Improving the RFNoC Polyphase Channelizer: Adding Downselection and Timestamping

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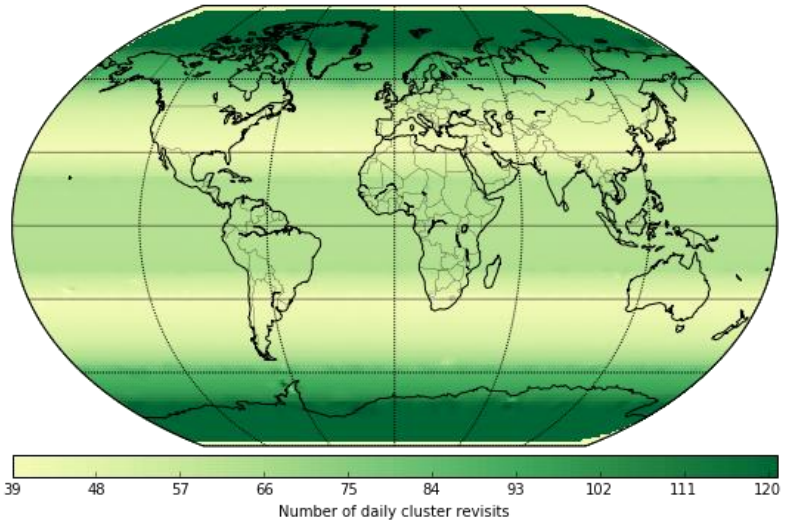
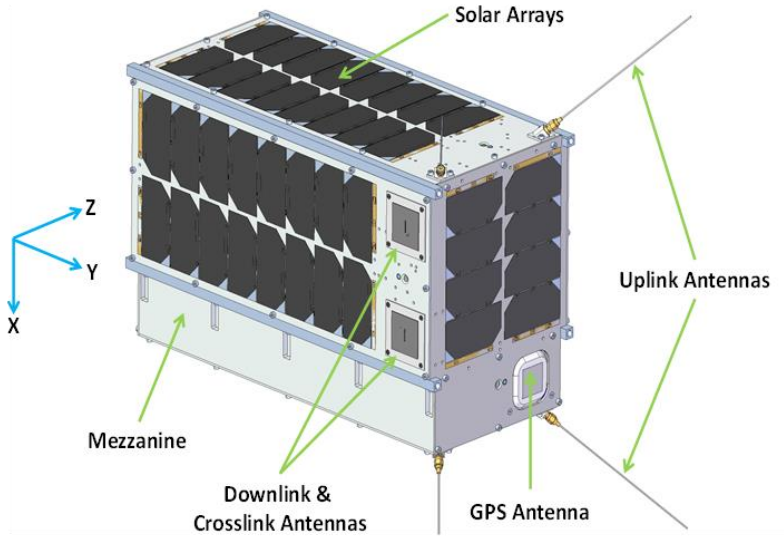
Introduction

- Venture-backed startup in Herndon, VA
- Technical Mission:
  - Launch a cluster of small satellites in Fall 2018
  - 3 satellites per cluster, flying in formation
  - Satellites in LEO (low earth orbit) in a polar orbit
  - Satellites share a common ground footprint and provide geometric diversity
  - Passively receive RF signals
  - Independently geolocate emitters from 100 MHz to 15 GHz ("DC to Daylight") using TDOA and FDOA measurements





Requirement to channelize spectrum using FPGA

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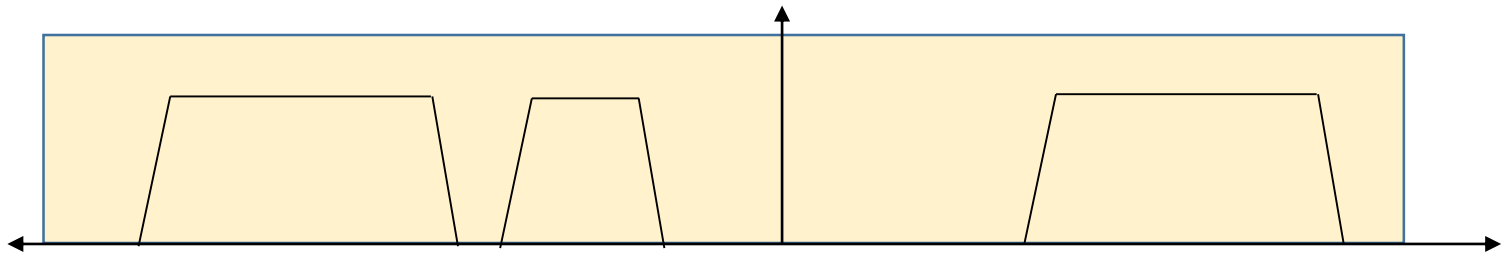
Introduction: Channelization

- We want to simultaneously process signals at multiple center frequencies
- Using a single RF front end, this can be accomplished in a few ways
- Option 1: Use a large sample rate to capture the entire chunk of spectrum
  - Perform down-conversion of each subchannel in software
  - Disadvantage: Wasted bandwidth in FPGA – Software transfer, downconversion and resampling load is placed on processor



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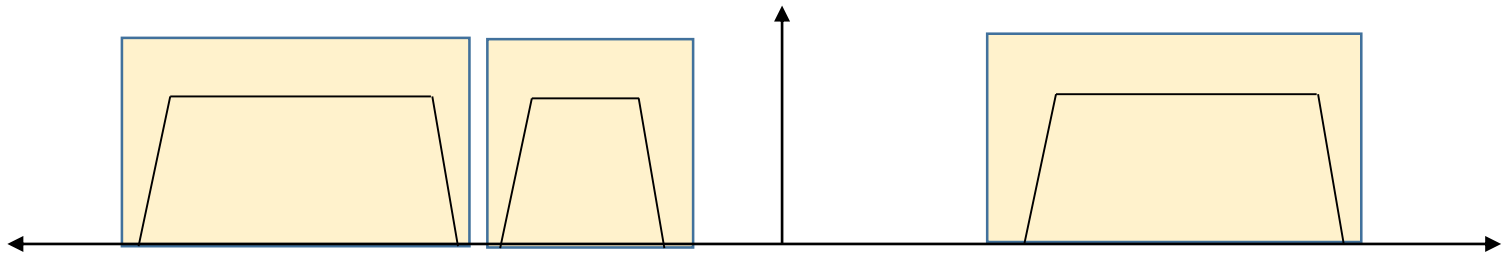
Introduction: Channelization

