Simulation of Various Channelizer Structures Directed by Cyclostationary Detector

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Introduction

We present a Software-Defined Radio (SDR) system for detecting and tuning multiple signals of interest. Detection is performed by a cyclostationary detector, which exploits the cyclostationary properties exhibited by most digital signals with a fixed symbol rate. Tuning, filtering, and decimating are performed by a configurable filter bank, so that many signals can be isolated simultaneously. The block diagram shown in Figure 1 illustrates this system.

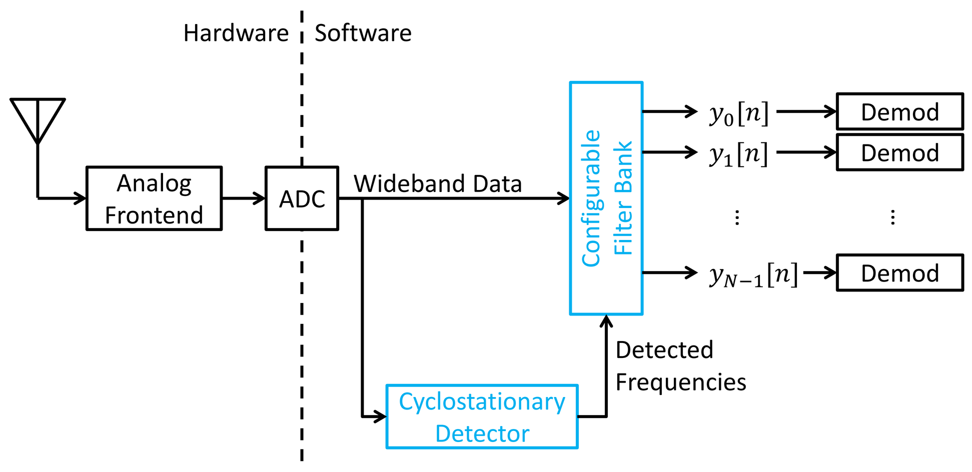

Fig. 1: High-level block diagram of our system. An analog front-end and ADC are used to bring wideband data into our Software-Defined Radio. There, a detector directs a configurable filter bank to isolate N signals of interest, which are then demodulated. The highlighted detector and filter bank are the components examined here.

We are primarily concerned with two components: the cyclostationary detector, and the configurable filter bank. Two different filter bank structures are examined: an overlap-save filter bank, and a combined polyphase analysis/synthesis filter bank, composed of a polyphase analysis filter bank followed by several polyphase synthesis filter banks. These structures are evaluated on two important criteria: 1) Their ability to accurately reproduce every detected signal, and 2) Their computational efficiency when combined with a cyclostationary detector.

Cyclostationary Detection

Many digital communications exhibit a statistical property called *cyclostationarity*, which implies the signal has some parameter which varies periodically with time. The frequency of this variation is called the cyclic frequency, α [1]. Of particular interest for us is second-order cyclostationarity, where a signal has a periodic auto-correlation, $R_{xx}(t, t+\tau)$:

$$R_{xx}(t, t+\tau) = E\{x(t)x^*(t+\tau)\} = \sum_{\alpha} R_{xx}^{\alpha}(\tau)e^{j2\pi\alpha t}$$

The function $R_{xx}^{\alpha}(\tau)$ is the cyclic auto-correlation function (CAF), given by:

$$R_{xx}^{\alpha}(\tau) = \lim_{T\to\infty} \frac{1}{T}\int_{-T/2}^{T/2} R_{xx}(t, t+\tau)e^{-j2\pi\alpha t}dt$$

Estimates of the CAF can be used for signal detection in the time domain [2, 3, 4]. Another useful function for detection is the Fourier transform of the CAF, called the Spectral Correlation Density (SCD), given by:

$$S_{xx}(\alpha, f) = \int_{-\infty}^{\infty} R_{xx}^{\alpha}(\tau)e^{-j2\pi f\tau}d\tau$$

Estimates of the SCD can be used for detection in the frequency domain [4, 5, 6], as illustrated in Figure 2. This is the approach we use in our simulation.

