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Resource-Efficient Multi-Band Channelization

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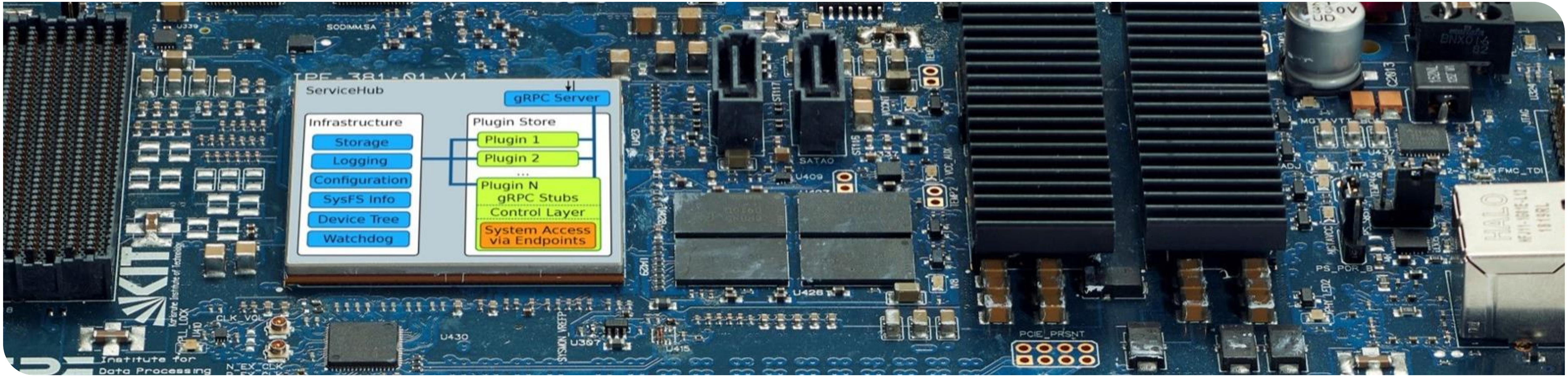

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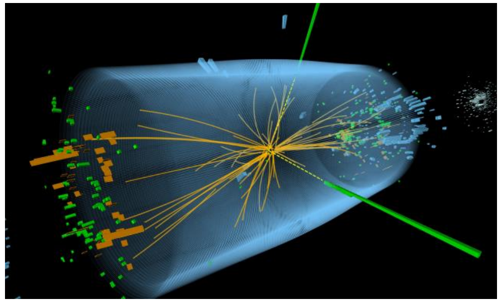
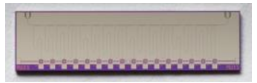
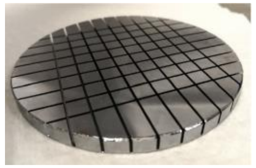
Research background of our working group

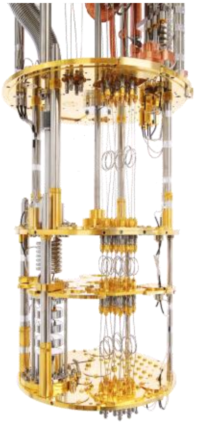
Low-latency readout and processing electronics for high-energy physics



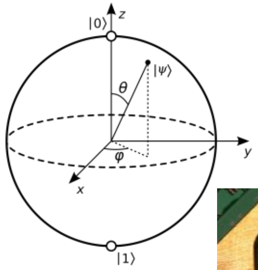
Frequency multiplexed readout systems for quantum sensors

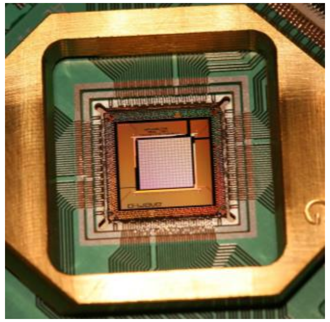






Quantum computing and qubit characterization platform

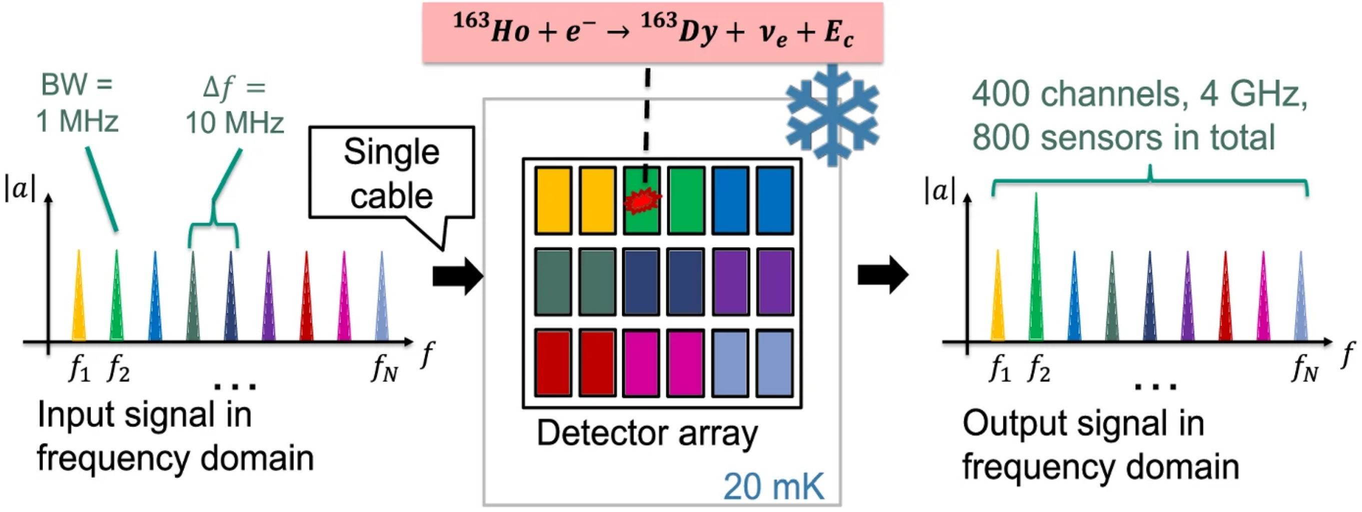




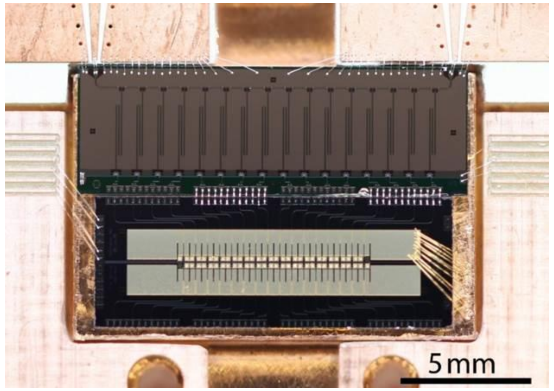
Tools and methods for modular and scalable next-gen DAQ systems

Experiment I : ECHo

- **E**lectron **C**apture of **Ho**lmium^{163}
- Goal: Finding upper limit of electron neutrino mass
- Frequency multiplexed magnetic microcalorimeters (MMC)
- Detector bandwidth: 1 MHz

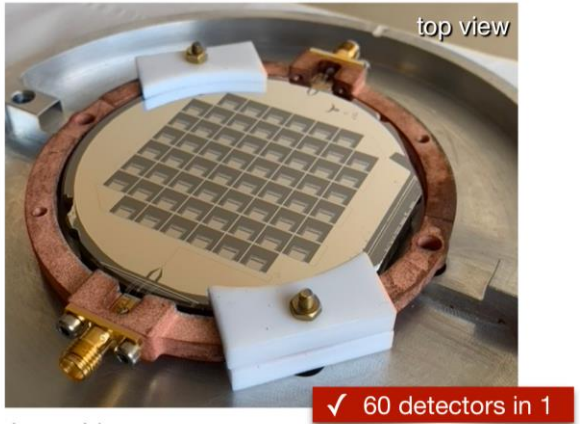


ECHo multiplexer with 16 channels:

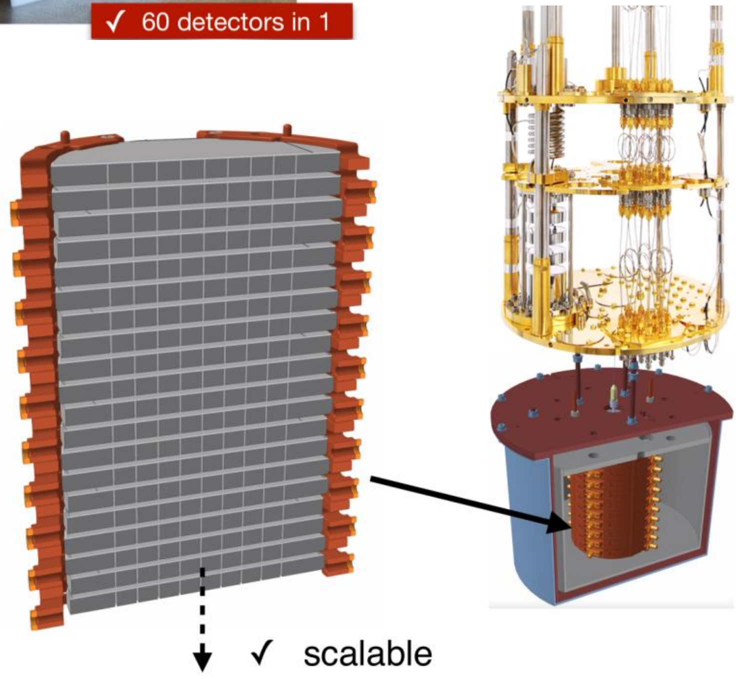


Experiment II : BULLKID

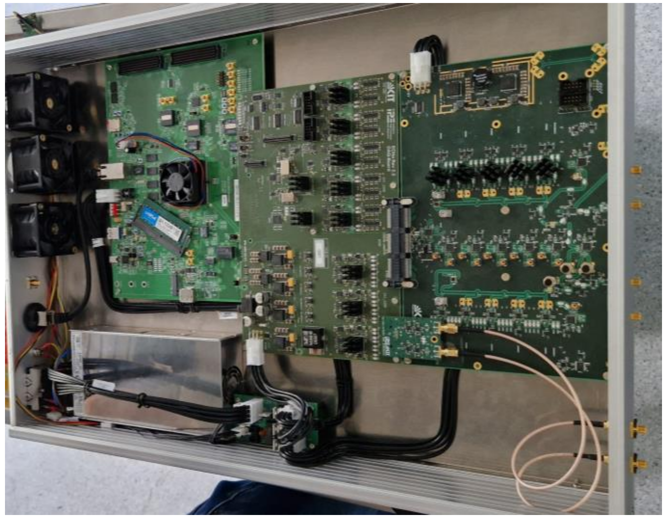
- Goal: Direct dark matter search with kg-scale targets
- Frequency multiplexed kinetic inductance detectors (KID)
- Detector bandwidth: < 100kHz
  - Slower signal rise time
  - Resonatores can be placed more densely



BULLKID multiplexer with 60 channels

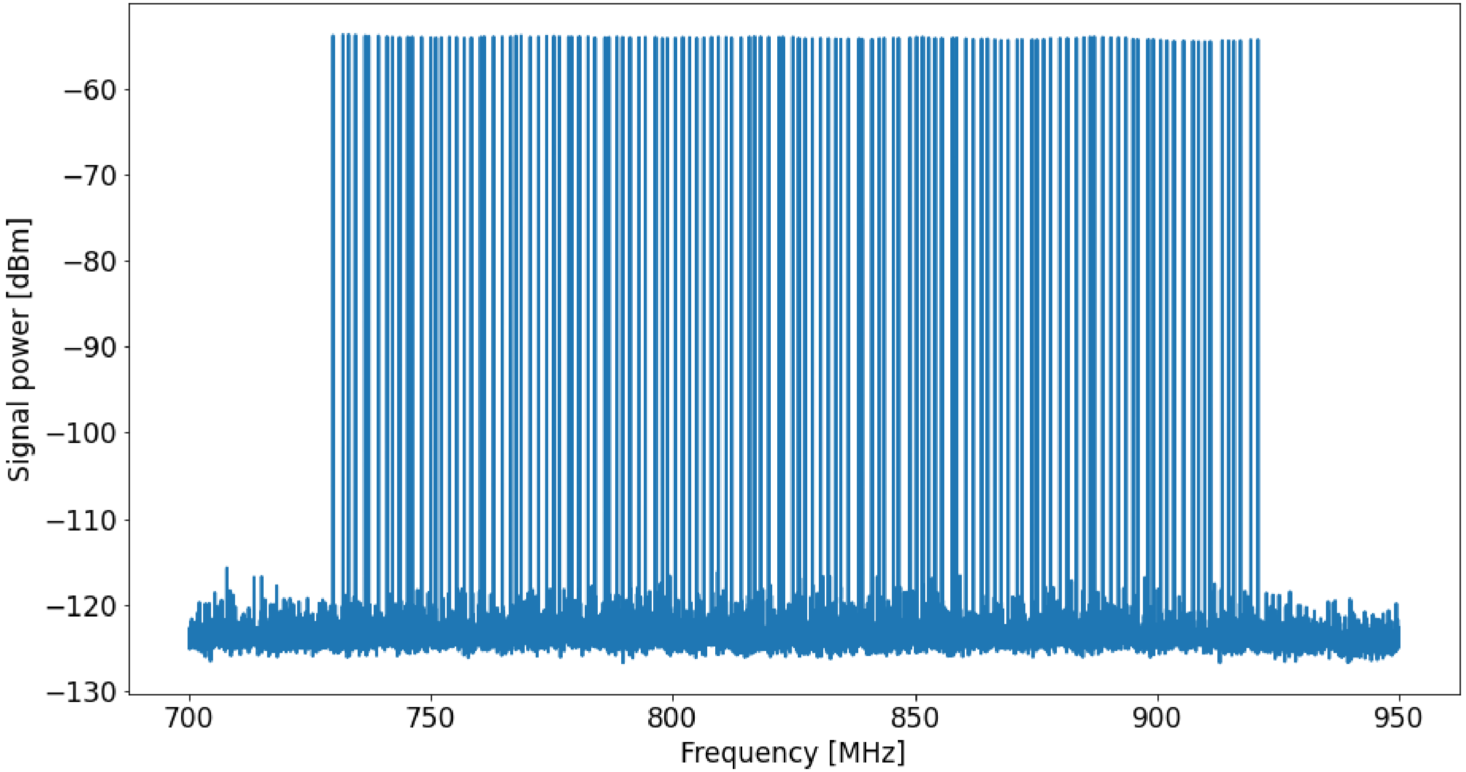


Hardware & build system

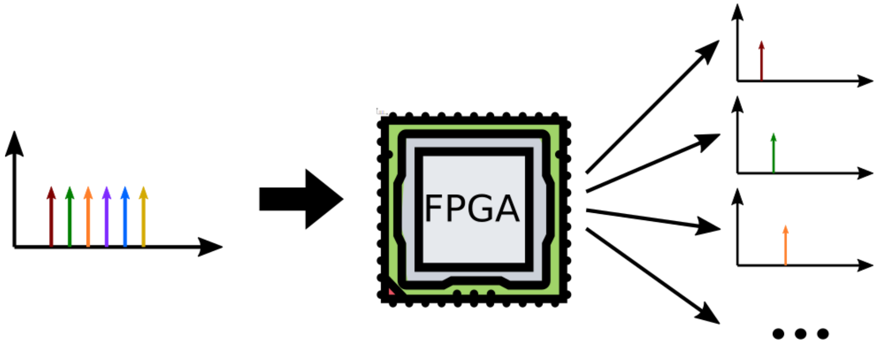


- Supported device family: AMD Zynq UltraScale+
  - MPSoC
  - RFSoC
- PL firmware in VHDL (Vivado 2020.2)
- Device image creation with custom build system based on Yocto