- We want to simultaneously process signals at multiple center frequencies
- Using a single RF front end, this can be accomplished in a few ways
- Option 2: Perform channelization (filtering and downconversion) of individual channels in the FPGA
  - Place processing load on FPGA, improve bandwidth usage in data transfer
  - Interleave channels in FPGA, deinterleave stream in software (carefully!)



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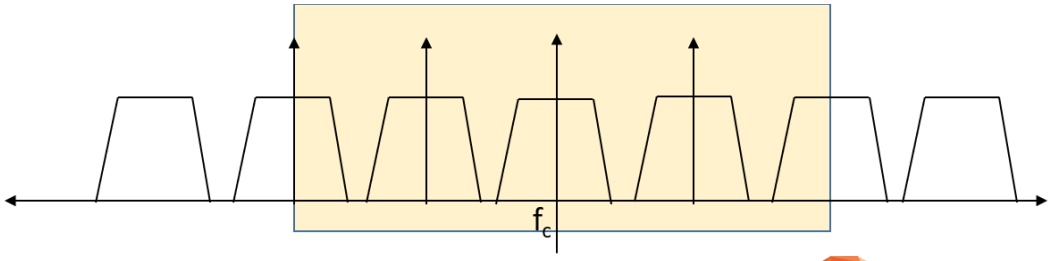
Introduction: Channelization

- There are many possible ways to design a channelizer
  - Brute force mixing and filtering separately for each desired channel
  - Efficient architectures leveraging channel symmetry, FFTs
  - 'fred harris' style designs which utilize polyphase filters and FFT for mixing
    - 2X oversampled version used by [1]
- Interesting and efficient polyphase channelizers can be designed, when channels are evenly spaced
- Why channelize in FPGA?
  - Downsample higher bandwidths!



[1] Vallance, P. "Channelization using RFNoc", GRCON 2017.

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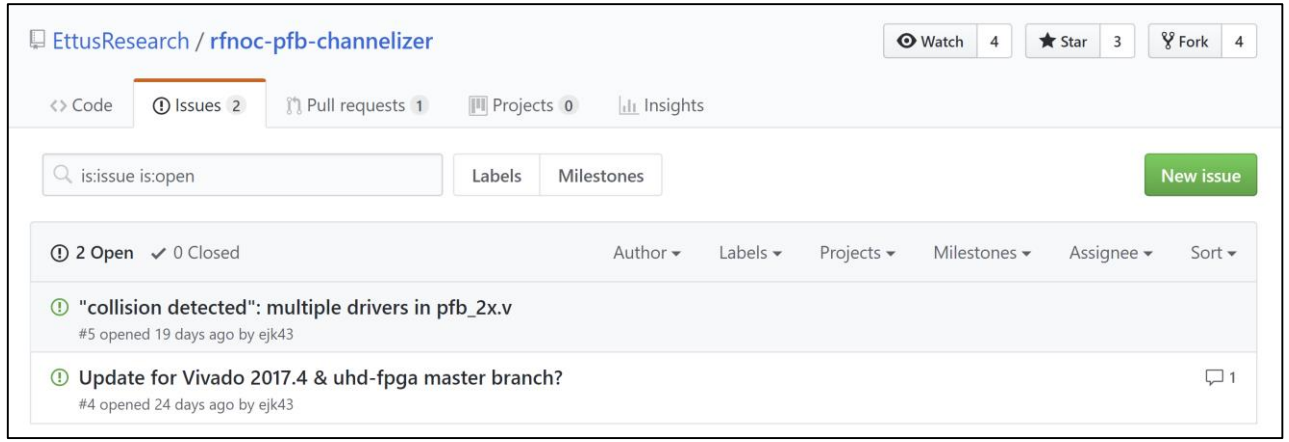
Open Source Channelizer: Current Status?

- Great talk and paper at GRCon 2017
- Missing channel selection, muxing, and timestamping
- Commits may have gotten lost in translation?
  - Would love to see this working!



Back to the basics…

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Polyphase Channelizer Basics

- Suppose we want to channelize N streams which are evenly spaced in center frequency
- Each channel k consists of a mixing operation, downsampling and low pass filtering. The noble identities allow us to rewrite into this form:

$$y_k(m) = \sum_{n=0}^{NP-1} x(n + mN) e^{-j2\pi kn/N} h(n)$$

- Each channel k contains the same low pass filter h(n) of length N * P.

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Polyphase Channelizer Basics

- This equation may be reorganized into the following form:

$$
\begin{aligned}
y_k(m) = \quad & h(0)x(t) && + \ \ldots \ + && h(N-1)x(t-N+1)e^{-j2\pi f_s k(N-1)/N} \\
+ \quad & h(N)x(t-N) && + \ \ldots \ + && h(2N-1)x(t-2N+1)e^{-j2\pi f_s k(N-1)/N} \\
& \vdots && && \vdots \\
+ \quad & h(NP-N)x(t-NP+N) && + \ \ldots \ + && h(NP-1)x(t-NP+1)e^{-j2\pi f_s k(N-1)/N}
\end{aligned}
$$

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$$

- In this form, each column can be seen to be a phase of filter h(n) with P taps per phase

[2] S. Faint, W. Read, "A Comparison of FFT and Polyphase Channelizers," DRDC Ottawa, 2013.

