Sandia National Laboratories

Optimal Quantum Transfer from Input Flying Qubit to Lossy Memory

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Overview

- Challenge: Transfer a traveling qubit into stationary memory
- Requirement: Reflected signal needs to be cancelled out by output from resonator
- Question: For a lossy resonator, how do we ensure continuous cancellation to optimize qubit absorption?
- Solution: Dynamically tune resonator's output coupling rate
- Important issue: How do we optimally generate an initial "seed" population in resonator so that resonator output can then continuously cancel out reflected input?
- We demonstrate that **transfer fidelity of ~99.9%** can be reached given practical parameters
- **See results in *Journal of Physics A: Mathematical and Theoretical* (see below for more information)**

Full-Quantum Solution

- Model traveling qubit as coming from lossless resonator (s)
- "Output coupling rate" κ_s of fictitious resonator is ratio between real resonator input rate and source "population"
- Use Hamiltonian (H) to model interaction between resonators, and Lindbladian (L) to model losses:

$$H_{\mathrm{T}} = \mathrm{i}\frac{\sqrt{\kappa_{\mathrm{s}}(t)\kappa(t)}}{2}\left(a_{\mathrm{s}}^{\dagger}a - a_{\mathrm{s}}a^{\dagger}\right),$$

$$L_{\mathrm{T}} = \sqrt{\kappa_{\mathrm{s}}(t)}a_{\mathrm{s}} + \sqrt{\kappa(t)}a.$$

$$L_{\mathrm{i}} = \sqrt{\gamma}a.$$

- Dynamically tune output coupling rate $\kappa(t)$ to zero out input-output loss L_T, incorporate intrinsic loss into Hamiltonian
- Analytical solution for optimal output coupling profile $\kappa(t)$ as function of input rate $r_{in}(t)$, intrinsic loss rate γ, and initial population $\beta^2(t_i)$
- For fixed input rate, κ decreases with increasing population, since lower output coupling rate is required to produce same raw output for cancelling reflected input:

$$\kappa(t) = \frac{r_{\mathrm{in}}(t)}{\mathrm{e}^{-\gamma(t-t_{\mathrm{i}})}\left(\beta^2(t_{\mathrm{i}}) + \int_{t_{\mathrm{i}}}^{t}\mathrm{d}t'\,\mathrm{e}^{\gamma(t'-t_{\mathrm{i}})}r_{\mathrm{in}}(t')\right)}.$$

Seeding an Initial Population

- Need to break zero-input-output-loss condition initially to generate enough population so that resonator output can then dynamically cancel out reflected input
- Solution: Set output coupling rate to maximum value κ_{max} until threshold population is reached (since this minimizes input-output loss and optimally speeds up filling of resonator to threshold)
- Time t_c at which threshold population $r_{in}(t_c)/\kappa_{max}$ is reached is solved numerically from the following:

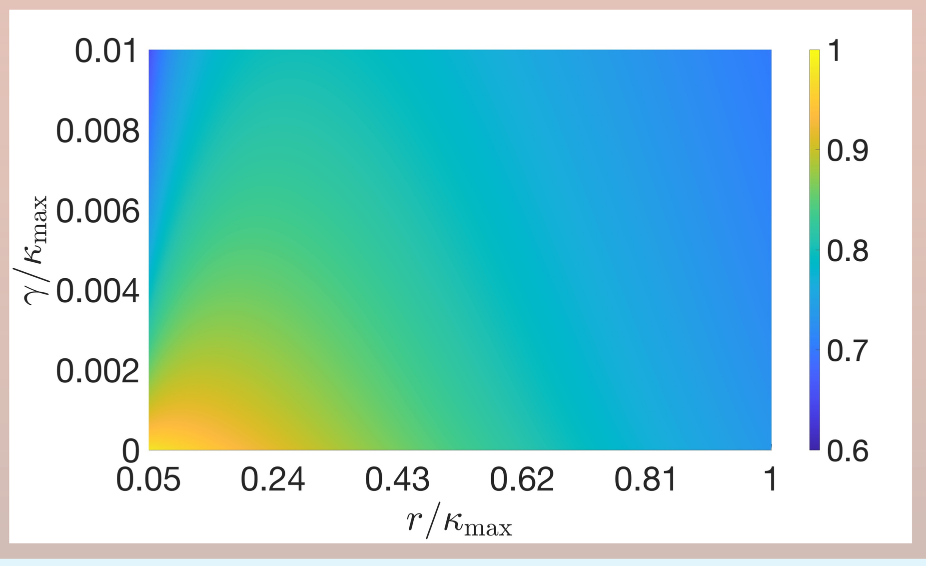
$$\frac{\sqrt{r_{\mathrm{in}}(t_{\mathrm{c}})}}{\kappa_{\mathrm{max}}}\,\mathrm{e}^{\frac{\kappa_{\mathrm{max}}+\gamma}{2}t_{\mathrm{c}}} = \int_0^{t_{\mathrm{c}}}\mathrm{d}t'\,\mathrm{e}^{\frac{\kappa_{\mathrm{max}}+\gamma}{2}t'}\sqrt{r_{\mathrm{in}}(t')}.$$

