RFSoC-based Readout and Characterization Platform Development at SLAC

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RFSoC Platforms Supported at SLAC

RFSoC – one-stop shop for readout:
- RF ADCs
- RF DACs
- PL
- PS

Evaluation Platforms

- Open-source firmware and software and example projects with commercial evaluation hardware – great for small scale R&D projects
  [https://github.com/slaclab/Simple-ZCU208-Example](https://github.com/slaclab/Simple-ZCU208-Example) and other platforms

- **ZCU111 – RFSoC GEN 1 XCZU28DR**
  - 8x 4.096GSPS ADCs and 8x 6.554GSPS DACs
  - Support GEN1 device based hardware

- **ZCU216 – RFSoC GEN 3 XCZU49DR**
  - 16x 2.5GSPS ADCs and 16x 9.85GSPS DACs
  - High channel count applications

- **ZCU208 – RFSoC GEN 3 XCZU48DR**
  - 8x 5GSPS ADCs and 8x 10GSPS DACs
  - High bandwidth applications

- **ZCU670 – RFSoC DFE XCZU67DR**
  - 8x 2.95GSPS ADCs, 2x 5.9GSPS and 8x 10GSPS DACs
  - Applications need higher RF input frequency

- **RFSoC 4x2 Kit – RFSoC GEN 3 XCZU48DR**
  - 4x 5GSPS ADCs, 2x 9.85GSPS DACs
  - Academic applications with low channel count
  - Low cost and low barriers to entry

Science Drives

Microwave SQUID multiplexing (µMUX) for CMB experiments


Axion dark matter experiment


Quantum Sensing R&D For Dark Matter

Kurinsky @ Aspen23

Heterodyne-based radio astronomy receivers


LLRF control of Linac
SMuRF – µMUX at scale for CMB

SLAC Microresonator Radiofrequency Electronics = SMuRF

- Generate and readback up to 3328 RF carriers in 4-8 GHz bandwidth.
- Unique "tone-tracking" ability sets SMuRF apart from other systems
  - Game changer – enables >1000x channel readout/RF line
    C. Yu et al., Rev. Sci. Instrum. 94 (2023)

An integrated 6x SMuRF system – readout for >20,000 TESs

48x SMuRF systems deploying now on Simons Observatory in Chile

SMuRF readout for 1x 2000 TES CMB wafer

RF modules

4-6 GHz

6-8 GHz

RF into cryostat

LO

RF modules can be chained

LO

RF back from cryostat

FPGA board

SAT1 SAT2 SAT3
10kTES/SAT

Truck (for scale)

LAT 30kTES
SMuRF Electronics and SMuRF-RFSoC

Readout System Summary

- **SMuRF electronics**
  - Analog mixers
  - Discrete data converters with JESD interface
- **SMuRF-RFSoC - upgrade path for SMuRF**
  - Integrated ADCs and DACs datapath
  - NO JESD interface
  - NO analog mixer needed for 4-6 GHz
  - Lower cost and barriers of entry
- **µmux firmware as example**
  - SMuRF firmware ported to RFSoC platform
  - Firmware and software are just scaled down or modified versions for other application
  - Performance characterization widely applicable
Motivation for Characterization

Higher order Nyquist zone / Direct RF sampling

- Reduced complexity of RF front end
  - DAC generating RF signal at 2\textsuperscript{nd} Nyquist zone
  - ADC direct sampled and aliased image as signal
- Reduced analog impairments: matching and LO leakage
- Compact size, low cost and low barriers of entry
- Does performance meet HEP requirements???

