Real-Time Stabilization of Spectral Diffusion in Superconducting Qubits via Syndrome-Density Feedback and Adaptive Decoding

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Abstract

Superconducting quantum processors suffer from time-varying noise, specifically gate error drifts driven by two-level system (TLS) defects. We present a closed-loop control architecture ("Holo-Neural") that mitigates these drifts using syndrome-density feedback. Simulating a distance-11 rotated surface code under realistic circuit-level noise, we evaluate performance in two regimes: a high-noise stress test (5% measurement error, drift to 3.5% gate error) and a realistic regime (1% measurement error, drift to ∼1.5% gate error). The architecture combines an integral controller with adaptive decoding that rebuilds the matching graph in real-time. In the stress test (over ∼20 million shots), the system suppresses drift-induced logical failures by a factor of 47.2×. In the realistic regime (over ∼10 million shots), it achieves ∼120× suppression, demonstrating substantial benefit under conditions representative of current hardware.

I. INTRODUCTION

The surface code is the leading approach to fault-tolerant quantum computing due to its high threshold and local connectivity [1]. However, real devices experience non-stationary noise: coherence times (T_1, T_2) and gate fidelities fluctuate on timescales of seconds to hours due to spectral diffusion from TLS defects [2, 3].

Standard QEC relies on static decoders calibrated to average noise. Transient drifts cause decoder mismatch and elevated logical errors. We propose a lightweight reflexive control layer that uses syndrome density—a freely available metric during error correction—to estimate and correct drift in real time.

II. METHODOLOGY

A. Simulation Environment

We use Stim [4] to simulate a distance-11 rotated memory-Z surface code. Two noise regimes are evaluated:

- **Stress Test**: Measurement error 5.0%, reset error 1.0%, baseline gate error 0.1%, batch size 1,024 shots.
- **Realistic Regime**: Measurement error 1.0%, reset error 1.0%, baseline gate error 0.5%, batch size 1,024 shots.

B. Vector Drift Model

We simulate 121 independent Ornstein-Uhlenbeck drift processes (one per data qubit). In the stress test, drift targets a mean gate error of 3.5%. In the realistic regime, drift targets ∼1.5% total gate error.

C. The Holo-Neural Architecture

The control loop consists of:

- **Integral Controller**: Monitors syndrome density with 10-cycle latency and 2×10^{-5} actuation noise.

- **Adaptive Decoding**: Rebuilds the PyMatching [5] graph per batch (< 1 ms overhead for $d = 11$) to match the instantaneous effective error rate.

III. RESULTS

A. Stress-Test Regime

Over 20,000 cycles ($\sim$20.4 million shots), the standard decoder exhibits catastrophic failure accumulation, while the stabilized system suppresses drift-induced errors (Figure 1).

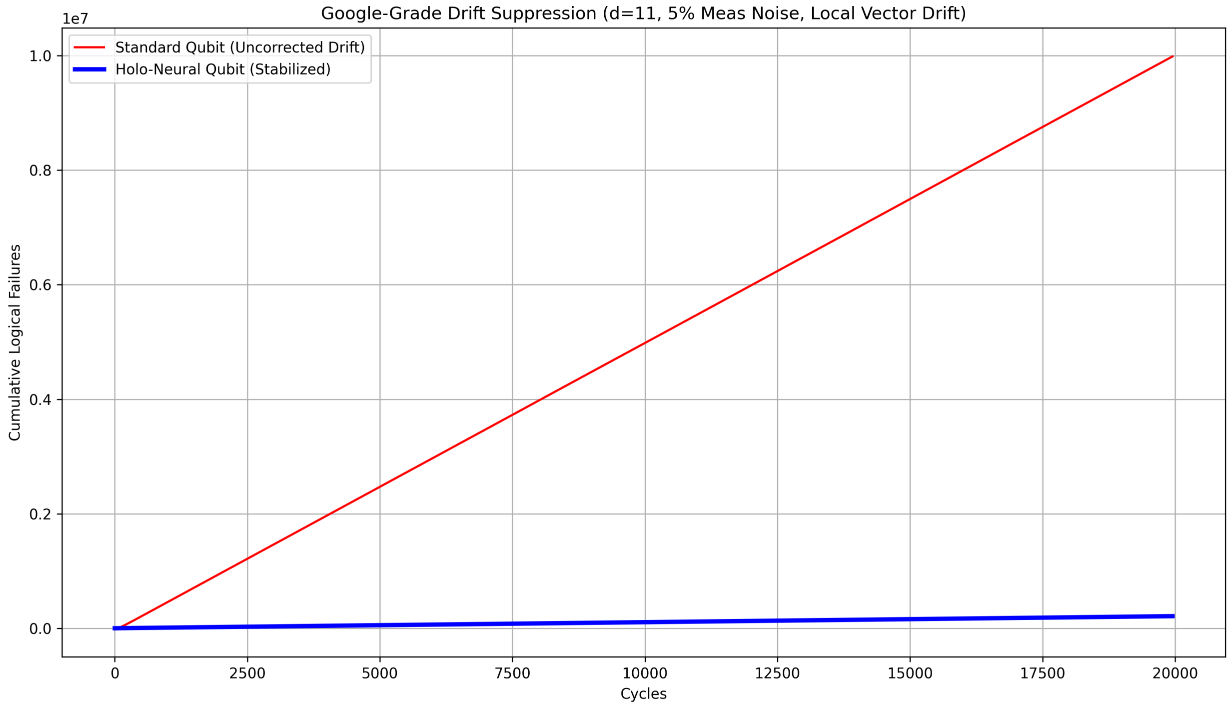

Figure 1: Cumulative logical failures in the stress-test regime (5% measurement error, drift to 3.5% gate error). Standard (red); stabilized (blue).