Problem statement



- One tone per resonator
- Realtime generation and analysis
- Nonuniform spacing of tones
- Independent processing



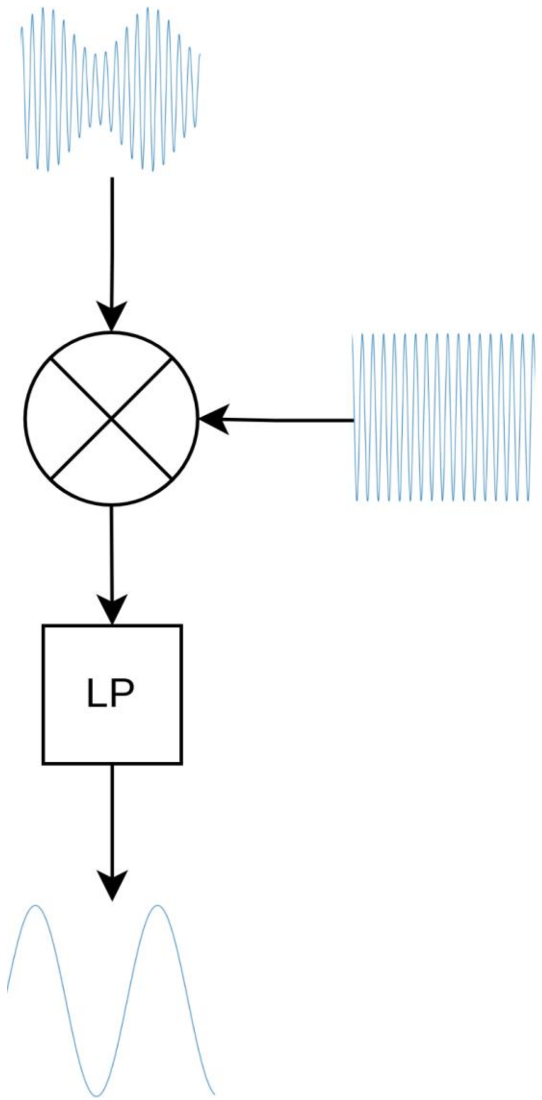
Intuitive solution

- Direct downconversion by mixing readout tone to DC

- Advantages:
  - Full control of DDC frequency
  - Optimal resolution in time

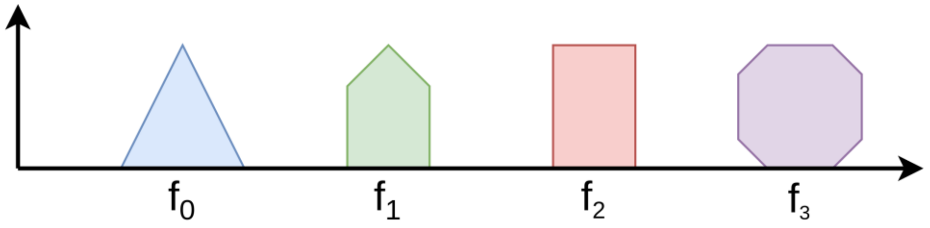
- Disadvantages:
  - One mixer and filter needed per resonator tone
  - Full parallelisation of processing, no pipelining possible

  → **Many PL resources required!**

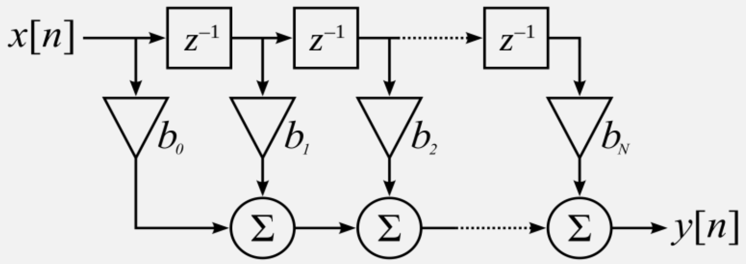


Polyphase channelizer algorithm I: FIR

Input spectrum:

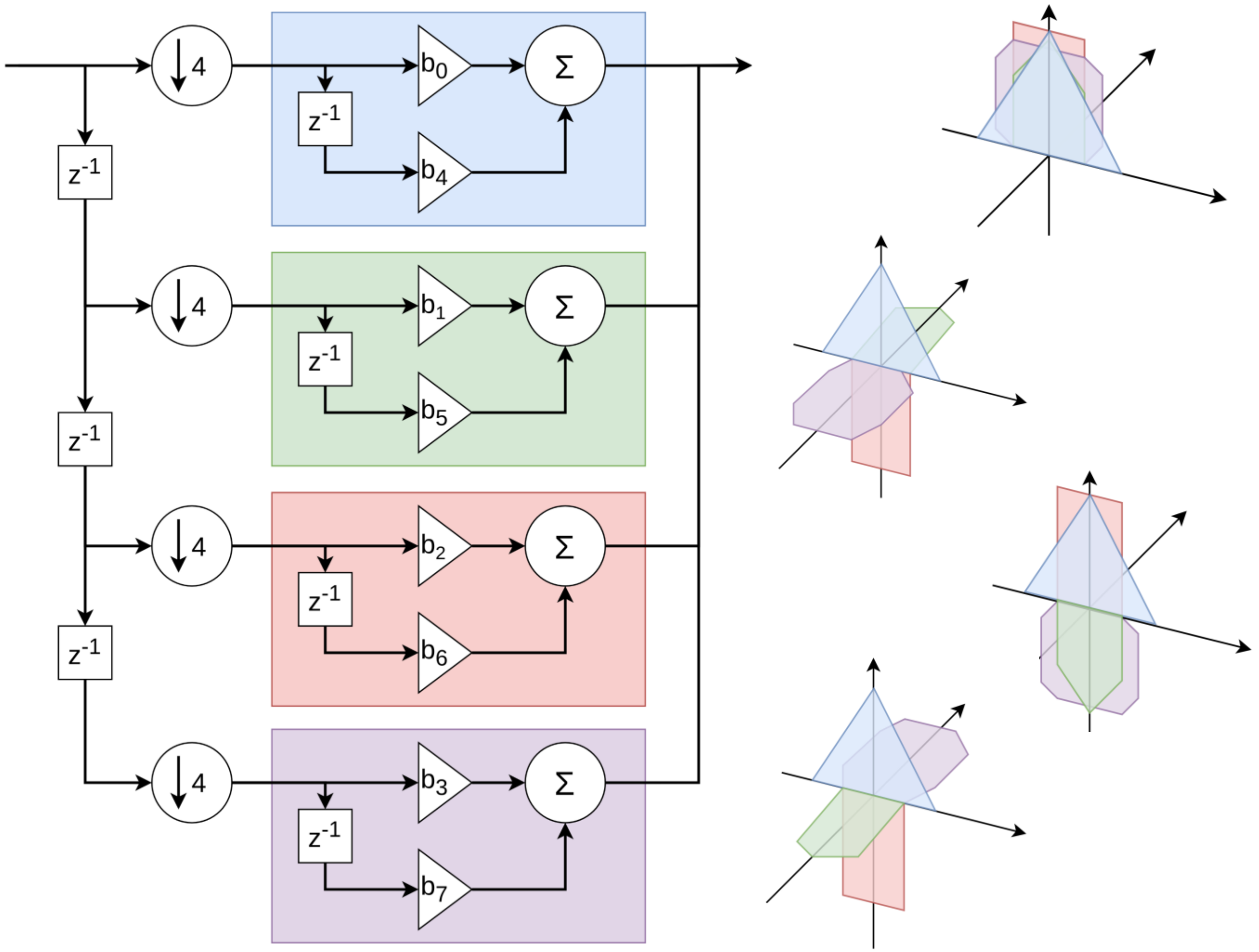


Finite Impulse Response (FIR) Filter:

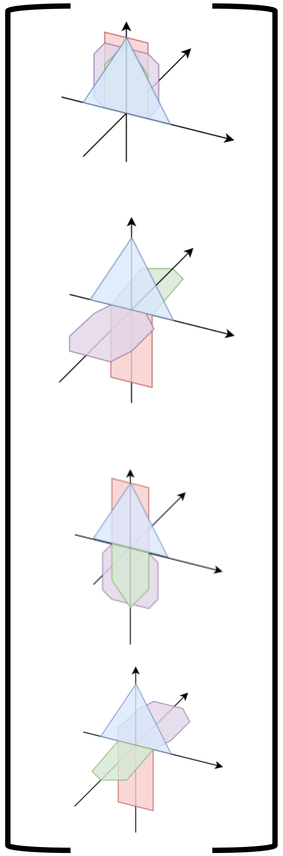


https://en.wikipedia.org/wiki/Finite_impulse_response

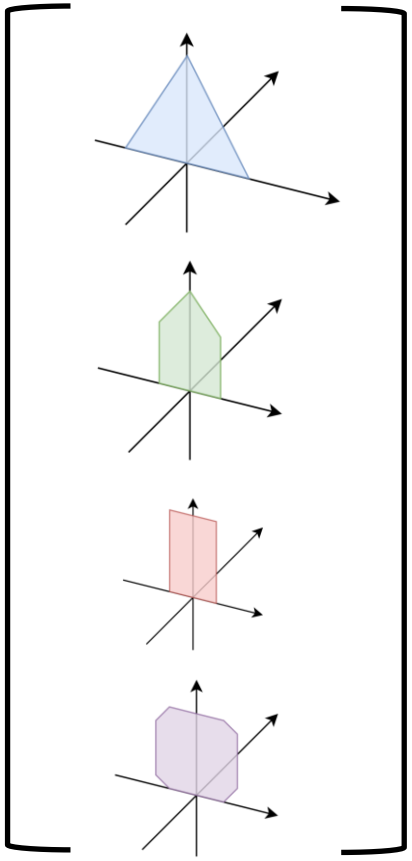
Diagrams based on:
Polyphase Channelizer Demystified [Lecture Notes]
(doi: 10.1109/MSP.2015.2477423)



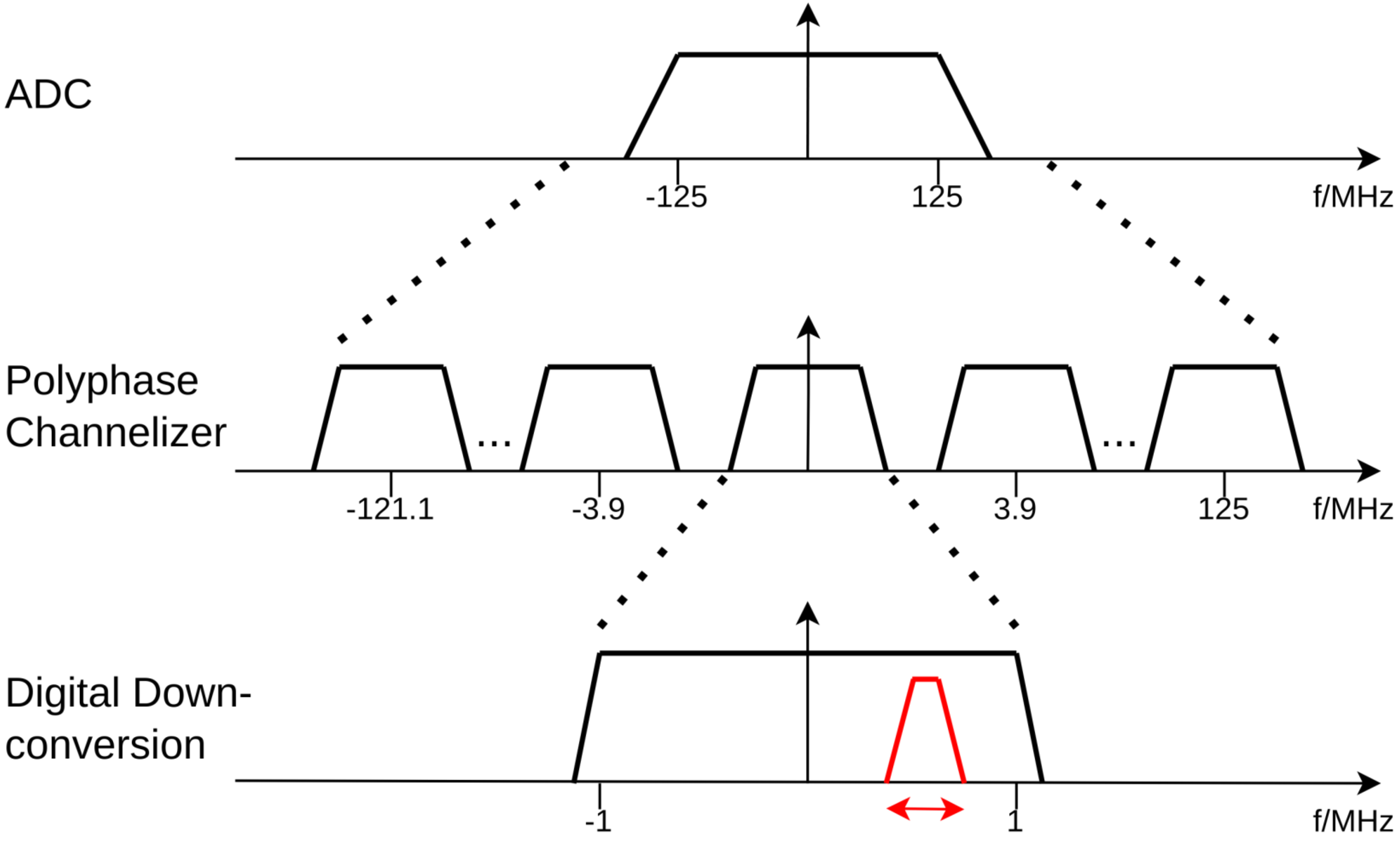
Polyphase channelizer algorithm II: DFT



$$\times \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -j & -1 & j \\ 1 & -1 & 1 & -1 \\ 1 & j & -1 & -j \end{bmatrix} =$$



Channelization concept



Parameters for BULLKID:

Input spectrum 250 MHz

64 channels with
2.1 MHz banwidth

200 kHz variable bandpass filter

Channelization concept (2)