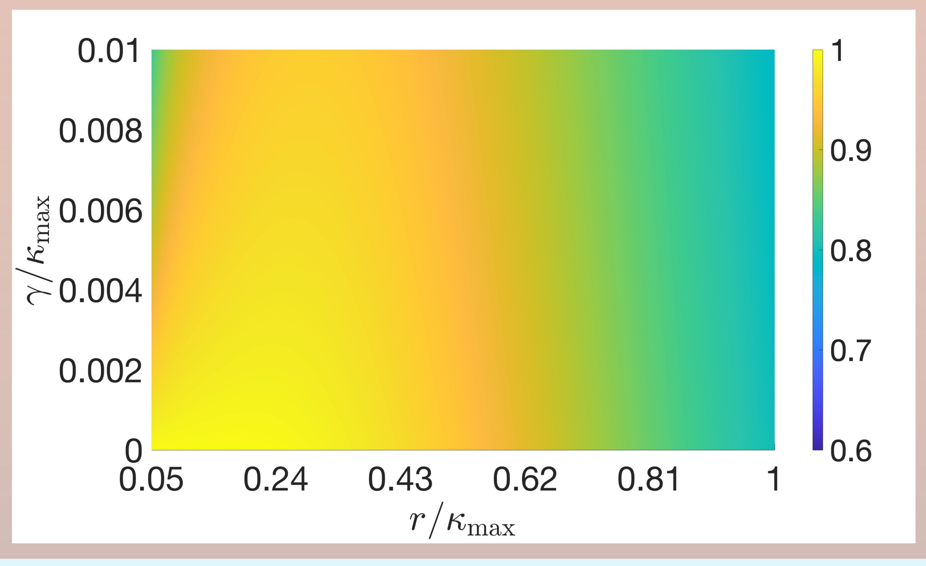
- This sets the optimal output coupling profile for the second (zero input-output loss) stage:

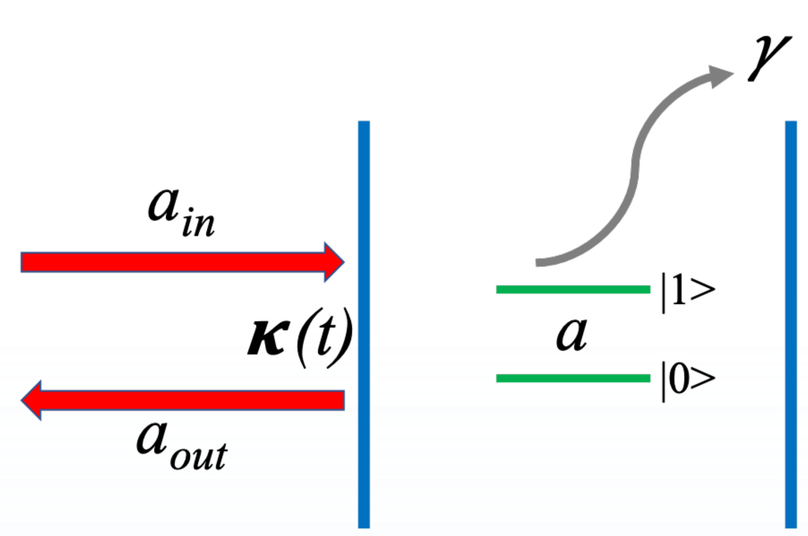
$$\kappa(t) = r_{\mathrm{in}}(t)\mathrm{e}^{\gamma t}\left(\frac{r_{\mathrm{in}}(t_{\mathrm{c}})}{\kappa_{\mathrm{max}}}\mathrm{e}^{\gamma t_{\mathrm{c}}} + \int_{t_{\mathrm{c}}}^{t}\mathrm{d}t'\,\mathrm{e}^{\gamma t'}r_{\mathrm{in}}(t')\right)^{-1}.$$