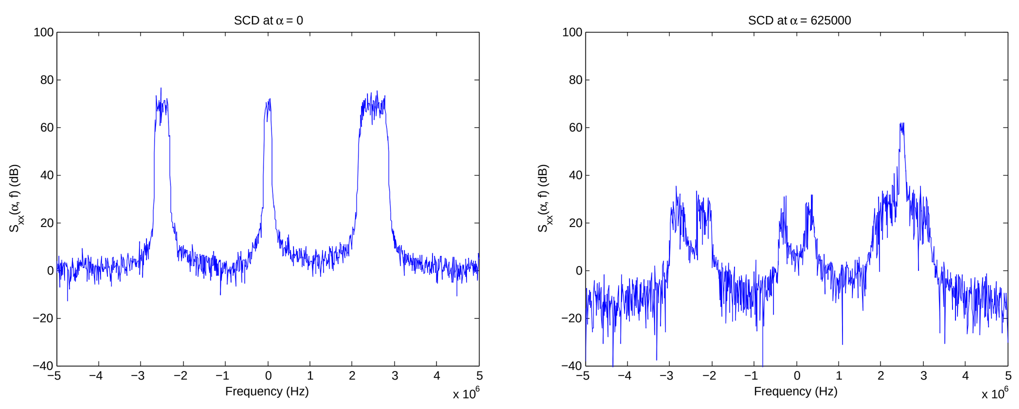

Fig. 2: SCD Estimates for three QPSK signals at 156.25, 312.5, and 625 kbaud. SCD at $\alpha = 0$ Hz is equivalent to PSD, SCD at $\alpha = 625$ Hz highlights signal at that baud rate.

Polyphase Filter Bank

Polyphase analysis channelizers split a signal into M channels separated in frequency by f_s/M and decimated from the original sample rate by $D = M$. While synthesis channelizers perform the reverse process - combine M channels [7]. Non-maximally decimated versions of these structures, where $D = M/2$ [8], are shown in Figure 3.

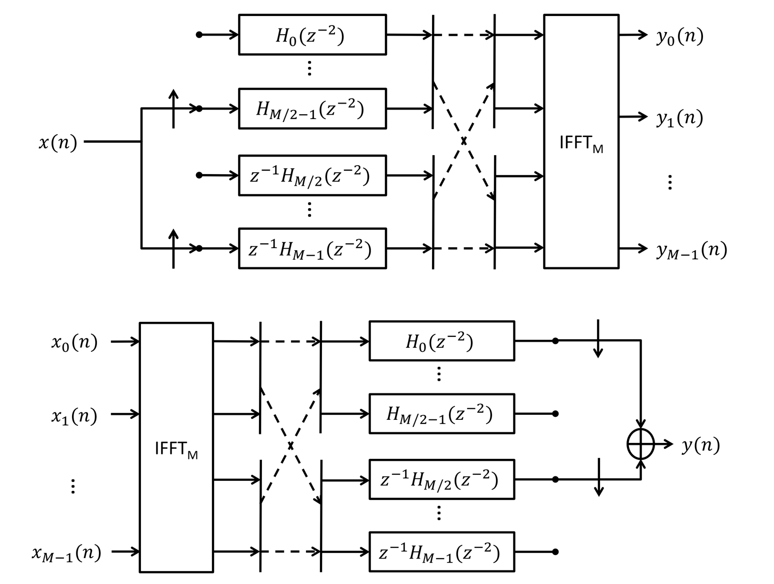

Fig. 3: Non-maximally decimated ($D = M/2$) polyphase analysis and synthesis channelizers

Non-maximally decimated analysis and synthesis channelizers can be used together to first split up a frequency spectrum into several small, discrete channels, and reconstruct it around certain signals of interest [9]. This structure is shown in Figure 4.

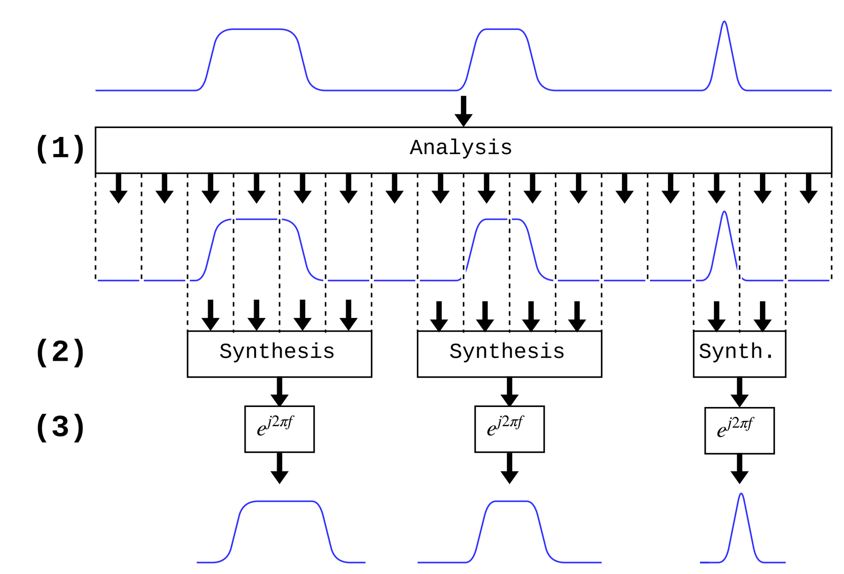

Fig. 4: Using polyphase analysis and synthesis channelizers together to create a highly configurable and efficient filter bank. Note polyphase channelizers operate in the time domain, but in this figure signals are shown in the frequency domain to illustrate the concept.

