Improving Signal-to-Noise Ratio (SNR) for Readout Signals Using Adaptive Filters on Reconfigurable Controls Hardware

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Abstract — **This study investigates the optimization of Signal-to-Noise Ratio (SNR) in superconducting quantum computing readout signals through adaptive filtering. Quantum computing technology has the potential to revolutionize various fields by delivering exponential speedup in solving certain computational problems. However, the technology's practical implementation is hindered by the difficulty of extracting clean, reliable signals during the readout phase, with various sources of noise presenting a significant barrier to clean signals. This noise, often present in readout profiles due to imperfect isolation, degrades the system's overall SNR, thus impeding the ability to extract the quantum state accurately. The research leverages the power of adaptive filtering to improve the SNR of quantum computing readout signals. Specifically, an adaptive filter is implemented in a PYNQ overlay on an FPGA, and eventually will be connected to a quantum computing system. The system models the noise with a Least Mean Squares (LMS) adaptive filter, and then subtracts the estimated noise from the received signal to improve the SNR. A Direct Memory Access (DMA) channel is used to handle the signal processing, delivering efficient, high-speed data transfer between the PYNQ system and the hardware. The study explores the benefits of this adaptive filtering technique, potentially providing a significant contribution to practical and fast quantum computing.**

Keywords—Quantum Computing, Adaptive Filters, Controls Hardware, RFSoC FPGA, Digital Signal Processing (DSP), Superconducting Qubits, Machine Learning

I. Intro

The transition of quantum computing from theoretical principles to practical application is facing significant challenges, particularly in the extraction of clean and reliable readout signals. At the intersection of quantum and classical information, the way we interact with our control signals is the foundation for creating reliable quantum algorithms. As readout signals are passed back into our control systems, the signal-to-noise ratio (SNR) during the readout phase greatly impacts the overall performance of a quantum system. Given the importance of this aspect, this research focuses on implementing an adaptive filtering technique to enhance fast and reliable readout and low SNR for superconducting quantum computing readout signals using a specific control system through a Field Programmable Gate Array (FPGA).

The enhancement of the Signal-to-Noise Ratio (SNR) plays a crucial role in the advancement of quantum computing for various reasons. Firstly, an important element in quantum computing is the precise discernment of a qubit's state. In superconducting quantum computing systems, these states are typically denoted by a specific point in the IQ plane. However, noise accompanying the readout signals often obstructs clear state discrimination [1]. Improving the SNR significantly amplifies the clarity of the qubit states, leading to a substantial boost in the accuracy of quantum computations. This improvement in SNR plays a significant part in enabling error correction and fault-tolerant quantum computing, two key components required for the realization of large-scale, operational quantum computers.

II. Discussion and Research

The current process for benchmarking our discernability between a ground state and an excited state in a two-state system using superconducting qubits coupled with Superconducting Radio Frequency (SRF) cavities is done by taking around 100,000 single-shot time traces on the readout and averaging them to get an ideal ground state and excited state signal. These signals represent the real (I) values of the IQ quadrature for a qubit ground state and excited state, and their complex (Q) values can be extrapolated using this information for a specific integration window of our choosing that matches our pulse shape. However, averaging is all done in post-processing for our systems, and it also requires significant resources and time to complete.

The noise profile for both the ground and excited state in a single time trace is approximately an order of magnitude higher than the desired signal. This is shown with the single shot amplitude hovering around 200 mV_{pp} for one time trace, and 20 mV_{pp} for the 100,000 averaged time traces. This order of magnitude is consistent across different experiments. 100,000 averaged time traces are the best trade-off identified for time, accuracy/precision, and resource utilization so far. This suggests that there is a significant improvement that could be made with an appropriate filter. However, the problem with implementing a filter in real-time is that it must be done on the control hardware itself right as the readout is interpreted. This is made possible with the integration of Fermilab's Quantum Instrumentation Control Kit (QICK) [2] which is a control kit built on FPGA. Even so, selecting an appropriate filter is a difficult task as many of the FPGA's resources are dedicated to the intricate symphony that is the QICK. This means that whatever filter we choose to implement, it must take up minimal memory and operational resources, and work harmoniously with the current QICK firmware.

The dynamic nature of an adaptive filter is indeed a critical advantage in both improving SNR and over static filters, particularly in environments with non-stationary signals such as in quantum computing readout processes. Quantum computing readout signals can exhibit substantial variations due to several factors, such as fluctuations in quantum states, changes in environmental conditions, and inherent quantum noise. Simply put, if we look at the ideal noise profile found with 100,000 averages, we can see an amplitude shift that converges to zero at a time that is dependent on the input parameters of our experiment and resonator cavity. A standard static filter (such as an FIR filter) can fit the profile for one experiment's input variables, but finding and changing the coefficients across multiple experiments is a non-trivial task. This variability means that a static filter might not provide an optimal solution across different experiments or even within the same experiment over time. An adaptive filter, on the other hand, is equipped to handle such signal variations. As its name suggests, an adaptive filter can dynamically adjust its coefficients based on the input signal characteristics. It uses an algorithm, such as the Least Mean Squares (LMS) algorithm, to continuously estimate the error between the desired and actual output, and then iteratively adjusts its coefficients to minimize this error.