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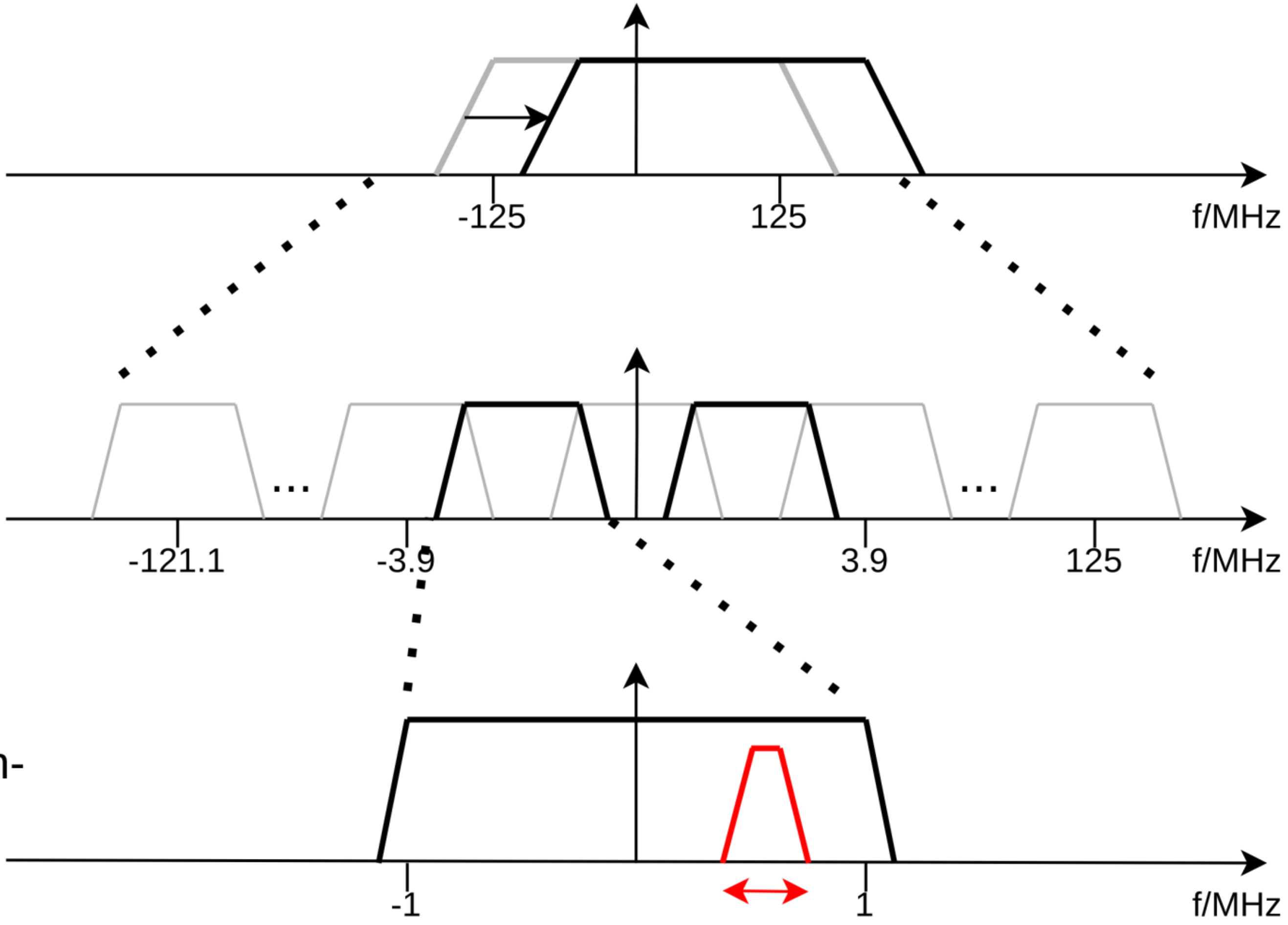
Parameters for BULLKID:

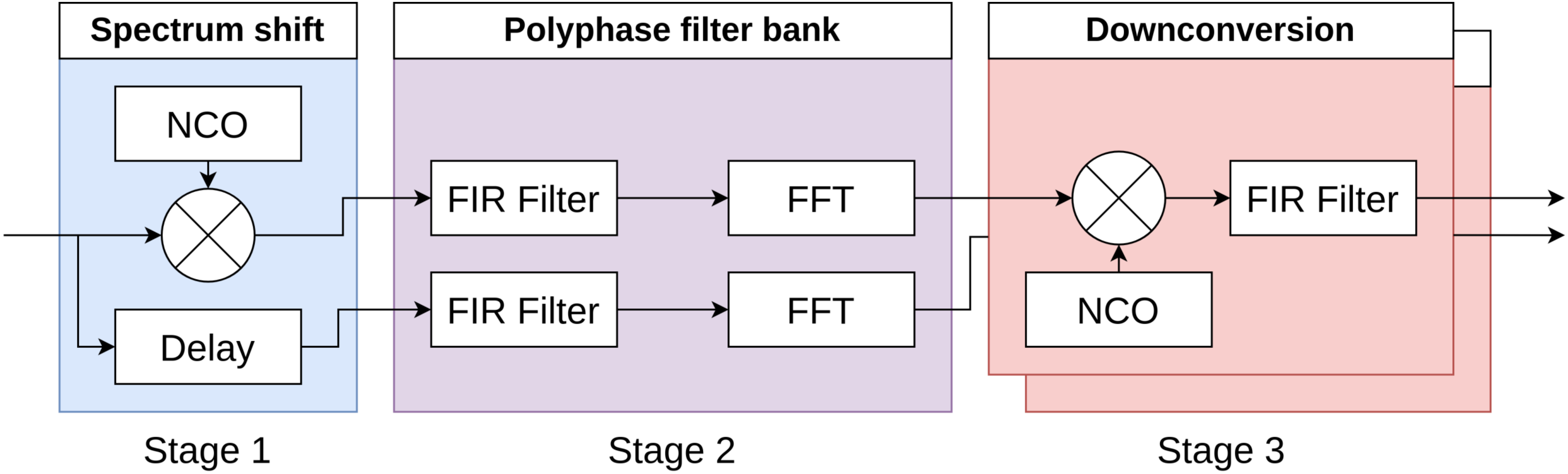
ADC — Input spectrum 250 MHz

Polyphase Channelizer — 64 channels with 2.1 MHz banwidth

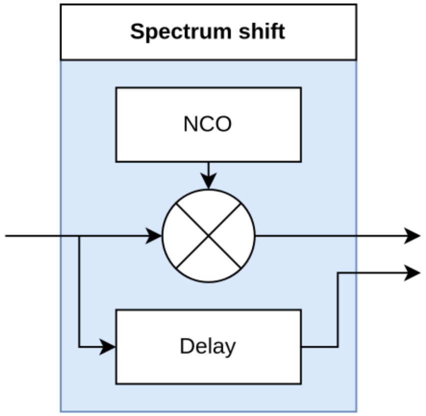
Digital Down-conversion — 200 kHz variable bandpass filter



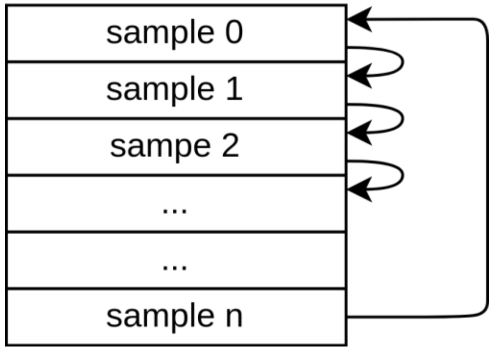
Block diagram of full channelization stage



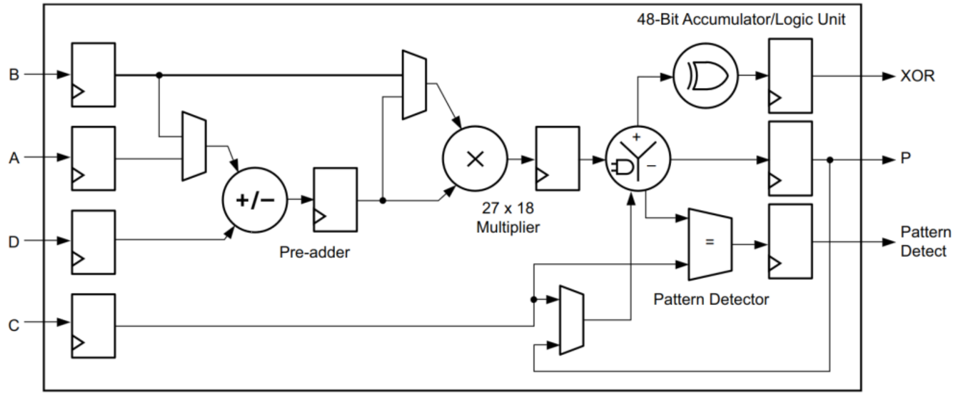
Stage 1: Spectrum shift



NCO:

