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Title: Adding Noise to Preserve Quantum Process Fidelity

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STEM Degrees: 0 **STEM Participants:** 2

Major Goals: The goal of this project was to begin preliminary testing of a theoretical procedure for improving coherence in quantum systems. The procedure was put forward by Marshall, Campos Venuti, and Zanardi in their 2017 PRA. It specifies adding a new type of noise, termed "generalized Markovian" noise, to a quantum system in order to counteract decoherence due to Markovian background noise. Several types of corrective generalized Markovian noise have been proposed. In this project, we had the goal of developing a testbed for screening these noise recipes. A secondary goal was to test the simplest noise recipe--adding Poisson telegraph noise--and see if coherence could be improved. Finally, we had the goal of determining future paths in experimental and theoretical research into this topic, to be continued with a possible full ARO grant.

The original specific aims of the project, which map onto these project goals, were:
1) Fabricate a superconducting qubit with long-lived phase coherence (> 10 ????); degrade this coherence by an order of magnitude with added excess “environmental” white noise.
2) Add in corrective Poissonian telegraph noise and test whether qubit coherence can be recovered above the value measured in Aim 1.
3) Explore the limits of this experimental procedure to guide future theory and experiment.

Accomplishments: Please see PDF document for detailed description of project activities. A full testbed for experimental measurements and numerical simulations was developed. Poisson telegraph noise was tested both numerically and experimentally, with no clear improvement in coherence due to the corrective noise. Shortfalls in the theory were identified and we have begun collaborative work with theorists to address these shortfalls.

Training Opportunities: Two PhD students, Evangelos Vlachos (Physics) and Haimeng Zhang (Electrical Engineering), were trained in quantum trajectory simulations and in superconducting qubit measurement during this project.

Results Dissemination: No dissemination took place during the reporting period. Project activities during this period will be reported on in the APS March Meeting, abstract placement pending.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Graduate Student (research assistant)
Participant: Haimeng Zhang
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Evangelos Vlachos
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Shirin Jamali
Person Months Worked: 4.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: PD/PI
Participant: Eli Markus Levenson-Falk
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

ARO STIR Final Report

"Adding Noise to Preserve Quantum Process Fidelity"

W911NF-19-1-0070

Eli Levenson-Falk, University of Southern California

Summary

The goal of this STIR project was to test a proposed protocol for preserving the fidelity of a quantum state in the presence of a Markovian noise background. The specific proposal, put forward by Marshall, Venuti, and Zanardi [1], calls for adding so-called "generalized Markovian" noise in order to partially correct the effects of Markovian environmental noise. We have developed numerical and experimental tools for testing various forms of corrective noise. While we see clear structure in our numerical simulations indicating interesting physics, we have yet to see improvements in fidelity with the noise we have tested so far. Experimental data shows fidelity improvement but may be attributable to an artifact of the noise coupling method. We are moving forward with simulations of more sophisticated noise models; in parallel, we are developing experimental techniques that are immune to the artifacts that complicated our past measurements.

Theoretical Background

Noise in a qubit's spectrum can cause dephasing; we can write this with the density matrix as

$$\rho(\mathrm{t}) = \left(1 - \mathrm{p(t)}\right)\rho_0 + \mathrm{p(t)}\sigma_z\rho_0\sigma_z,$$

where ρ_0 is the initial state, and probability of dephasing p(t) = 0.5(1 – e^{-t/τ_0}). A white noise source (which is necessarily Markovian) causes coherences (off diagonal elements of $\rho(t)$) to decay exponentially in a time τ_0. This process can be described equivalently by a dynamical equation of the form

$$\frac{\mathrm{d}\rho}{\mathrm{dt}} = \left(\frac{1}{2\tau_0}\right)(\sigma_z\rho\sigma_z - \rho) \equiv L_0\rho.$$

It was shown in [1] that if one can add on top of this Markovian type noise a more general form of dissipation, so that the dynamics take the form

$$\frac{d\rho}{dt} = L_0\rho + L_1\int_0^t e^{-(t-t')/\tau_1}\,\rho(t')dt' \quad (\text{Eq. } 1)$$

then the effective decay rate (originally $1/\tau_0$) is replaced by $\tau^{-1} = 0.5(\tau_0^{-1} + \tau_1^{-1})$. That is, provided that $\tau_1 > \tau_0$, the decay rate is reduced and coherence is preserved. Here L_1 has the same spectral decomposition as L_0 but is time-independent. The functional form of the decoherence is now more complicated, with decaying oscillations of the form

$$\frac{e^{-t/\tau}\cos(\omega t + \varphi)}{\cos(\varphi)} \quad (\text{Eq. } 2)$$

where ω, φ depend on τ_0, τ_1, and the strength of the noise. From Eq. 2 it is clear that at certain times along the evolution (e.g. when ωt = 2π) the decoherence is reduced.

