delay accumulation during real-time digital data processing.



Hypothesis

We hypothesize it is possible to identify and reduce the delay accumulation in the data correlation process with low computational burden, enabling real-time mitigation of RFI and enhancing the convergence speed by using the Wavelet transform (WLT) in conjunction with a modified least mean squares algorithm (Modified-LMS) [4].

General and Specific Objectives

Developing a mathematical model that analyzes and predicts the minimum complexity of the spectral coefficient estimator in an adaptive filter, 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 through multiscale signal Wavelet transform and its impact on time convergence
- Studying algorithmic solutions to assess the complexity of the spectral coefficient estimator in adaptive RFI filtering of astronomical signals
- Developing a platform to facilitate the validation of various RFI mitigation algorithms over multi-port Ethernet from a remote CPU

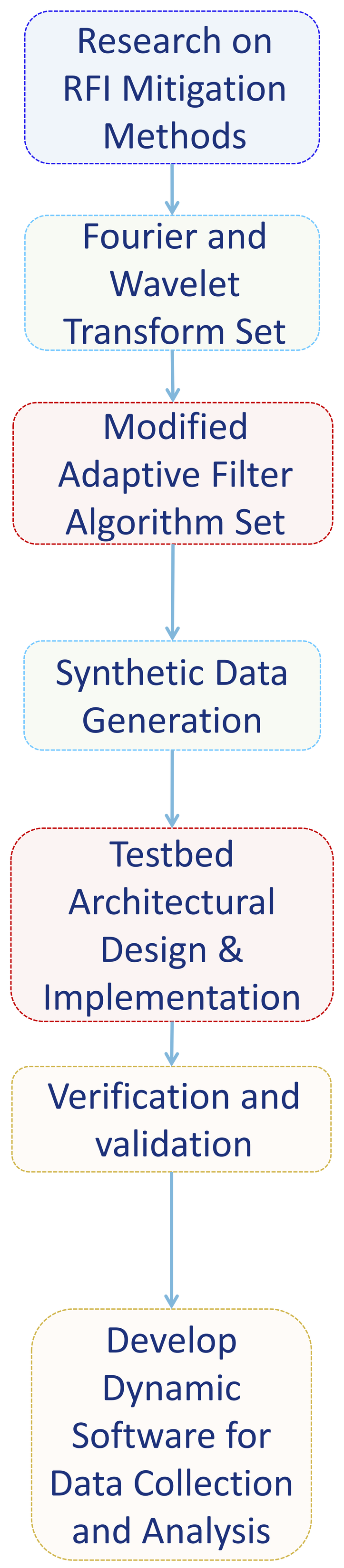
Data Specifications and Parameters