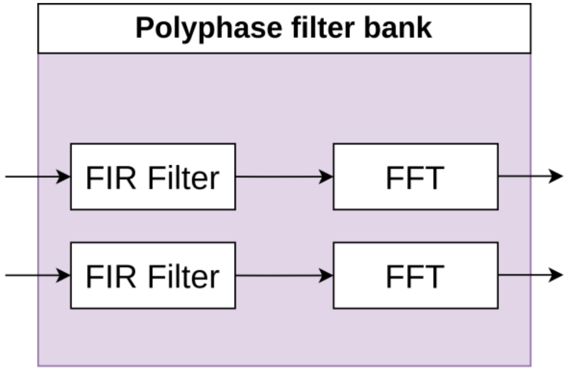


Zynq US+ DSP-Slice for complex mixing:



- Required NCO frequency: $f_{spacing} / 2$
- NCO memory is automatically optimised for pointer increment of 1
- Fixed configuration during runtime
  - No extensive control logic required
  - No user interface required
- Delay original spectrum for synchronicity

Stage 2: Polyphase filter bank

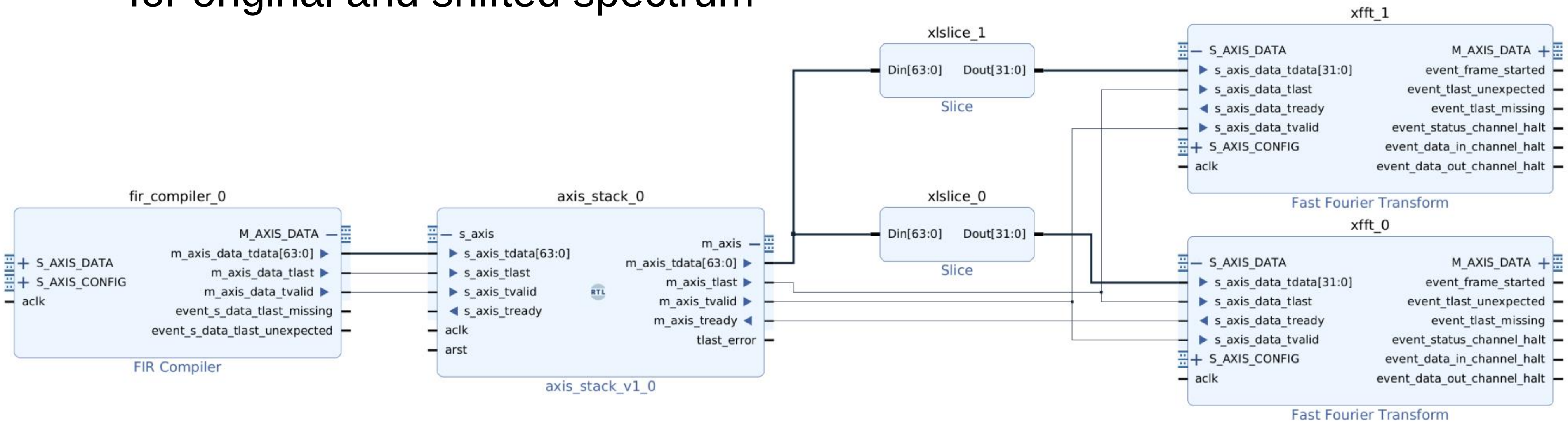


<u>FIR-Compiler</u>:

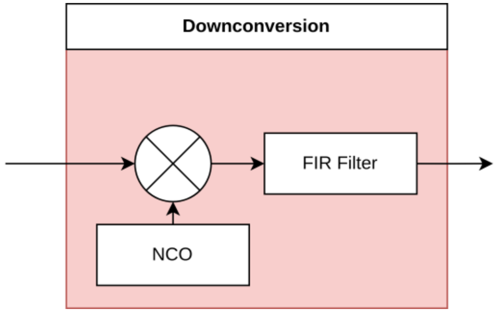
- AMD IP-Core: fir_compiler (v7.2)
  - Support for multiple channels
  - User-defined filter taps (.coe-file) with MATLAB + python scripts
  - Parallel paths -> One common filter for original and shifted spectrum

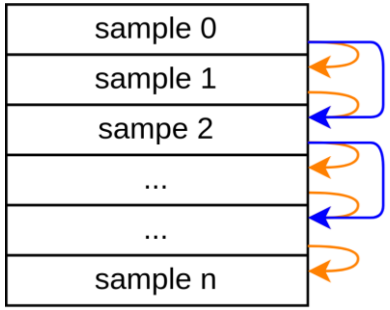
<u>FFT</u>:

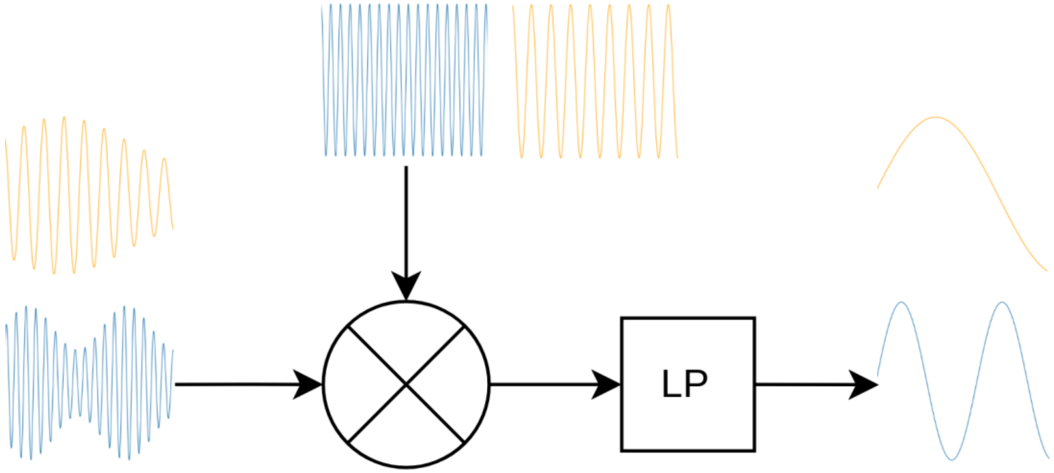
- AMD IP-Core: xfft (v9.1)
  - Transform length = Number of subbands
- Channel reorder required (see Xilinx XAPP 1161)



Stage 3: Fine downconversion







- Multiple tones in TDM scheme
- Single NCO + complex mixer in interleaved pipeline
- Channel-specific NCO frequency adjustable via AXI-lite interface at runtime