In [1], it is proposed that one can engineer the required noise by coupling a Hamiltonian (in our case σ^z) to a classical stochastic field $B(t)$, e.g. $H(t) = H_0 + B(t)\sigma_z$ [2]. The requirements on $B(t)$ are that $\langle B(t)\rangle = 0$ and $\langle B(t)B(t')\rangle \sim e^{-(|t-t'|/\tau_1)}$, where the angle brackets denote expectation values. These criterion are easily satisfied in a lab setting with random telegraph noise in the qubit spectrum, which has a power spectrum $1/(1+(f\tau_1)^2)$. This is a Poisson distributed signal which fluctuates between 'high' and 'low' with transition probability determined by τ_1. That is, the signal is of the form $B(t) = (-1)^{\eta(\tau)}B_0$, where $B_0 = \pm|B_0|$ is a coin-flip random variable, and $\eta(t) \in \mathbb{N}$ is a random variable Poisson distributed with mean $t/2\tau_1$. The free parameter $|B_0|$ can be used to tune the oscillation frequency ω, with the requirement $2\sqrt{2}|B_0| > |1/\tau_0 - 1/\tau_1|$, thus providing a tuning knob for probing the system.

Unfortunately, as shown below, we now have reason to doubt that this simple telegraph noise can generate the required dynamics.

Quantum Trajectory Simulations

We can numerically simulate the exact quantum trajectory taken by a qubit under the influence of a noisy environment by simply taking an initial state and calculating the time evolution using the time-dependent Schrödinger equation $i\hbar\frac{d\psi}{dt} = H\psi$ with our noisy Hamiltonian. We start with a state $\sigma_x = 1$ and a Hamiltonian $H = (\omega_0 + \omega_M(t) + \omega_{GM}(t))\sigma_z$ (working in units where $\hbar = 1$). Here ω_0 is the qubit energy splitting (typically set to 0 for simplicity), $\omega_M(t)$ is the Markovian noise background, and $\omega_{GM}(t)$ is the generalized Markovian corrective noise. We generate Markovian noise simply as a gaussian white noise with bandwidth up to our numerical sampling rate, while Poisson corrective noise is generated with a variable strength and autocorrelation time. Computing the time evolution is then a simple matter of calculating an integrated phase shift

$$\phi = \int_0^t (\omega_0 + \omega_M(t') + \omega_{GM}(t'))dt'$$

and applying this to the initial state. We calculate fidelity by computing the overlap of the initial and final state. In order to better simulate experimental conditions, we apply a π rotation about the x-axis to the state halfway through the trajectory, simulating a spin echo experiment. In order to capture the average dynamics under such evolution, we generate many trajectories, each with different time series for their noisy environments (but the same noise parameters) and average the fidelities, again in analogy to a real experiment. We then plot the fidelity decay time constant as a function of Poisson noise strength and autocorrelation time. Sample data is shown in Fig. 1, plotting the percentage change in coherence time. As you can see, while there is interesting structure to the data, no overall improvement in coherence time is achieved, and the corrective noise often makes the coherence time shorter. Interestingly, the behavior is best both when the corrective noise amplitude is 0 (i.e. with no corrective noise) and when its amplitude is equal to ~ 10% of the Markovian noise amplitude with autocorrelation time $\tau_1 > \tau_0$. We discuss this below.

Experimental Measurements

We conducted tests of the same corrective noise scheme using a transmon superconducting qubit. The device was provided to us by the group of Dr. David Pappas at NIST in Boulder, CO, and contains 4 transmons on a single chip. We picked just one qubit which is frequency-tunable via magnetic flux through a two-junction SQUID loop forming the Josephson element of the qubit. An on-chip fast flux line allowed us to couple fast noise into the qubit. We first added a dc flux bias to make the qubit frequency flux-sensitive. We then used an arbitrary waveform generator (AWG) to add Markovian noise to the qubit frequency, up to the bandwidth of our AWG; we increased the noise strength until the qubit coherence time T_{2E} was reduced by at least a factor of 5, thus ensuring that the dephasing was dominated by a Markovian environment. We then added

