Square Kilometer Array South Africa

Internship technical report

KAT-7 GPU-accelerated Inverse Polyphase Filterbank

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Glossary

FIR	Finite Impulse Response. 3
FPGA	Field Programmable Gate Array. 4
lo	Local Oscillator. 3
PFB	Polyphase Filter Bank. 3
PR	Perfect Reconstruction. 4
VLBI	Very Long Baseline Interferometry. 3

Contents

1 Introduction

At its core Very Long Baseline Interferometry (VLBI) is an interferometry process where the output from several radio antennae are combined to form an equivalent output to a telescope of the size equal to the distance between the furthest two antennae in the VLBI array. For a comprehensive overview of the technique the reader is referred to the detailed introduction by Middelberg et al. [1]. Several such extended arrays exist including the European VLBI network and the Very Long Baseline Array. The hope is to include the KAT-7 in future VLBI observations.

Traditionally the process required raw data to be dumped to a storage medium, say tape and physically shipped to a correlator where the data from several telescopes could be combined. The new trend in VLBI is to perform real-time correlation between antennae using high-speed internet connections and is known as 'eVLBI'. Both the Australian Long Baseline Array and the European VLBI network has performed successful eVLBI observations.

Ultimately the problem being investigated (at least in part by this report) can be boiled down to converting data sent over the SPEAD protocol (employed internally by the KAT-7 array) to the VDIF format. This conversion process includes a necessary first step where the current sampling rate of 800 MHz [1] is reduced to 128 MHz through *Digital Downconversion*. The basic operation involves the following three steps:

1. Mixing. Where the signal is shifted down to *baseband* (frequency 0 of the spectrum), by mixing the signal with a tone produced by a Local Oscillator (lo). This is simply a generated sine wave at the lower end of the sub-spectrum to be extracted. This is simply done by an element-wise multiplication of the original signal with the local oscillator tone. In essence mixing is not a *linear* (refer to [2, ch. 5]) process. If f was a single channel in the frequency domain then mixing produces replicated channels at $f - f_{lo}$ and $f + f_{lo}$.
2. Filtering. In order to eliminate aliasing in the frequency domain due to mixing and frequencies above the new sampling rate we use a Finite Impulse Response (FIR) filter with the cutoff set at the rate $\frac{1}{2}f_{decimated}$ to comply with the Nyquest sampling theorem (see [2, ch. 3]).
3. Interpolation and Decimation. The reader is referred to `http://www.dspguru.com/dsp/faqs/multirate/basics` for an overview of the process.

There is, however, a further complication to deal with, before this downconversion process. The KAT-7 beamformer produces a series of frequency spectra[2]. If no filtering was applied these spectra the undo operation would only have involved applying the inverse Discrete Fourier Transform. However, the original voltage data went through a filter-bank operation in a process known as the Polyphase Filter Bank (PFB). This method is also known as the Weighted Window Overlap method. The reader is referred to `https://casper.berkeley.edu/wiki/The_Polyphase_Filter_Bank_Technique` for a detailed description on this technique.

2 Method

The forward PFB process can be thought of as a very basic analysis filter bank, whereas the inverse process can be thought of as a synthesis filter bank. The analysis filter bank uses a Hamming-windowed FIR with $P = 8$ banks of $N = 1024$ elements, with no up or down-sampling stages [3]. The key differences between the analysis and synthesis processes are:

[1] According to the KAT-7 Data Interface document
[2] Each with 1024 channels according to the KAT-7 Data Interface
[3] According to information provided by Jason Manley

1. If $H[n]$ is the prototype FIR filter and the analysis filter bank uses the subfilters $H_1[n], H_2[n] \ldots H_P[n]$ each of length N then the synthesis filter bank uses the subfilters $\bar{H}_1[N-n-1], \bar{H}_2[N-n-1] \ldots \bar{H}_P[N-n-1]$[4]

2. The commutator is flipped around (as shown on page 10 of Zhou's report) and therefore the sub filters should be processed in reverse order.

According to Parishwad Vaidyanathan [3] this basic filter bank cannot achieve Perfect Reconstruction (PR) and have to be modified in order to do so. This involves modifying both the analysis and synthesis filter banks. In our situation this is not plausible, since the only the basic form of an analysis filter bank is implemented on Field Programmable Gate Arrays (FPGA) due to their simple construction and fast evaluation times [3]. Vaidyanathan goes on to state that the synthesis filter bank requires subfilters of much greater length to obtain reasonably good reconstruction and is therefore computationally prohibiting.

[4]Findings published in an in-house final technical report titled 'A review of polyphase filter banks and their application'. Daniel Zhou. Air Force Research Laboratory, Information Directorate, Rome Research Site, Rome, New York.

References

[1] Enno Middelberg and Uwe Bach. High resolution radio astronomy using very long baseline interferometry. *Reports on Progress in Physics*, 71(6):066901, 2008.

[2] Steven W Smith et al. The scientist and engineer's guide to digital signal processing. 1997.

[3] Parishwad P Vaidyanathan. Multirate digital filters, filter banks, polyphase networks, and applications: A tutorial. *Proceedings of the IEEE*, 78(1):56–93, 1990.