Resource consumption

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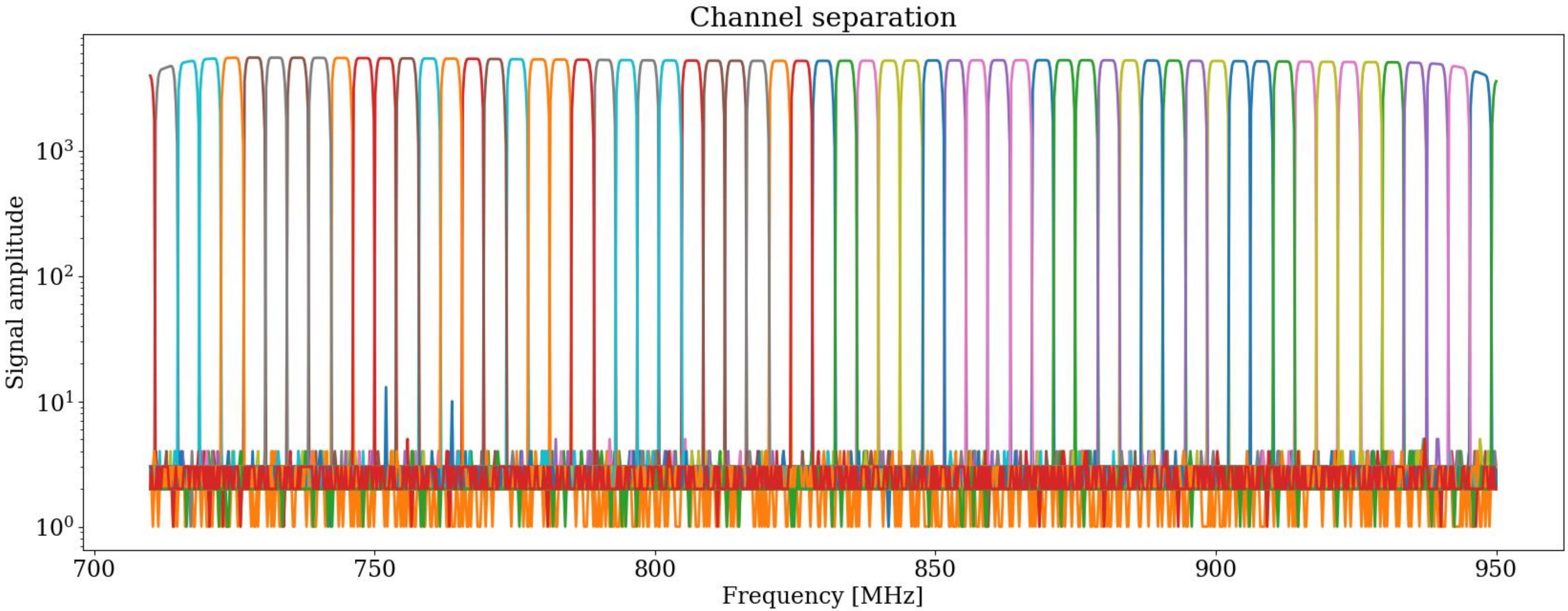
Parameters: 250 MHz input frequency, 64 subbands, 200 kHz channel bandwidth

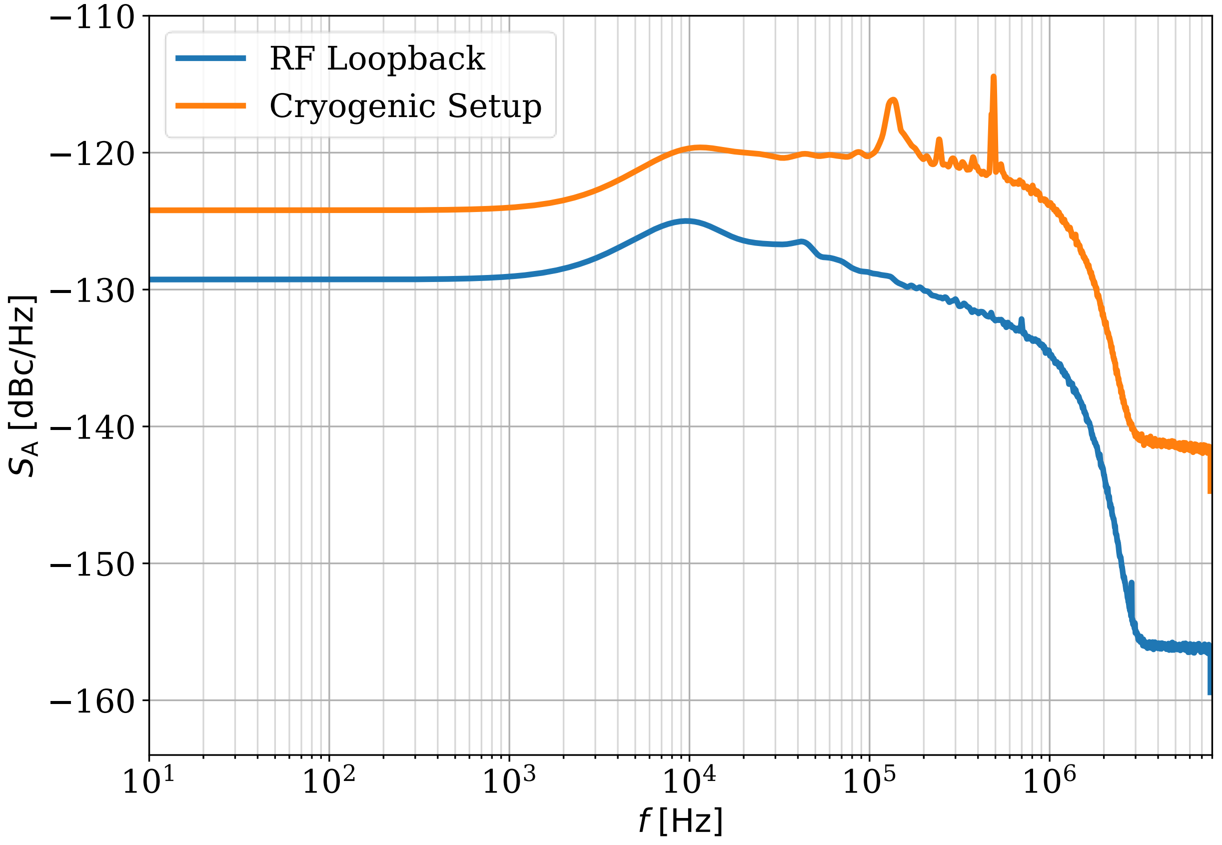
Module	DSP	BRAM	LUT	CLB
Spectrum shift	**3**	**0.5**	**133**	**54**
Polyphase filter bank	**64**	**0**	**4826**	**1053**
- FIR filter	52	0	2030	390
- FFT (x2)	6	0	1341	377
Fine downconversion (x2)	**7**	**12**	**3960**	**1343**
- NCO	0	8	3399	834
- Complex mixer	3	0	2	18
- FIR filter	4	4	330	389

Resources for one channel in brute-force approach

Output of channelization stage



Amplitude noise measurement



- Implementation for ECHo on MPSoC
- Low-pass filter of downconversion stage reduces noise above 1 MHz
- Channelizer is **not** the limiting factor for readout sensitivity

Conclusion

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- Full channelization stage for parallel tone processing successfully implemented
- Capable of frequency division multiplexed quantum sensor readout
- Modular system: input frequency, number of channels, bandwidth
  → Easy adaption to requirements of new experiments

Advantages:

+ Very efficient solution
+ Further processing in time division multiplex possible

Disadvantages:

- Limited tone separation capabilities
  - only one tone per subband
  - 2^n subbands