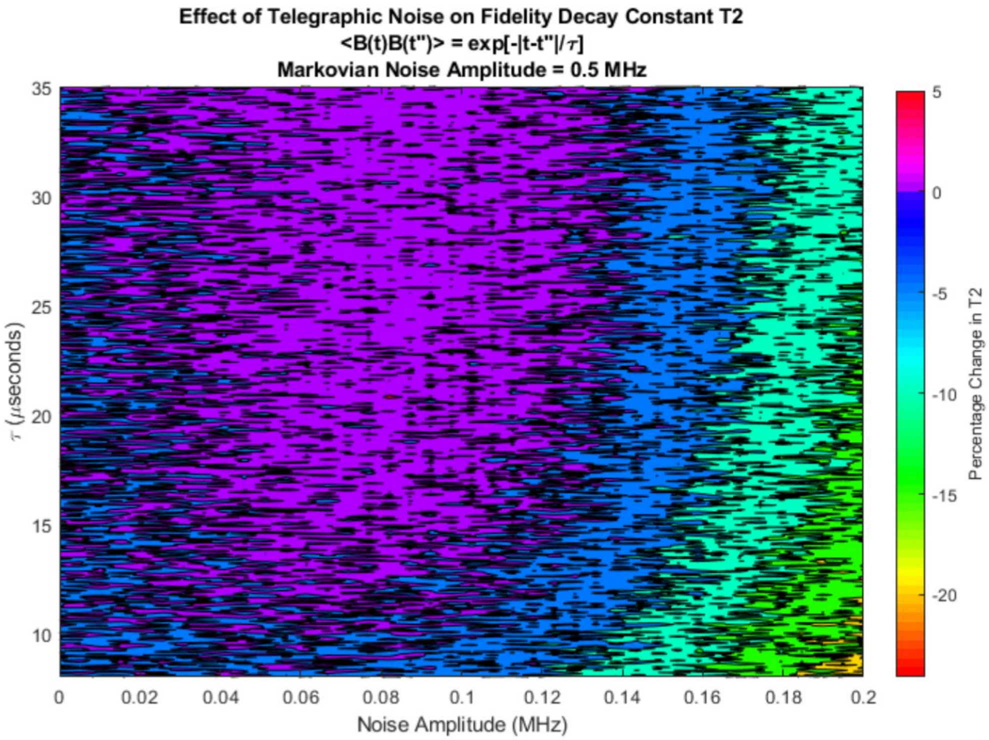

Figure 1

Percentage improvement/degradation in coherence time as a function of telegraph (Poisson) corrective noise amplitude and autocorrelation time. The background is a Markovian white noise of amplitude 0.5 MHz. There is clear structure to the data showing optimal behavior around ~0.07 MHz amplitude and above 15 μs autocorrelation time, but no areas where coherence is improved.

Poisson noise (again of varying strength and autocorrelation time) via the same AWG and measured coherence (i.e. fidelity) again. Results are shown in Fig. 2. Interestingly, we *did* see significant improvements in the coherence time, which continued to improve as we turned up the corrective noise strength. However, we believe that at least some of this improvement is due to the fact that the large Poisson noise amplitude shifted the qubit flux bias so much that the qubit sensitivity to flux noise was reduced. Therefore, the Markovian noise was simply less harmful to coherence, so the background uncorrected coherence time was longer. This was at least partially confirmed by measurements of coherence at varying flux bias with Markovian noise but without Poisson noise, as shown in Fig. 2. Coherence was indeed improved on one side of the starting flux bias (i.e. half the time under the Poisson noise), although the amount of improvement was not quite as much as we observed with the Poisson noise. In lieu of more careful disentangling of these effects, we have decided to develop a procedure that eliminates them entirely, discussed below.

Theory Pitfalls and Current Work

After careful examination of the theory, we believe we have discovered the culprit causing our lack of fidelity improvement. While we are quite confident that Eq. 1 and everything that follows it is valid, we believe there is an invalid assumption used to show that Poisson noise will give Eq.