Overlap-Save Filter Bank

The Overlap-Save (OS) Filter Bank uses OS Fast Convolution to simultaneously isolate N signals. By performing tuning in the frequency domain, or after the FFT in the time-domain, as shown here, a single forward FFT can be re-used for all N channels. This forward FFT can also be re-used for cyclostationary detection in certain situations, making for a very efficient structure.

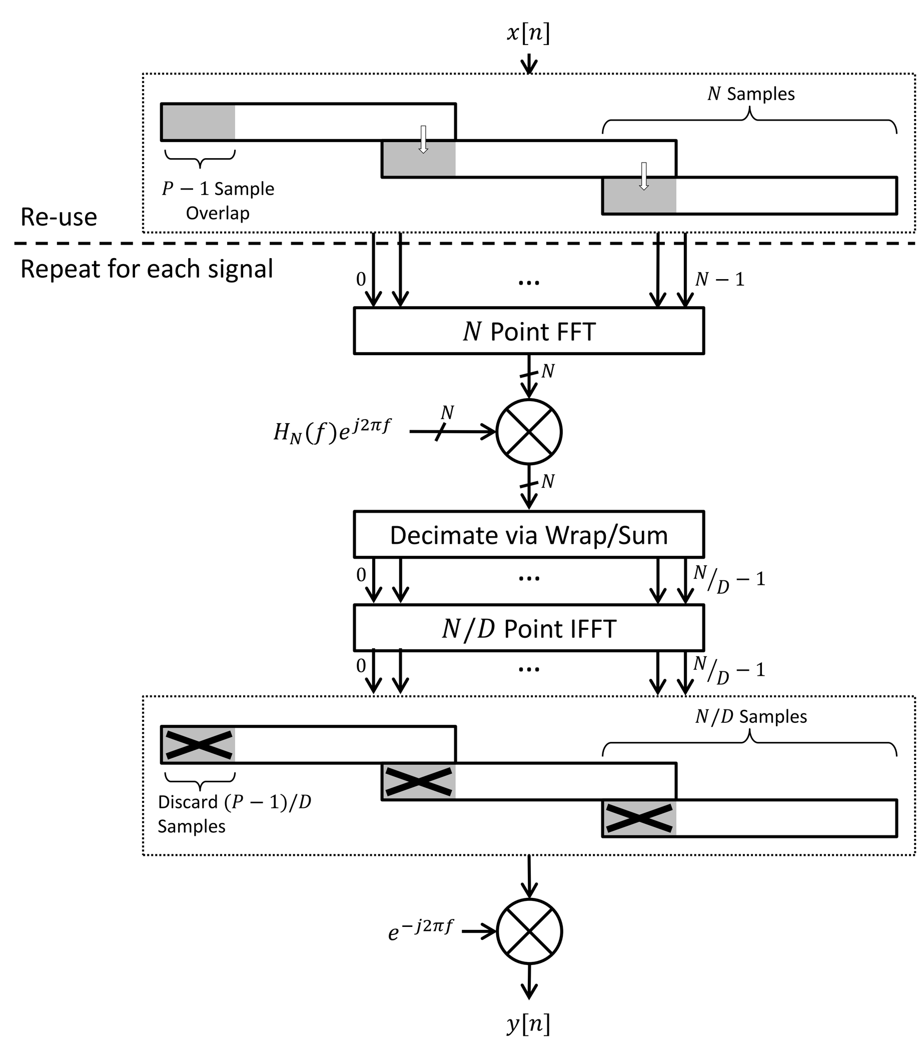

Fig. 5: Using polyphase analysis and synthesis channelizers together to create a highly configurable and efficient filter bank.

Decimation is also performed in the frequency domain via a "wrap/sum" approach, which means a smaller Inverse FFT can be used for each output [10].

Simulation Results

A simulation of these structures has been created and used to compare the efficiency of the two filter bank structures. A comparison of runtimes for the overlap-save structure and the polyphase structure can be seen in Figure 6. The plot shows the runtime when both structures are used to simultaneously detect and tune various numbers of signals. Each filter bank is configured to decimate every signal down to two samples per symbol.