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Polyphase Channelizer Basics

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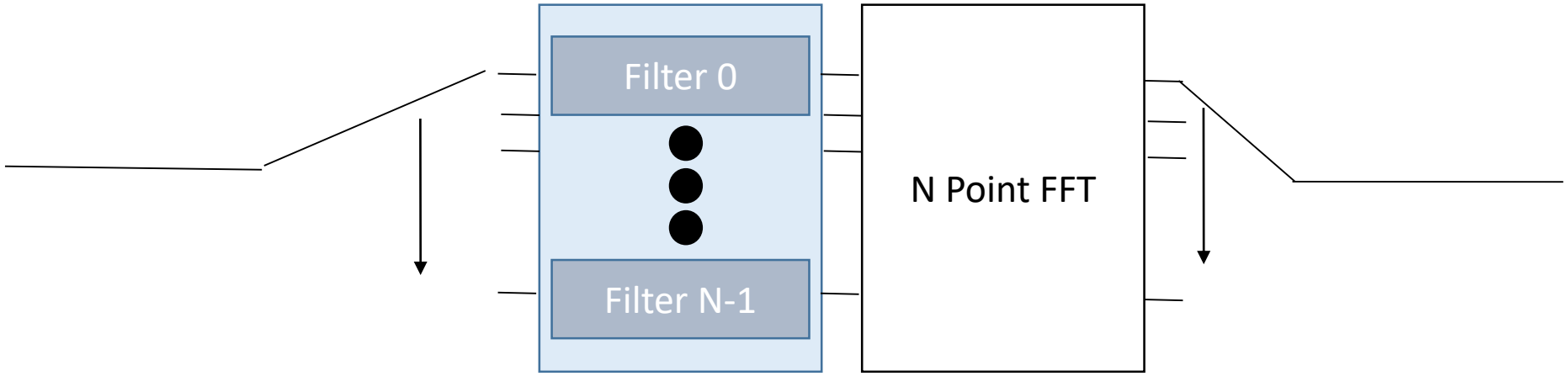
y_k(m) = \; & \boxed{h(0)x(t) + \ldots + h(N-1)x(t-N+1)e^{-j2\pi f_s k(N-1)/N}} \\
& + h(N)x(t-N) + \ldots + h(2N-1)x(t-2N+1)e^{-j2\pi f_s k(N-1)/N} \\
& \vdots \qquad\qquad\qquad\qquad\qquad\qquad \vdots \\
& + h(NP-N)x(t-NP+N) + \ldots + h(NP-1)x(t-NP+1)e^{-j2\pi f_s k(N-1)/N}
\end{aligned}
$$

- In this form, each column can be seen to be a phase of filter h(n) with P taps per phase
- Also, each row can be seen to be a discrete fourier transform

[2] S. Faint, W. Read, "A Comparison of FFT and Polyphase Channelizers," DRDC Ottawa, 2013.

Polyphase Channelizer Basics

- The operations may be implemented by a polyphase filter, where each lag is a phase of h(n), and a FFT



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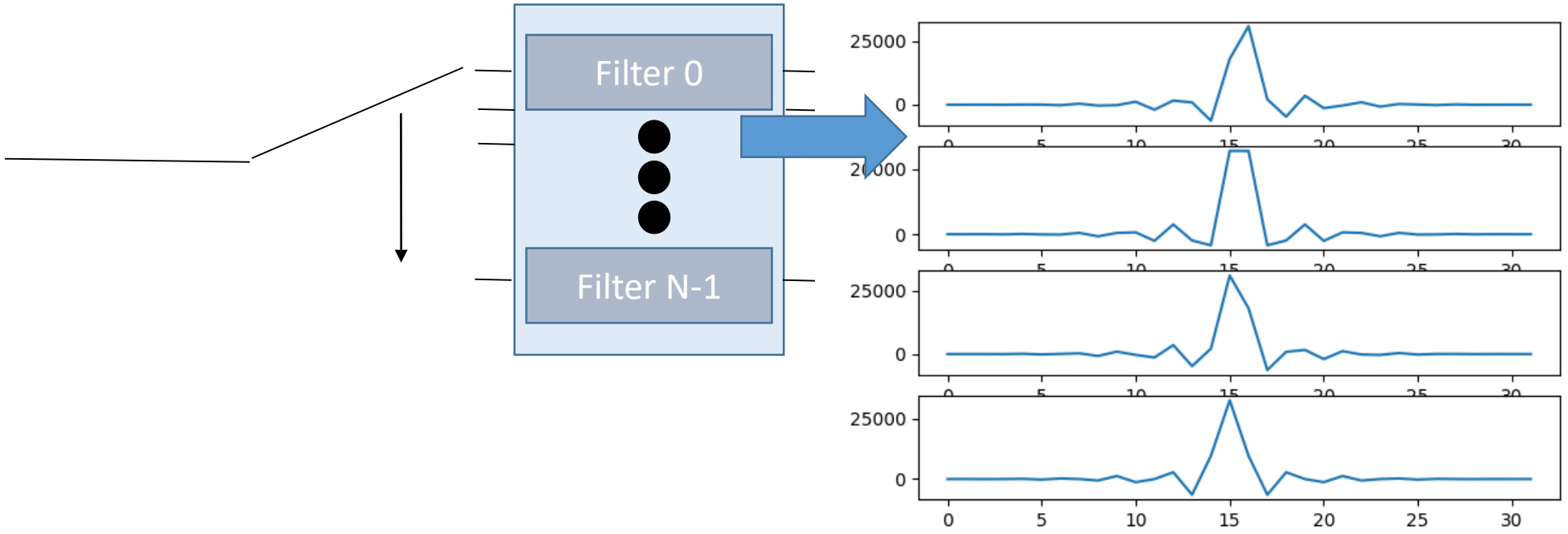

Group Delay

- The polyphase channelizer is a more efficient, but exact implementation of the same basic channelization equation

$$y_k(m) = \sum_{n=0}^{NP-1} x(n + mN) e^{-j2\pi kn/N} h(n)$$

- Viewing the equation, it is evident that the response is identical for each channel k
  - The same filter is used for each channel
  - k only affects the mixing frequency
- This is wonderful, as each channel can get the same timestamp in a given block!