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

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



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

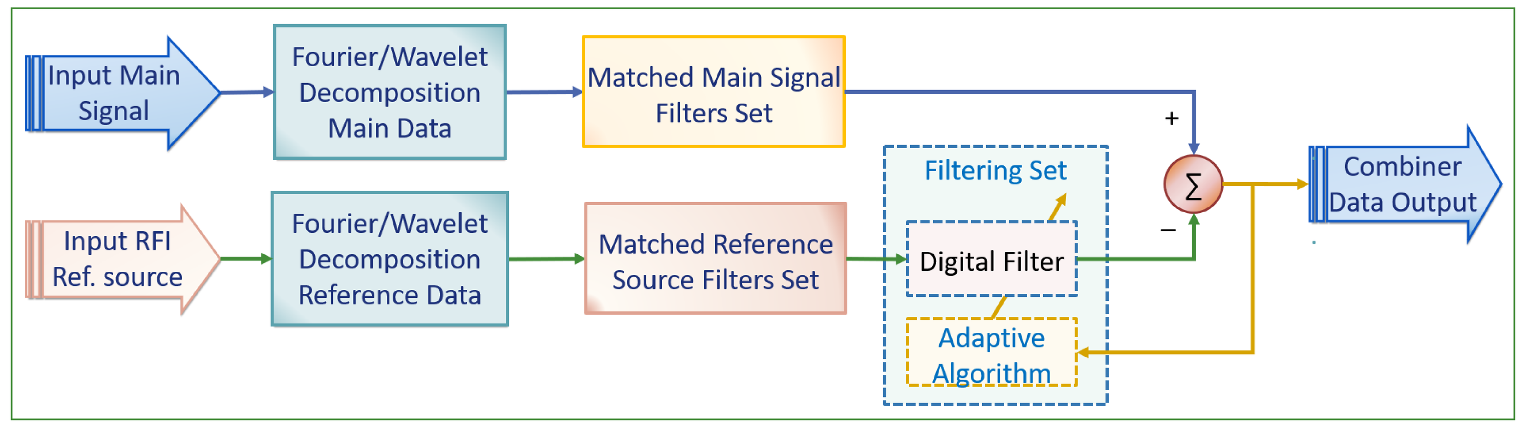


Fig. 1. Overview for the proposed methodology in digital receiver Back-End

Figure 2 Shows the architectural design facilitating cross-device interaction. A testbed providing enough GPU-RFSoC bandwidth and low-latency will enable bidirectional communication with CPU via optical fiber and a multiport Ethernet channel.

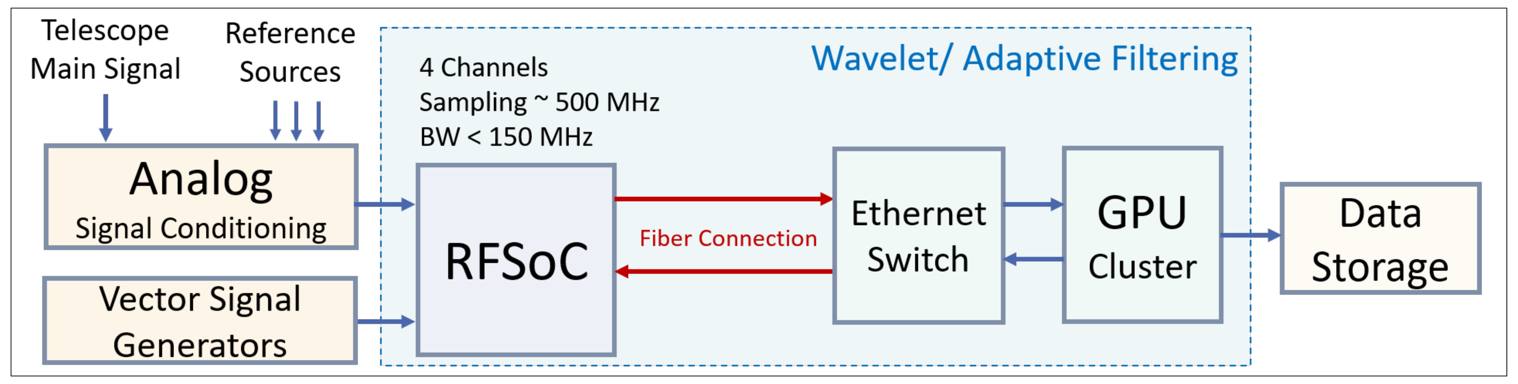


Fig. 2. Reconfigurable architectural design testbed

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

A full factorial experimental design analysis will be performed for validation, estimating variance and reliability of the filtering based on the delays observed in the data processing. The process for collecting and pre-evaluating the results is illustrated in Figure 3.

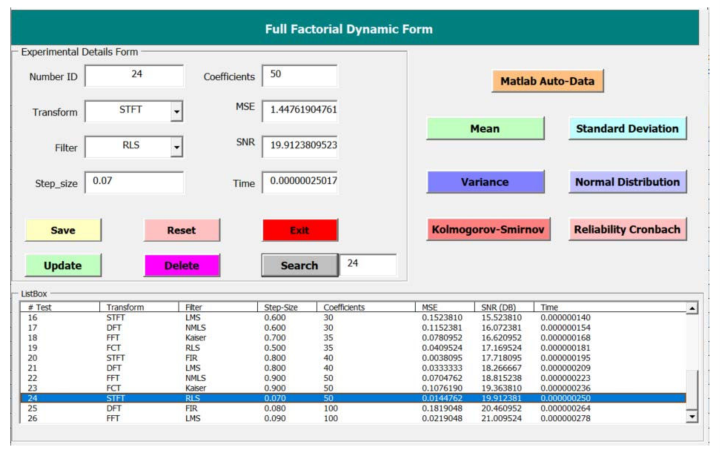


Fig. 3 Previous Reliability Analysis

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.