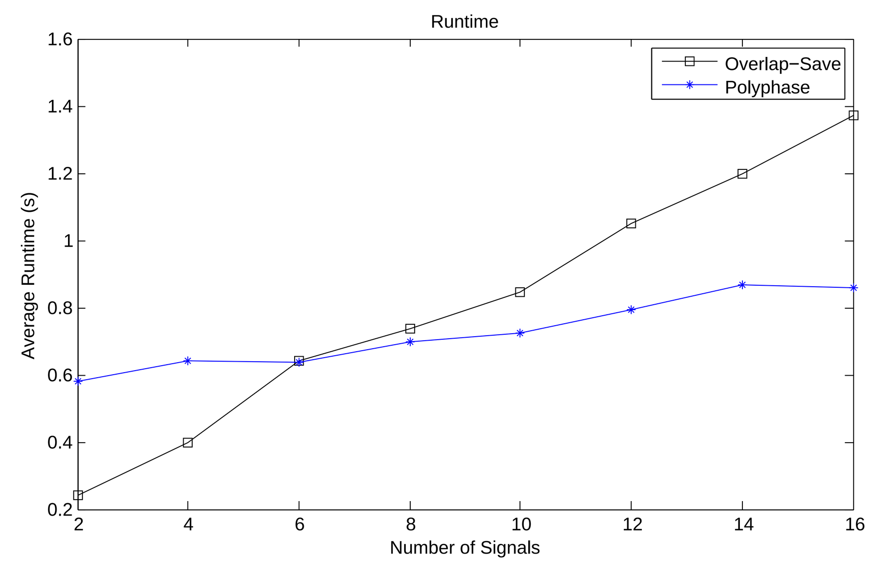

Fig. 6: Runtime comparison of detector combined with the overlap-save. Simulated 10 MHz acquisition with evenly spaced 78.125 ksymbol/s QPSK carriers.

There are two clear takeaways from this result: 1) there is a larger up-front cost when using a polyphase filter bank, but 2) the marginal cost for each additional signal being isolated is lower for the polyphase filter bank. Thus for higher numbers of signals the polyphase filter bank can be more efficient.

The situation simulated in this scenario represents a best-case scenario for both structures - the required decimation factor is a power of two. If a decimation factor with a large prime factor is used then both channelizer structues must perform an inefficient FFT. Figure 7 illustrates this effect for the polyphase filter bank.

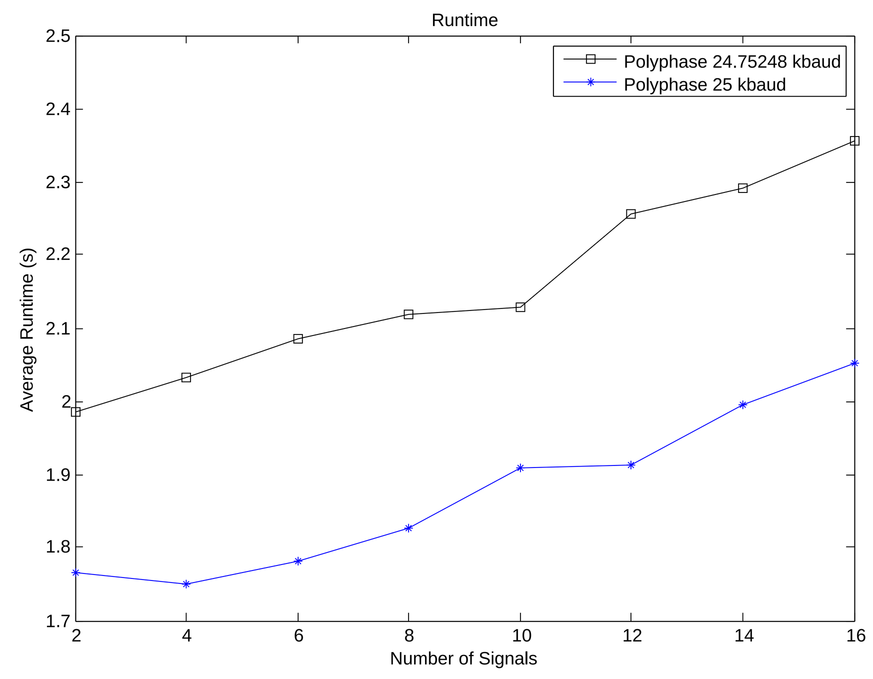

Fig. 7: Runtime comparison of detector combined with the polyphase filter bank. The 24.75248 kbaud signal requires a 202 point IFFT, while the 25 kbaud signal can use a 200 point IFFT. The former has a large prime factor, 101, leading to a much longer runtime. A similar effect can be seen in the overlap-save structure.

References

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All of the source for this simulation is available on Github: https://github.com/TheNeuralBit/cyclo_channelizer/