This adaptability becomes increasingly significant in the complex realm of quantum computing readouts. For example, the state of a qubit is represented in the IQ phase-space plane, and discerning different states requires high resolution which is directly tied to the Signal-to-Noise Ratio (SNR) of the readout signal. By continuously optimizing the SNR, an adaptive filter will allow for more accurate and reliable state discernment. Furthermore, as quantum computers scale up and systems become more complex, having adaptive control over noise becomes essential. Hence, adaptive filters provide a versatile and efficient solution that can keep up with the evolving noise characteristics, leading to improved overall system performance.

In the context of Field-Programmable Gate Array (FPGA) hardware, amplifying the Signal-to-Noise Ratio (SNR) has promising implications for the future of quantum computing. FPGA's parallel processing capabilities make them perfect for handling real-time adaptive noise filtering. With Xilinx's release of the Gen 1 through Gen 3 UltraScale+ RFSoCs, these devices make an ideal platform for pushing and interpreting RF control signals to and from available quantum systems. Another pivotal advantage of FPGAs is their inherent re-programmability, which enables continuous optimization and adaptation to the ever-changing requirements of quantum systems as they scale up. Through boosting SNR in FPGA-based systems, a strategic roadmap can be established for creating scalable and efficient quantum computing systems that can adapt and evolve alongside advancements in quantum technologies [3]. Notably, the QICK represents a major leap in providing researchers and engineers with customizable, cost-effective, and efficient tools tailored to their needs in the quantum computing controls domain.

For this research, we use VHDL (VHSIC Hardware Description Language) to program the FPGA hardware and build the adaptive filter. VHDL is a powerful language tailored for describing digital electronic systems and is ideal for our project due to its precision in defining the structure and behavior of digital systems versus its more weakly typed counterpart, Verilog. It allows for comprehensive control over hardware resources, facilitating intricate signal processing operations required in our quantum computing application.

We adopted a meticulous experimental setup to validate our adaptive filter design. We simulated quantum noise conditions and applied our adaptive filter to process the readout signals. However, at this time we are still currently awaiting a full integration into the QICK so that we can test on actual readout data coming out of one of our quantum computers in the dilution fridge. Our preliminary results demonstrate a significant improvement in simulated SNR, which supports the efficacy of our approach. We hope these findings will underscore our theoretical assertions and provide empirical evidence for our FPGA-based adaptive filtering solution's practical utility in enhancing the SNR for quantum computing readout signals in the very near future as the foundations for proof of concept are provided in this poster.

III. Poster Description

The poster starts with an introduction to the problem as well as the physical design of the FPGA controls system coupled with the superconducting quantum computing system used at SQMS left side. On the right side, the top displays the current methodology for readout starting with the individual time traces and shows what an ideal time trace looks like after 100,000 averages. For that ideal signal, we show what the phase space plot looks like in the form of the IQ quadrature for both the ground state and excited state for this specific experiment. There are two phase plots built for 100,000 time traces integrated ±1 μs around the zero-convergence point of the ground state. The left phase plot displays 1 point for every 10 traces, and the right phase plot displays 1 point for every 100 traces. Below that, a block diagram of the LMS filter is shown with the ideal signal as the reference signal. The block diagram defines all the signals into the system and shows how an FIR filter is adapted via an LMS algorithm. Simulation results are shown below this diagram for the working LMS IP block logic without a reference signal versus NLMS and FIR logic. The filters successfully extract a signal from a noisy signal (white-noise) at 6 GHz which verifies the logic to be implemented in HDL.

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References

[1] Bronn, N. T., et al. "Fast, High-Fidelity Readout of Multiple Qubits" IOP Conf. Series: Journal of Physics: Conf. Series 834, 2017, doi: https://doi.org/10.1088/1742-6596/834/1/012003.

[2] Stefanazzi, Leandro, et al. "The Qick (Quantum Instrumentation Control Kit): Readout and Control for Qubits and Detectors." Review of Scientific Instruments, vol. 93, no. 4, 2022, p. 044709., https://doi.org/10.1063/5.0076249.

[3] Johnson, Hans, et al. "Exploration of Optimizing FPGA-Based Qubit Controller for Experiments on Superconducting Quantum Computing Hardware." *2023 IEEE International Conference on Electro Information Technology (eIT)*, 2023, https://doi.org/10.1109/eit57321.2023.10187252.