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GNURadio Channelizer Design

- An architecture is required in which the core provides channelization in the FPGA
  - Split output into channels; Create timetags for each channel
- All channels are routed (interleaved) to **software**
  - RFNoC FPGA-routing of channels will be a future architectural improvement
- The implemented design provides a timestamping framework in which the core itself is replaceable
  - We chose the simple channelizer example presented
  - [1] may also be substituted

[1] Vallance, P. “Channelization using RFNoc”, GRCON 2017.

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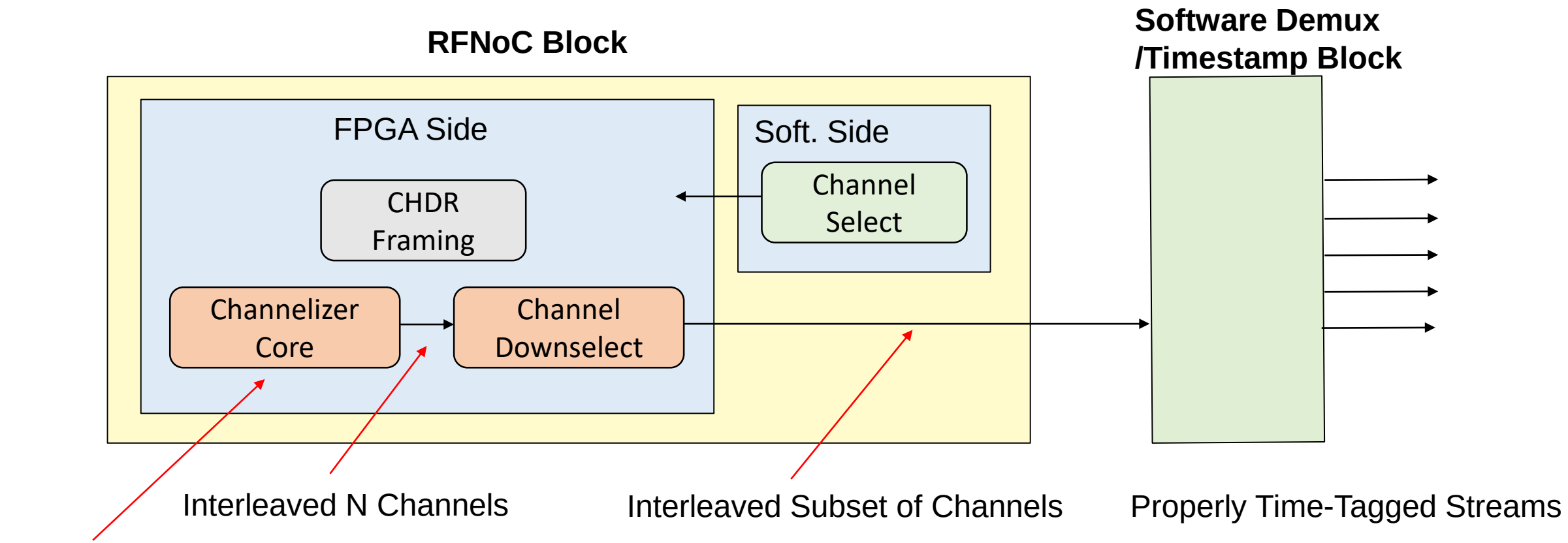
GNURadio Channelizer Architecture



Timestamping Methodology

- Channels are interleaved and downselected out of core into a single stream
- Stamping of tick count in FPGA must be done in a way that is deterministic when the stream is received in software
  - Must be able to associate a time tag with a channel number, given that we know which channels have been selected
  - Solution must be resistant to dropped packets, provide ability to re-tag deinterleaved streams reliably
- Solution: Manually form CHDR packets, with payload containing a number of samples that is a multiple of the channel select count. Stamp the packet as if the first sample was from channel 0.

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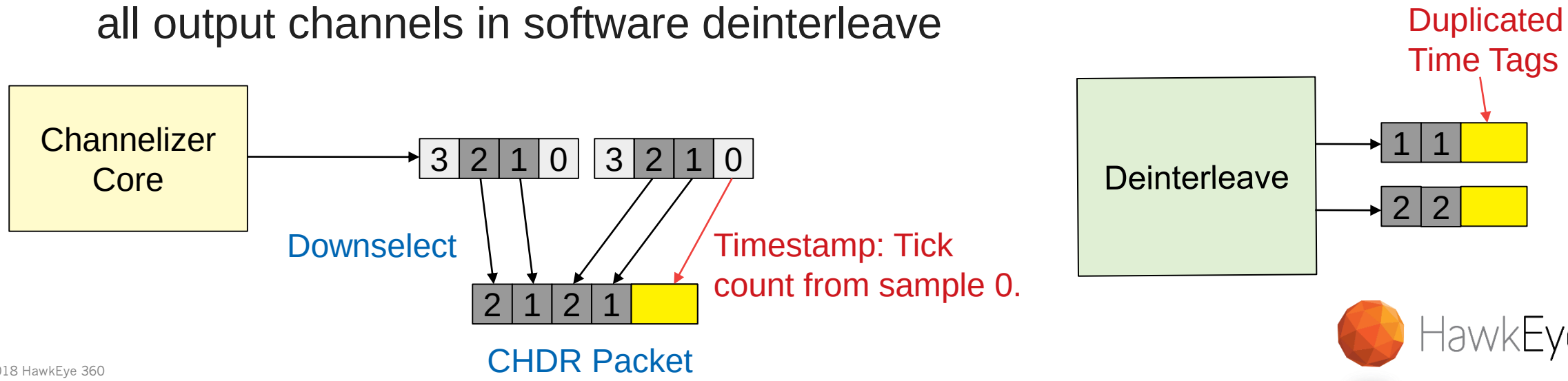
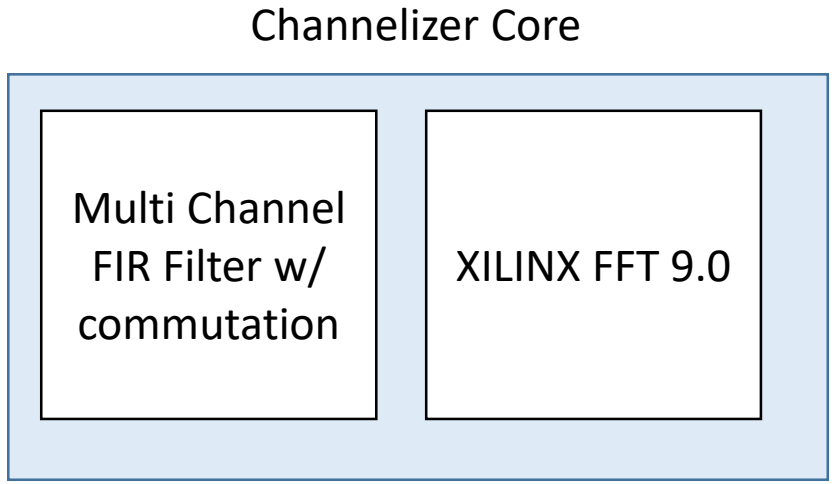
Timestamping Methodology Illustrated