Key performance parameters

- Spurious Free Dynamic Range (SFDR) – the overall dynamic range for measurement
- Intermodulation distortion – intermod-products can land on other resonators on same RF line
- RF dynamic range – measured at a specific offset of the carrier frequency and requirement for \( \mu \)MUX is -100 dBc/Hz at 30 kHz offset to achieve the high channel density

Ref: https://www.rfsocbook.com/

DAC in Zero-order Hold Mode

ADC in Higher order Nyquist zone sampling mode


SFDR and RF dynamic range

Ref: https://www.rfsocbook.com/
Single Tone Test Results of Direct RF Sampling

Test Summary
- DAC-ADC loop-back
- SFDR measured
  - 79.6 dB at 4.25 GHz
  - 81.2 dB at 5.25 GHz
- SFDR in Xilinx datasheet with CW power at –10 dBFS
  - 75 dB at 4.9 GHz
  - 74 dB at 5.9 GHz
- Performance at higher order Nyquist zones meet requirements

Spectrum of RF signal at 4.25 GHz
DAC: 2\textsuperscript{nd} order Nyquist zone
ADC: 2\textsuperscript{nd} order Nyquist zone

Spectrum of RF signal at 5.25 GHz
DAC: 2\textsuperscript{nd} order Nyquist zone
ADC: 3\textsuperscript{rd} order Nyquist zone
Inter-modulation Performance Test in 2\textsuperscript{nd} Nyquist Zone

DAC Two Tone Test in
SNR Optimized Mode

DAC Two Tone Test in
High Linearity Mode

DAC Two Band Test in
High Linearity Mode

Test Summary

- RFSoC DACs have two modes use different mechanism to select the unit current cells for decoding – the SNR optimized mode and high linearity mode. The \textbf{high linearity mode offers 8 dB better IMD performance} than SNR optimized mode.

- The two RF bands directly generated by the integrated DAC have a \textbf{low level of intermodulation products and leakage to other bands in high linearity mode}. 
RF dynamic range measured at all 4 500MHz bands is mostly below -110 dBc/Hz
Test Summary

- SMuRF-RFSoC to readout a superconducting sensor in the CMB dilution refrigerator
- Scan of complex transmission through a superconducting resonator
- Tracking the modulation of a SQUID-coupled resonator demonstrates tone tracking
- Recovered 100 mHz sine-wave signal injected into a transition-edge sensor (TES), demonstrating the successful readout of TES.
Jupyter Notebook for Prototyping

System Setup

Measurement and readout scripting and data capturing

Data processing and visualization

University and national lab users can prototype rapidly based on example notebook
Pizza Box for RFSoC based uMux Readout

RFSoC Chassis Ideal for Small Scale R&D and university project

- 3U module for rack mounting
- Flexible circuit connection
- 10 MHz external sync
- PL and PS Ethernet for data stream and remote updating
- Two front panel versions
Conclusions and Future Works

- Direct RF sampling delivered desired performance at higher order Nyquist zones
- Milestones for RFSoC based readout and control system development at SLAC
  - Demonstrating the successful readout of transition-edge sensor for CMB experiment
  - Highly configurable channelizer developed for axion dark matter search
  - LLRF control for Linac demonstrated with extremely low phase noise
- Commercial hardware and open-source firmware and software enable rapid and low-cost (but extremely powerful) R&D readout system prototyping
- Highly flexible system implementation with capability of data streaming at multiple stages of readout – essential for CMB and dark matter search experiments
- Open to collaboration for firmware and software library development
Backups
Motivations

- Intermodulation distortion (IMD) performance for the DAC is critical for frequency division multiplexing with high multiplexing factor
- Exploring the optimum DAC configuration to achieve the best performance with the integrated datapath in RFSoC
Integrated Datapath Characterization Test Setup

Setup Summary

- Single tone test
  - Full loopback
  - Dynamic range
- Comb of tones test
  - Tone power
  - Intermodulation level
  - Phase noise

Analog BPF

3000-4300 MHz / 4900-6200 MHz
Low side band rejection and not enough damping for the first Nyquist zone image

ADC
4.9152 GS/s
4.25/5.25 GHz’s mirror in 1st Nyquist zone NCO
8x Decimation Data rate: 614.4 MHz

Mixer

Decimation

BRAM

Digital

DAC
6.88128 GS/s
4.25/5.25 GHz NCO

Mixer

Interpolation

BRAM

RFdc

RFSoC

DC sequence