Supporting Quantum Measurements: A Software-Based Radio Approach

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1. Introduction

Commercial laboratory instruments used in quantum physics can cost $100,000–$200,000 (1). ~$20,000 software-defined radios offer a lower-cost, reconfigurable alternative by combining multiple RF measurement functions within a single device.

These modern radio chips achieve this flexibility through programmable FPGA firmware, enabling vector network analysis, spectrum analysis, and signal generation. QICK provides convenient prebuilt libraries for RF generation and readout (2), but is designed primarily for pulsed qubit measurements rather than continuous measurements of passive devices. Its resulting limitations motivate lower-level FPGA programming optimized for continuous RF instrumentation.

2. Terminology

- **Radio Frequency System-on-a-Chip (RFSoC):** FPGA integrated with high-speed RF ADCs and DACs
- **Digital-to-Analog Converter (DAC):** converts a discrete signal into a continuous signal
- **Analog-to-Digital Converter (ADC):** converts a continuous signal into a discrete signal
- **Vector Network Analyzer (VNA):** measures magnitude and phase of transmitted/reflected RF signals
- **S21:** transmission from Port 1 to Port 2

3. Abstract

A functional VNA was implemented using an AMD ZCU216, the QICK FPGA overlay, and Python control (2). The system uses the RFSoC's integrated DACs and ADCs to generate and measure microwave-frequency signals, reducing dependence on commercial VNAs for quantum measurement applications involving superconducting microwave circuits. QICK provided convenient prebuilt functions for RF generation and readout, although its pulse-oriented architecture limits frequency sweep efficiency for continuous passive-device measurements.

Performance was evaluated by measuring S21 transmission of filters of known values in the 10-100 MHz range. An initial calibration was conducted without a filter inserted, followed by measurements with high-pass and band-pass filters inserted. The recovered responses closely matched manufacturer data, demonstrating that the RFSoC can perform accurate VNA-like measurements while identifying opportunities for lower-level FPGA firmware optimized for continuous RF measurements.

4. Methodology

To obtain VNA-like measurements from the RFSoC, using Figure 2:

- The **DAC** acts as a signal generator, creating tones of different frequencies for testing
- The **Splitter** creates two **ADC** channels, a **TEST channel** and a **REFERENCE channel**
  - TEST channel analyzes the **Device Under Test (DUT)**
  - REFERENCE channel acts as a phase reference for TEST
- The **numerically controlled oscillator (NCO)** acts as a local oscillator, controlling readout frequency of both ADC channels
- **Mixers** perform frequency translation, calculating the difference between **reference frequency, R**, and **local frequency, L**, to provide values for S21 measurement
- The **PC** controls the frequency sweep via Python, directs the **RFSoC FPGA logic** to perform VNA measurements across a user-determined number of discrete points, and computes S21 measurement (2)
- An S21 measurement is calculated based on a ratio of the DUT measurement and initial calibration and determines DUT behavior (1)

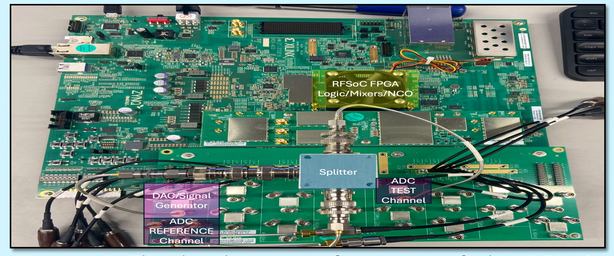


Figure 1: The hardware configuration of the RFSoC, highlighting visible key components of the VNA structure of Figure 2. The PC is connected to the AMD ZCU216 by a USB hub. No DUT is connected.

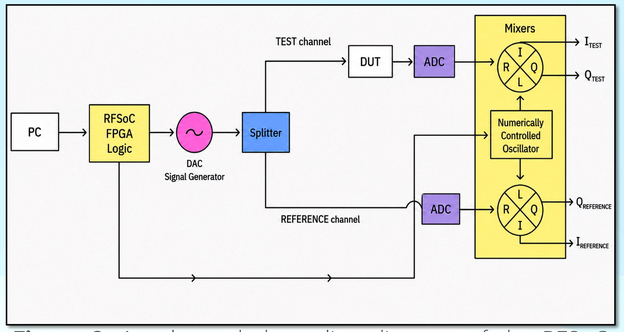


Figure 2: A color-coded one-line diagram of the RFSoC VNA architecture based on designs used in commercial VNAs and AMD documentation (3,4). Read left to right, a PC controls the RFSoC programmable logic from QICK using Python, and then to VNA hardware.

5. Results/Conclusion

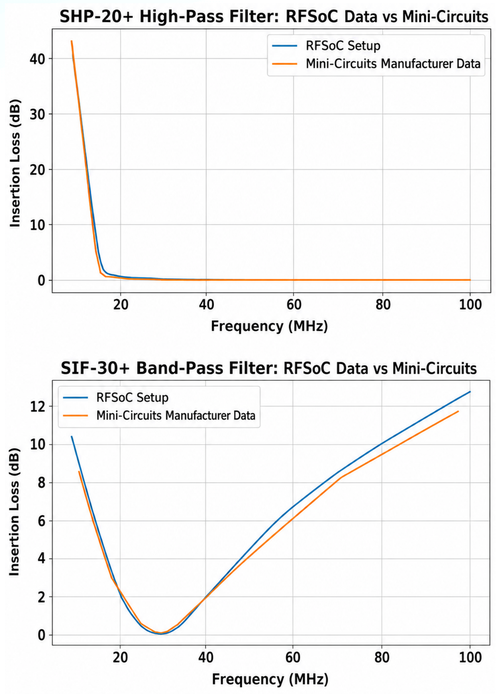


Figure 3: Frequency-dependent behavior was determined based on loss of power observed on a decibel (dB) scale. The band pass filter range is 25-35 MHz and the high pass filter is 20-1000 MHz. Expected attenuation is observed in the 10-20 MHz and 25-35 MHz range for the high pass filter and band pass filter respectively (5,6).

- **RFSoC was able to accurately recover frequency-dependent manufacturer data of a band pass filter and high pass filter using VNA methods as observed in Figure 3 across 1000 discrete points in 8.3 seconds (5,6).**
- RFSoC has the potential to save hundreds of thousands of dollars in lab equipment.
- QICK accelerated development through RFSoC generation and readout functions, but its architecture is optimized for pulsed qubit measurements rather than continuous passive-device characterization, limiting time efficiency of frequency sweeps.
- Future work will use lower-level custom FPGA firmware to implement more continuous processing, improve VNA efficiency, and extend the RFSoC beyond VNA applications.

References

[1] Shilinkov et al., "Open-Loop Active Load–Pull Setup Using the ZCU216 RFSoC," 2025. doi:10.1109/LMWT.2025.3633956.

[2] Stefanazzi et al., "The QICK: Readout and Control for Qubits and Detectors," 2022. doi:10.1063/5.0076249.

[3] Keysight, "Explanation of the Internal Architecture of a VNA," docs.keysight.com.

[4] AMD, ZCU216 Evaluation Board User Guide, UG1390, rev. 1.2, 2023.

[5] Mini-Circuits, "SHP-20+ High Pass Filter, 50 Ω, 20 to 1000 MHz," datasheet.

[6] Mini-Circuits, "SIF-30+ Coaxial Bandpass Filter, 50 Ω Constant Impedance," datasheet.

Acknowledgements

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