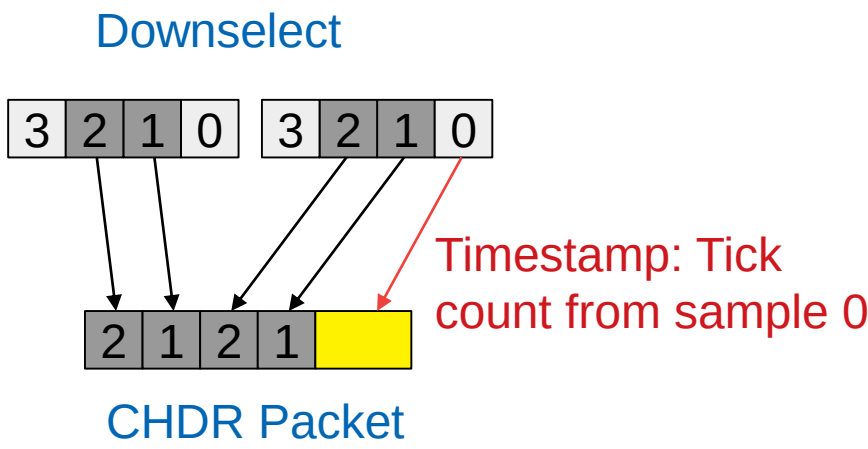
- Example: 4 channel channelizer core, channels (0,1,2,3)
- Downselect and output channels 1,2
- Packing a multiple of the channel select count into CHDR ensures that if a packet is dropped, stamps are deterministic
- Since group delay is equal on all channels, use duplicate time tag on all output channels in software deinterleave



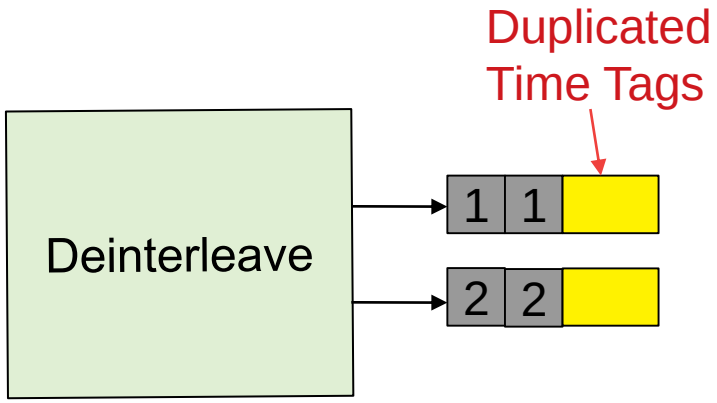
FPGA Side

- Noc Block:
  - Simple Mode (0)
  - Manual generation of CHDR packets
    - Input timestamps are placed in FIFO
    - Synchronization of output timestamps with data:
      - Newest stamp in FIFO is latched, on CHDR framer
      - XILINX FFT generates TLAST on block boundaries
    - Channel downselection
      - A downselect module pulls valid low on indices to be dropped
      - It also buffers each block, and moves TLAST to the highest channel selected. Example: 8 channel channelizer with select (0,1, 3, 5) TLAST will occur on 5
      - TLAST causes CHDR packet to be accepted with the latched timestamp
    - On TLAST, the timestamp is incremented by the tick-rate * N, where N is the channel count (pre-downselect), and latched for the next CHDR
  - An EOB resets everything, cannot tolerate timestamps on unknown channel idx





Software Side Deinterleave



- Existing GNURadio Deinterleave is used as core
- Around core, must time-tag each stream
  - We know that time tags will be received on the lowest index channel that was selected
  - We also know that group delay is identical on all channels
  - When received, **the same time tag is sent out on each stream**
- Don't forget about rate and offset!
  - There is a rate conversion of 1/N where N is total channel count
  - Rate parameter in tag must be updated accordingly
  - Also, the offset parameter must be updated for subsequent tags
  - To update offset, the number of output samples on each channel must be tracked internally