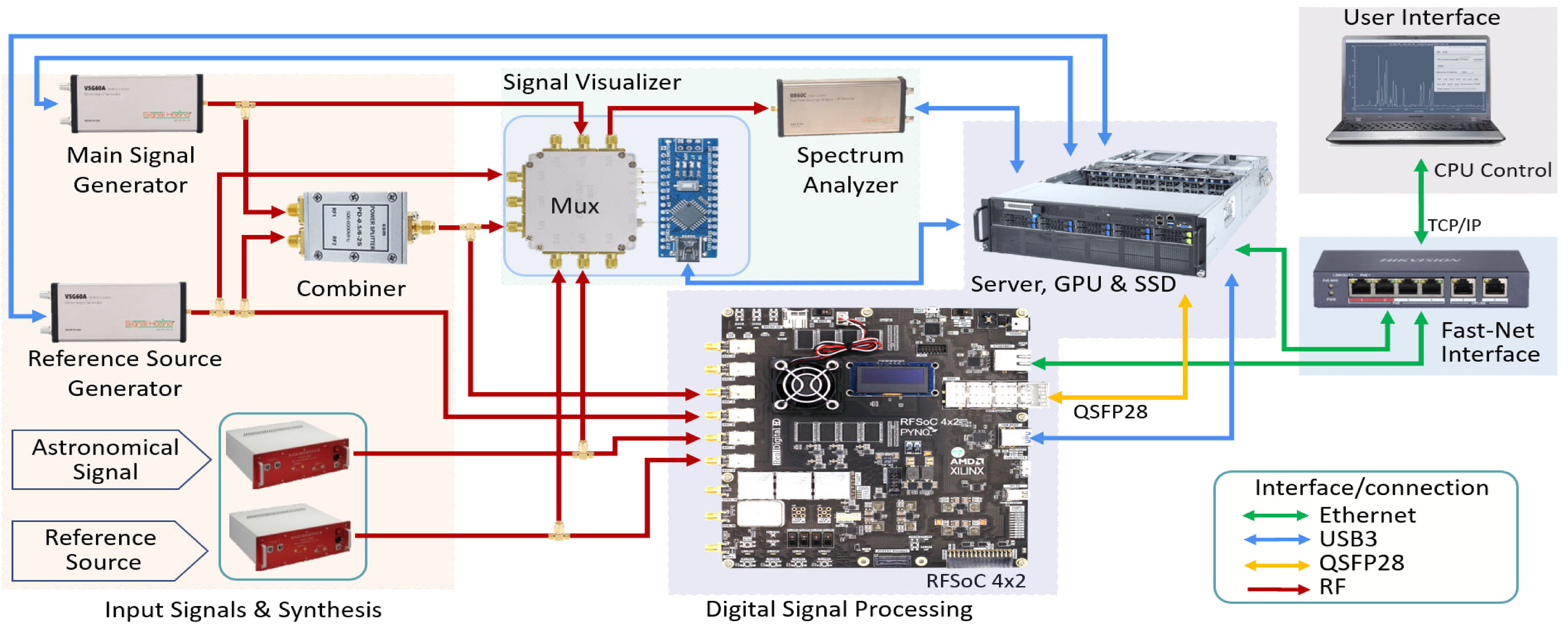


Fig. 4. Testbed Architectural Design Real-Connection

Preliminary Results

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

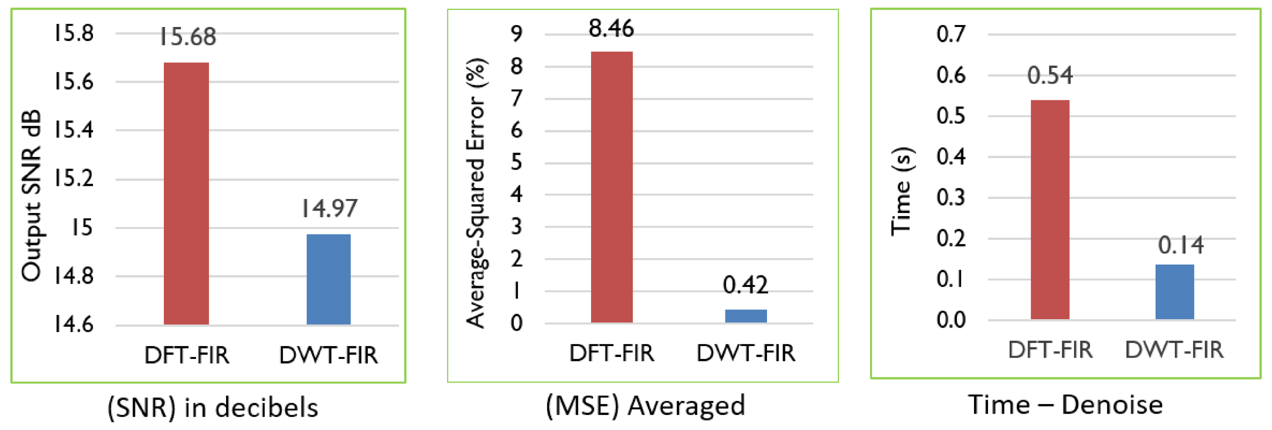


Fig.5 DWT, DFT and FIR filter performance analysis

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

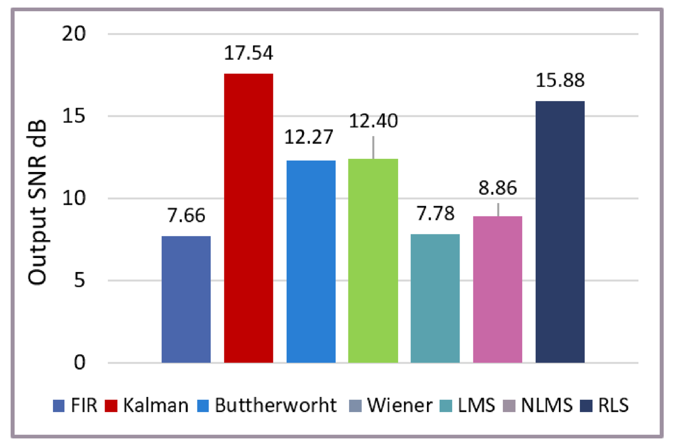


Fig.6 Adaptive Filter SNR performance

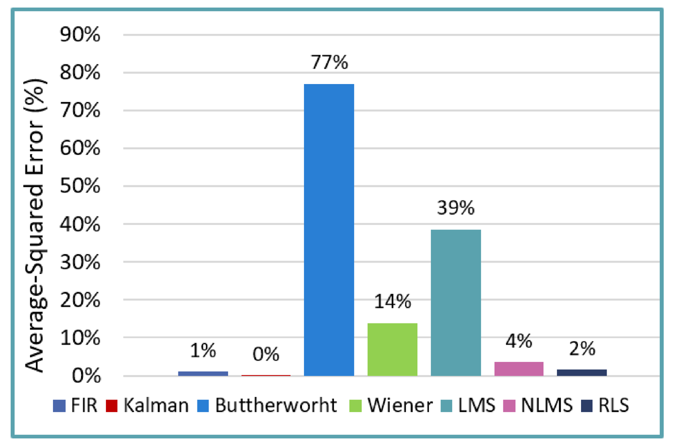


Fig.7 Adaptive Filter MSE averages

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

Conclusions

- Wavelet and Fourier transforms, alongside adaptable digital filter models, were chosen for analysis and testing.
- The instrument configuration model was validated, and the DBE testbed was acquired, assembled, and assessed.
- Its setup and performance were pre-evaluated, with ongoing efforts to implement upgrades and conduct control software testing.
- Testing with real and synthetic data in real-time remains pending.

References

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Acknowledgements

This work was supported in part by the NSF Center for Advanced Radio Sciences and Engineering, under Cooperative Agreement Award AST-2132229.