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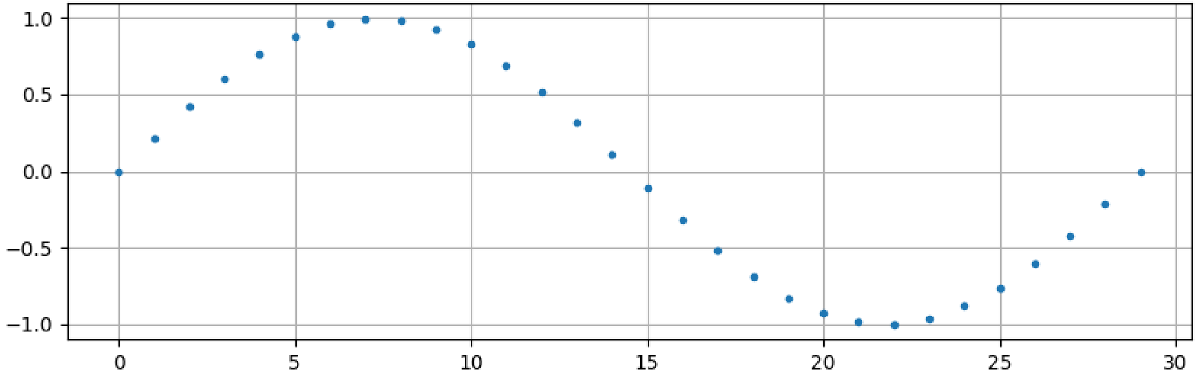
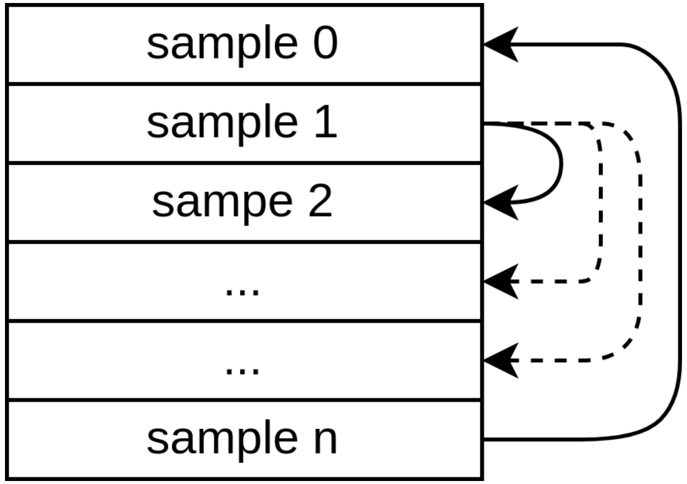
Backup

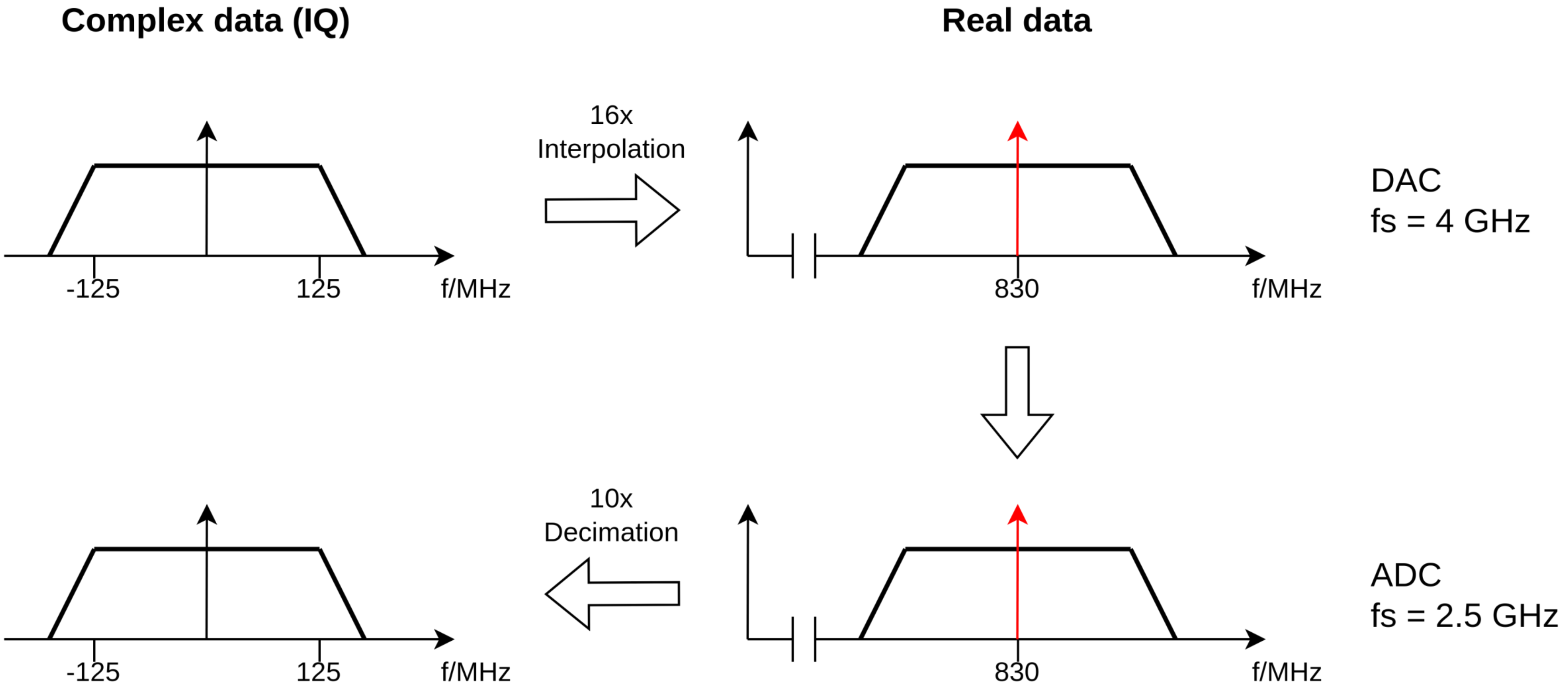
NCO (Numerically Controlled Oscillator)



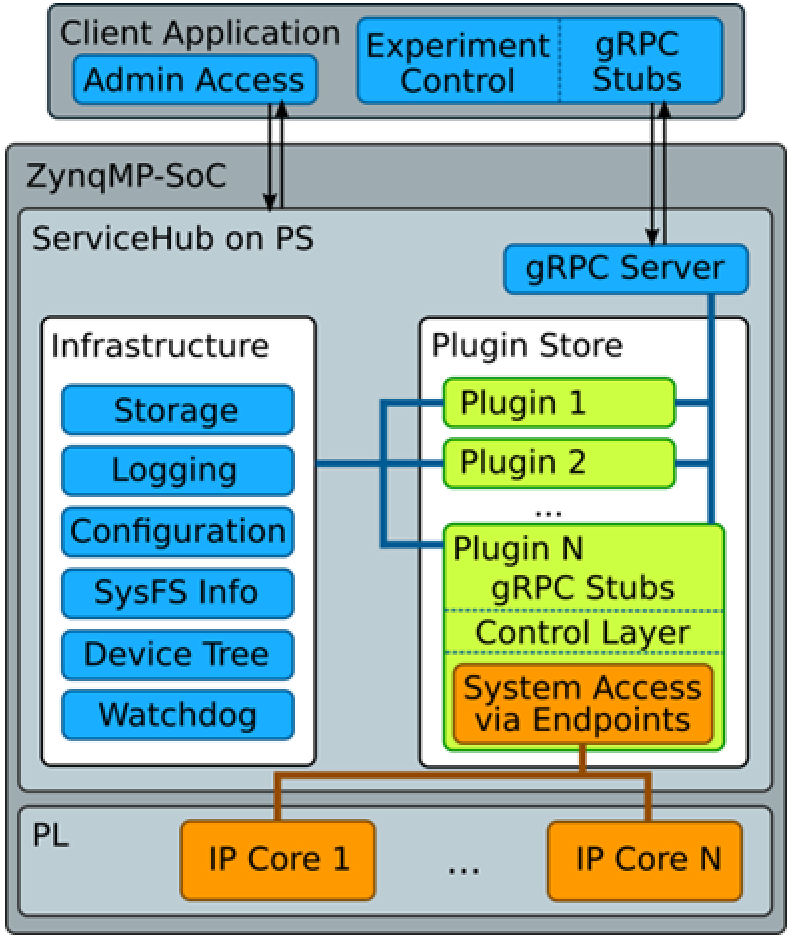


- Samples can be stored either in ROM or in LUT, depending on ressource availability
- Frequency resolution depends on number of stored samples
- Frequency and phase are adjustable at runtime by changing start point and increment of the read pointer

Analog downconversion



Software stack



- Custom C++ server daemon for communication with the platform
- Configuration and read-back of PL modules during runtime
- Commands are sent via gRPC to the user