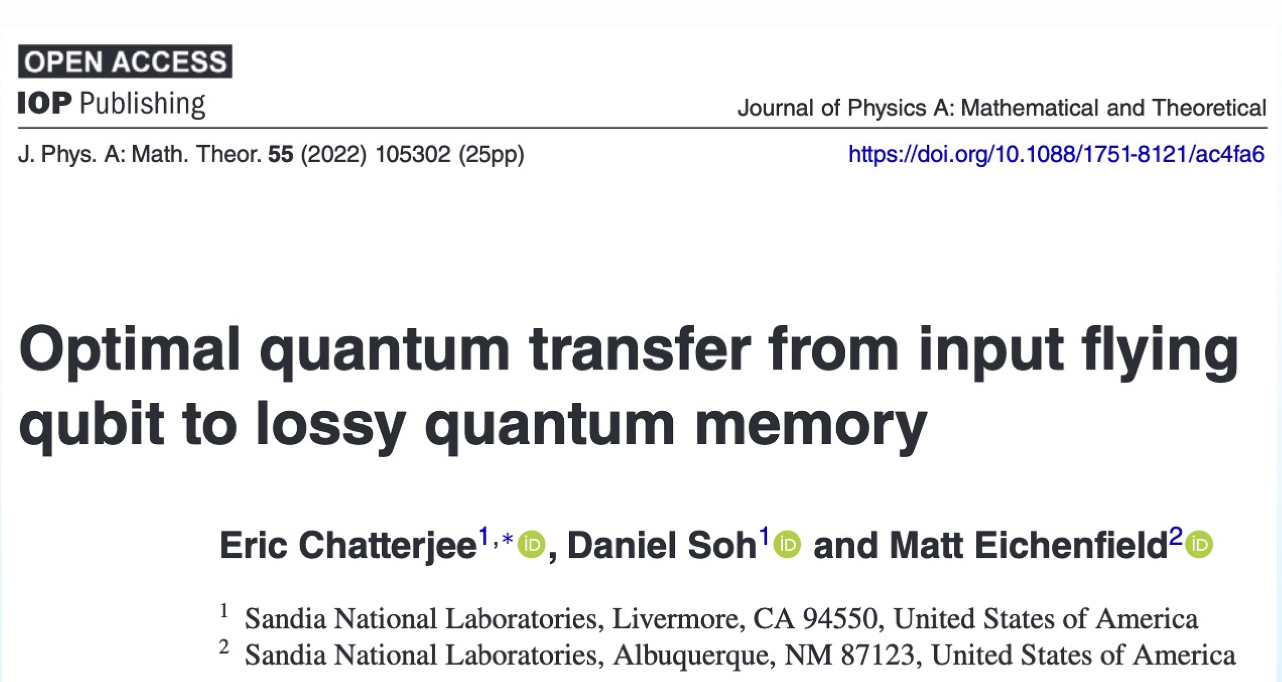
Fidelity Variation

- Fidelity varies inversely with intrinsic loss rate, as expected
- Relationship between fidelity and peak input rate r is more complicated: Higher r increases loss during initial "seeding" stage, whereas lower r increases loss during rest of transfer by increasing transfer time (and thus net intrinsic loss)
- Optimal r thus increases with intrinsic loss rate
- Fidelity plots for exponentially decaying input (left) and Gaussian input (right)