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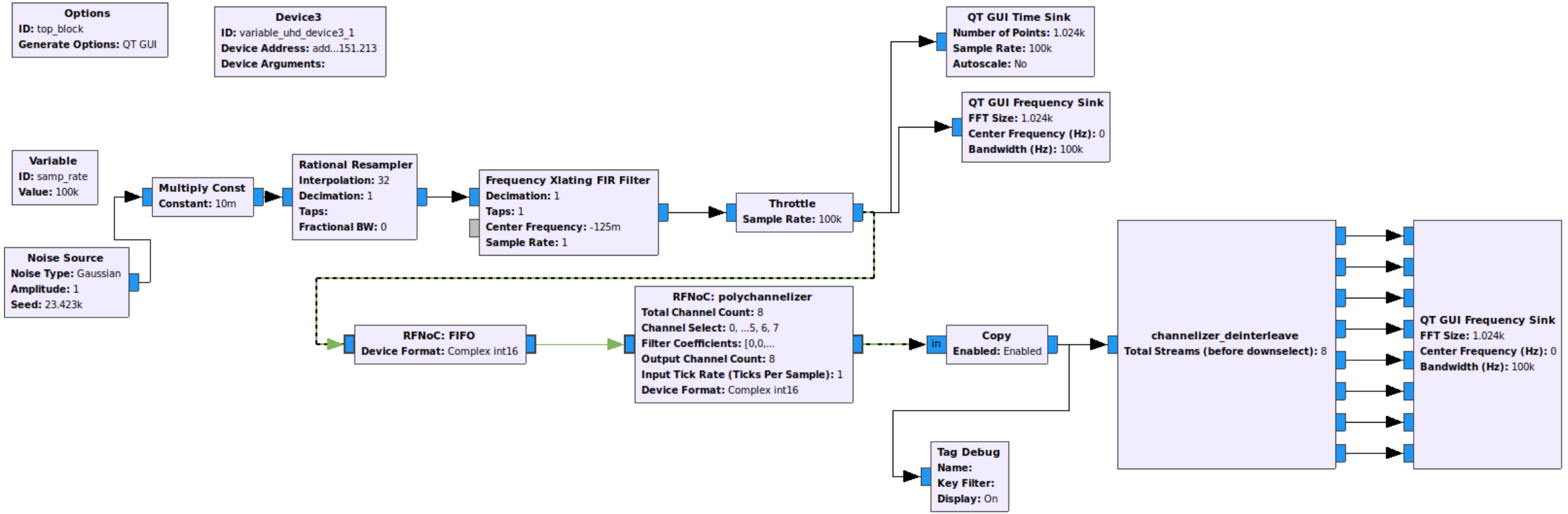
Example Flowgraph



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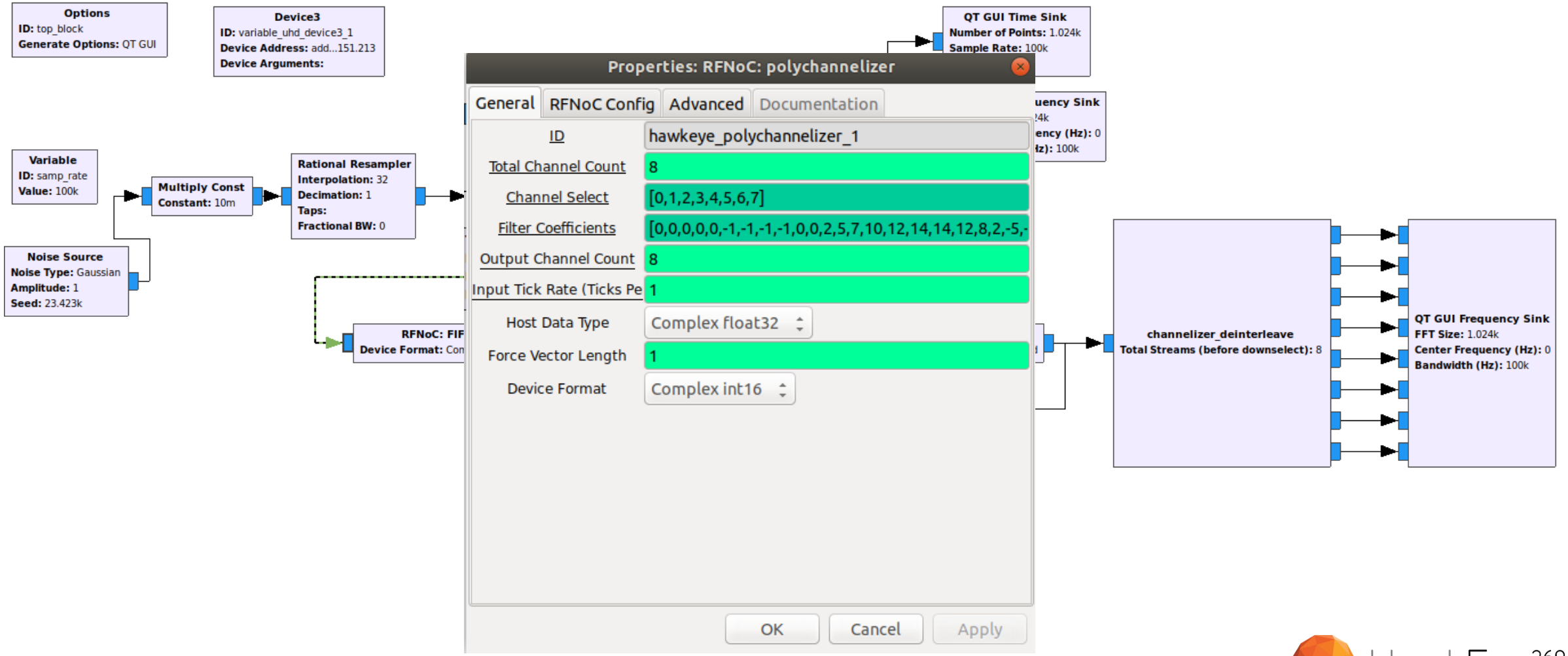
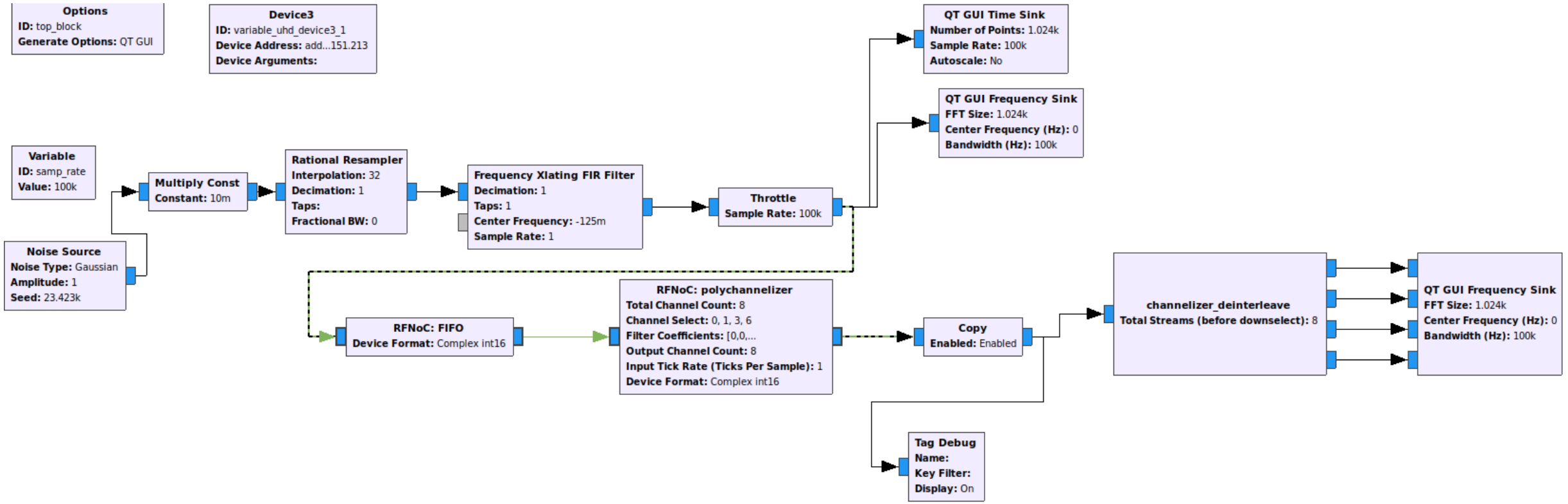
Example Flowgraph