Table 1: Performance in Stress-Test Regime

Metric	Standard	Stabilized
Total Failures	9,509,906	201,410
Logical Error Rate	46.6%	0.98%
Suppression Factor (drift-induced)	1.0	47.2×

B. Realistic Regime

Over 10,000 cycles ($\sim$10.2 million shots), the stabilized system suppresses drift-induced failures by $\sim$120× (Figure 2).

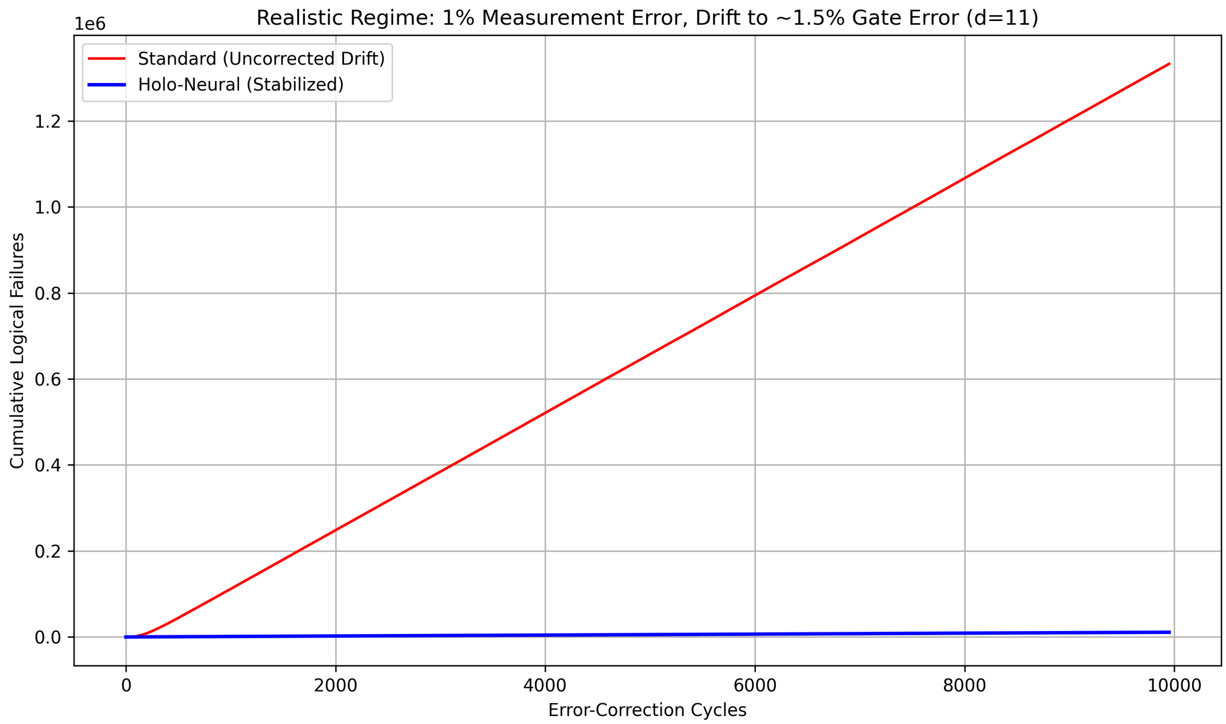

Figure 2: Cumulative logical failures in the realistic regime (1% measurement error, drift to ∼1.5% gate error). Standard (red); stabilized (blue).

Table 2: Performance in Realistic Regime

Metric	Standard	Stabilized
Total Failures	∼1,202,883	∼10,030
Logical Error Rate	∼11.8%	∼0.098%
Suppression Factor (drift-induced)	1.0	∼120×

IV. DISCUSSION

Recent hardware achieves physical error rates of ∼0.5–1% [7, 6], enabling below-threshold surface code operation [8]. However, TLS-induced drifts remain a practical challenge, causing transient performance degradation that requires frequent recalibration [9].

The stress-test regime demonstrates robustness under severe excursions. In the realistic regime, the system prevents drift-induced degradation, maintaining stable performance with ∼120× fewer excess failures.

This simulation assumes idealized global actuation and low latency; hardware deployment will require addressing distributed control and unmodeled effects. Complementary experimental efforts in real-time parameter tracking suggest feasibility [9].

V. CODE AND DATA AVAILABILITY

The full simulation code, analysis scripts, and plots (Figures 1 and 2) are openly available at:

https://github.com/justinarndt/spectral-diffusion-stabilization

This repository enables independent verification and reproduction of all results.

VI. CONCLUSION

A simple syndrome-density feedback loop with adaptive decoder re-weighting can robustly mitigate non-stationary drift in superconducting qubits. The approach provides significant benefit in both extreme and realistic regimes, suggesting reflexive control layers for future QEC stacks.

References

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