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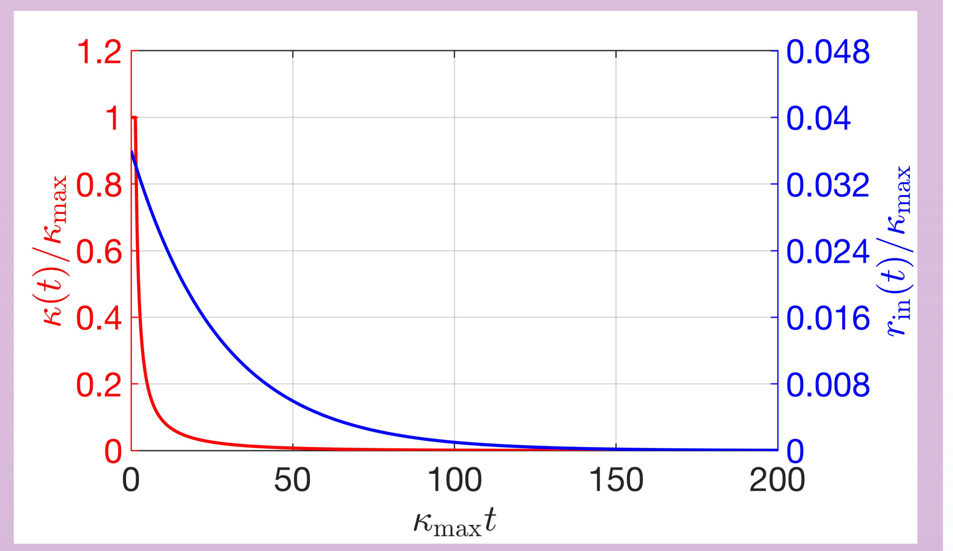
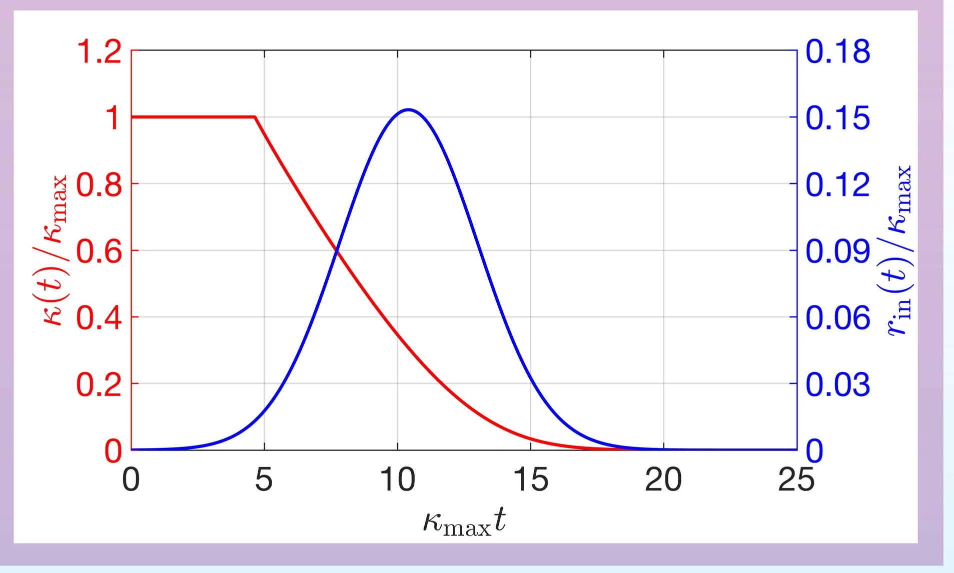
Optimal Temporal Profiles

- Exponential input: 97% fidelity (optimal parameters)



- Gaussian input: 99.87% fidelity (optimal parameters)



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