Example Flowgraph with Downselection



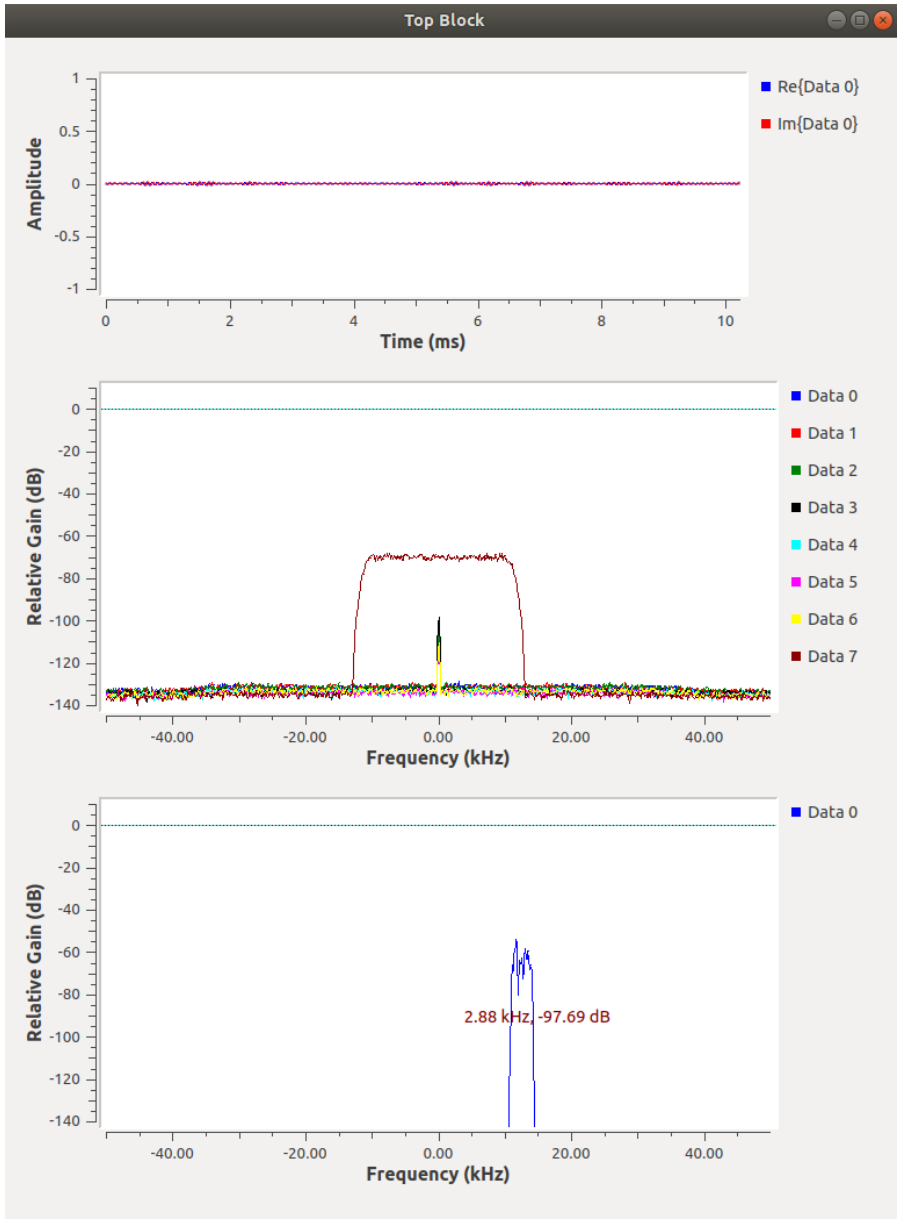
Total Channels = 8

Output Channels = 4

Example Flowgraph Output

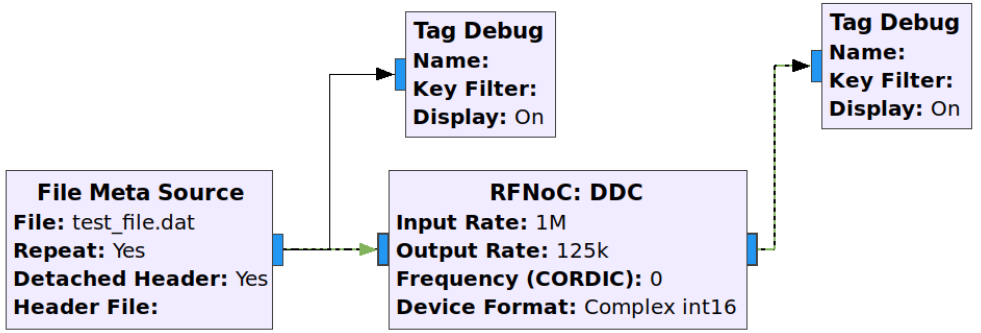
Deinterleaved Output

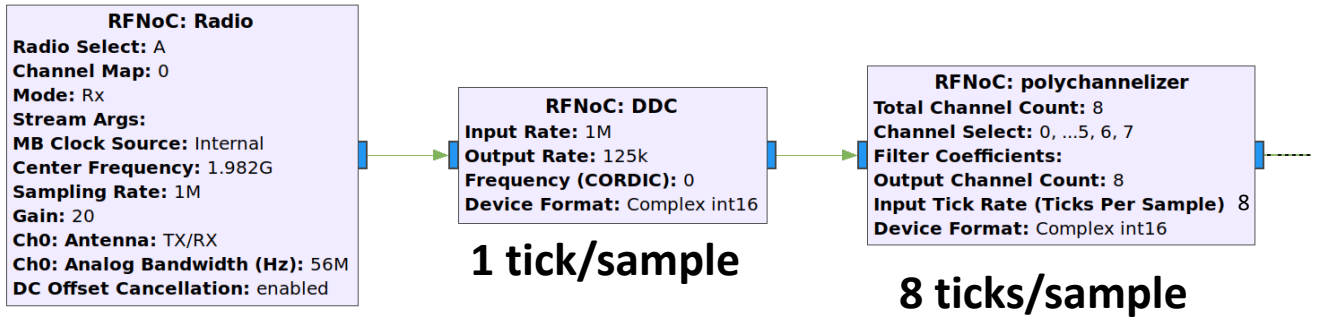
Input



Lessons Learned: RFNoC/Gnuradio Infrastructure Updates

- Add Gnuradio item tags on output samples
  - Time, Frequency, Sample Rate
- Provide RFNoC timestamp metadata from "file meta source"
  - Allows accurate tests of RFNoC time propagation during playback
- Expose "ticks per sample" to RFNoC CEs





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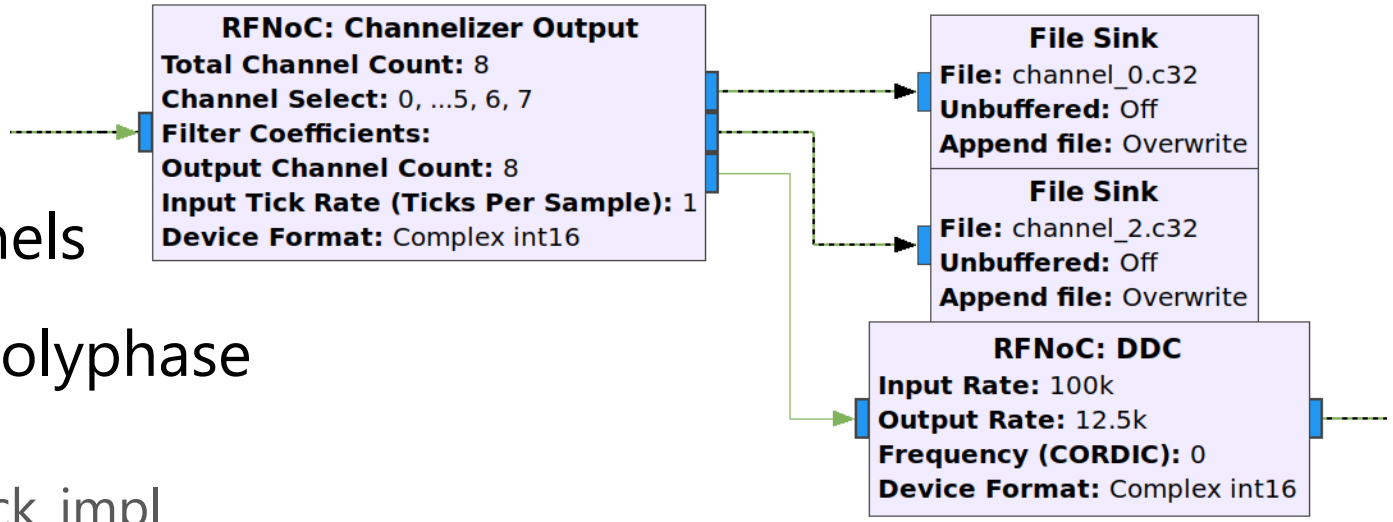
Future Work

- Reconfigurable number of channels
- Demux channels inside RFNoC polyphase channelizer gnuradio block
  - Override general_work in rfnoc_block_impl
- Route channels to downstream FPGA blocks
  - Channels need to be de-interleaved and timestamped individually in the FPGA (rather than in software)
  - Nontrivial development. Requires N axi_wrappers?
- Polyphase reconstruction
  - Using multiple adjacent channels, reconstruct a larger channel than the “minimum” channel size



Summary

- Trying to revive the RFNoC channelizer
- Implemented channel downselection in FPGA
- Implemented channel muxing in software
- Confirmed and implemented accurate FPGA and Gnuradio timestamp propagation behavior across channels

FPGA channelizer will be an invaluable utility!

We are actively looking for more interaction and support.

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Thank You

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