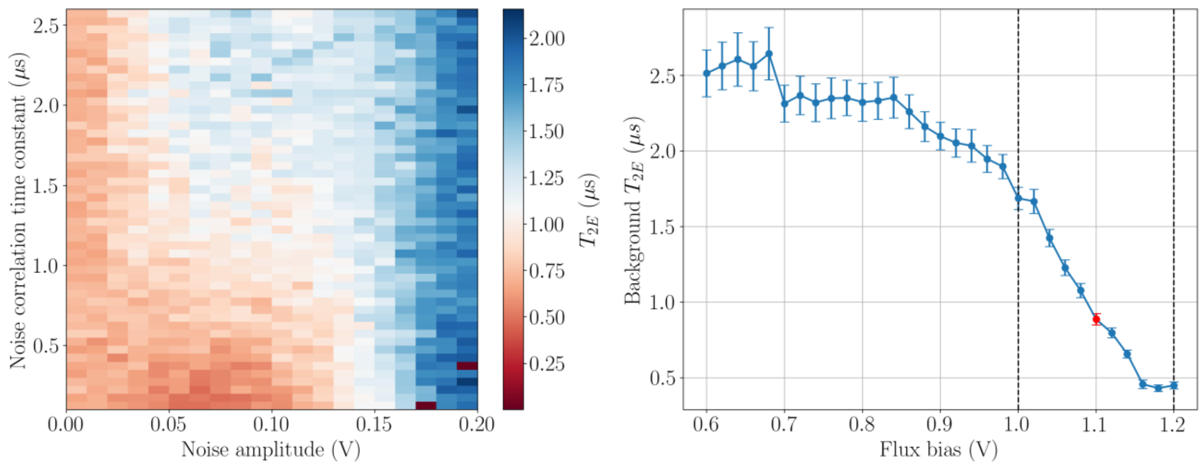

Figure 2

(Left) Experimental data showing spin echo decay time T_{2E} (i.e. coherence time) as a function of Poisson noise amplitude and autocorrelation time. A background Markovian environment reduces T_{2E} to $\sim 0.75\ \mu$s; adding Poisson noise seems to increase the coherence. However, we attribute this effect mainly to a reduced susceptibility to the Markovian noise when flux bias is changed by the Poisson noise; (right) shows background coherence (without Poisson noise) as a function of constant flux bias, with our original bias point highlighted. A Poisson amplitude of 0.2 V_{pp} moves the flux bias to the regions indicated by the dashed lines, improving coherence on one side just by moving the constant bias point.

1. The theory makes the approximation that $\langle B(t)B(t')\rho(t')\rangle \approx \langle B(t)B(t')\rangle\langle\rho(t')\rangle$. Essentially, the theory assumes that the corrective generalized Markovian noise *does not dominate* the dynamics of the system, so that the system's evolution is only weakly correlated with the corrective noise. However, the theory also requires that $2\sqrt{2}|B_0| > |1/\tau_0 - 1/\tau_1|$, which is essentially a requirement that the noise is much *stronger* than the background dynamics. These requirements are in tension with each other and so may lead to behavior which is not predicted by the theory. We note that the area where simulations showed the best (least harmful) behavior are those where we expect both conditions to be only moderately violated.

We are currently exploring other generalized Markovian noise models, including the so-called "oscillating decaying noise" cited in [1] which has a decaying oscillating autocorrelation function. Numerical simulations of this noise are time-consuming, as it must be directly calculated from the autocorrelation (rather than procedurally generated) and there is an extra dimension of parameter space (noise strength, decay time, *and oscillation frequency*). Still, we are making headway with simulations on a high-performance computing cluster, and anticipate more results soon.

We are also working with theory collaborators Marshall and Zanardi in order to develop recipes for generalized Markovian noise capable of generating Eq. 1. We anticipate that this will be an ongoing effort.

Experimental Directions

Our prior experiments were plagued by the fact that our qubit had a non-linear susceptibility to flux noise. This meant that adding generalized Markovian noise would also affect the background decoherence rate, and so it was difficult to disentangle the two effects. We are currently working to develop an experimental procedure where the qubit frequency is tuned (i.e. noise is added) by driving the qubit measurement cavity with an off-resonant tone with a variable amplitude. This tone causes an AC Stark shift in the qubit frequency, dependent on the tone's amplitude. Importantly, this effect is mostly linear, and so we expect no added complexity to the interpretation of the effects of generalized Markovian noise.

Summary

In closing, we have developed robust numerical and experimental procedures for testing the effects of generalized Markovian noise on qubit coherence. We do not yet see any definite improvement in qubit coherence due to the corrective noise, a fact which we attribute to an incorrect assumption in the theory that we used to pick the form of the noise. We are currently testing other forms of noise and simplified experimental testing techniques, and are working with collaborators to work out a more rigorous theory. Our results will be presented at the 2020 APS March Meeting, crediting ARO for the support.