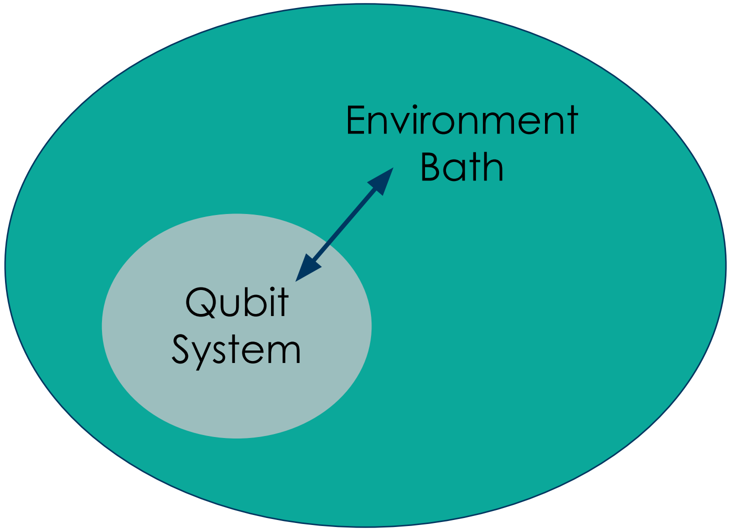
Simulating Non-Markovian Noise in Quantum Circuits with Tensor Networks

Shivane Dadi

Introduction & Motivation

Quantum Computers are Open Quantum Systems

- Effective Quantum Simulations should model realistic conditions
- Closed System
  - Ideal Quantum Circuit
  - Unitary Evolution
  - MPS/MPO
- Open Memoryless System
  - Local Markovian Noise
  - Non-Unitary Evolution
  - MPDO/LPDO
- Open System
  - Non-Markovian Noise
  - **Process Tensors**



Process Tensor Formalism

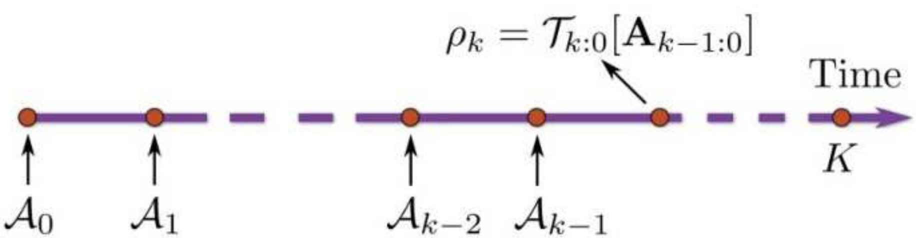
Non Markovian Systems map to Process Tensors

$$\rho_S(t) = \mathrm{Tr}_E\left[\mathcal{T}\exp\left(-i\int_0^t H_{SE}(s)\,ds\right)\,\rho_{SE}(0)\right]$$

From State Based Evolution to Operation Based Evolution

(c)

[1]



- Discretize the system evolution
- Memory Stored in Correlations
- Each operation becomes an input
- Maintains CPTP map

Markovian limit: $\mathcal{T}_{k:0} = \Lambda_{k:k-1}\cdots\Lambda_{1:0}$

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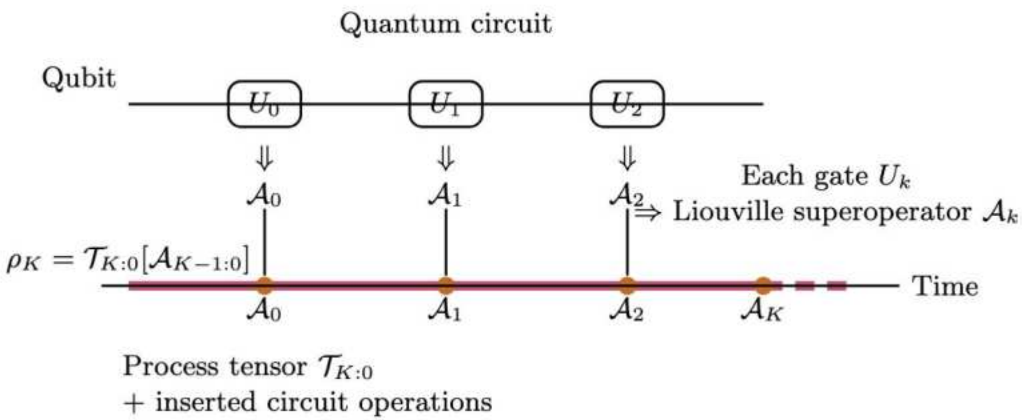
Simulating Quantum Circuits

How do we Introduce this System Evolution into a quantum circuit

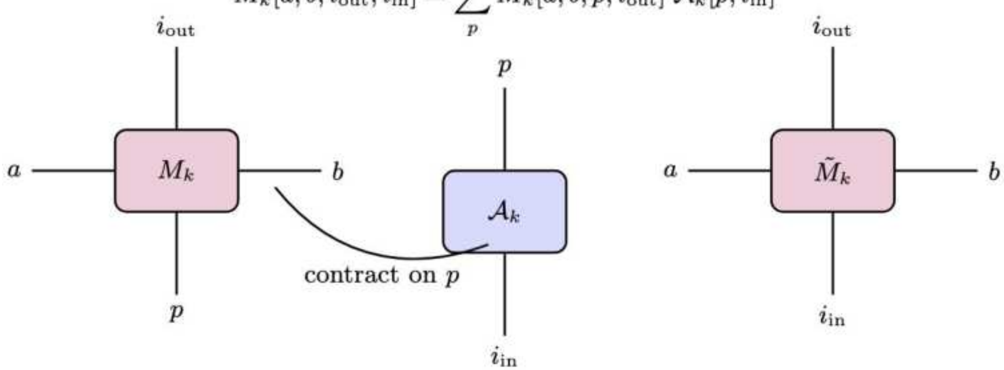


$$\mathcal{U}(\rho) = U \rho U^{\dagger}.$$

$$S_U = U \otimes U^{*}.$$

$$|\rho\rangle\rangle = \mathrm{vec}(\rho), \qquad |\rho'\rangle\rangle = \mathrm{vec}(\mathcal{U}(\rho)),$$

$$\tilde{M}_k[a, b, i_{\mathrm{out}}, i_{\mathrm{in}}] = \sum_p M_k[a, b, p, i_{\mathrm{out}}]\, \mathcal{A}_k[p, i_{\mathrm{in}}]$$



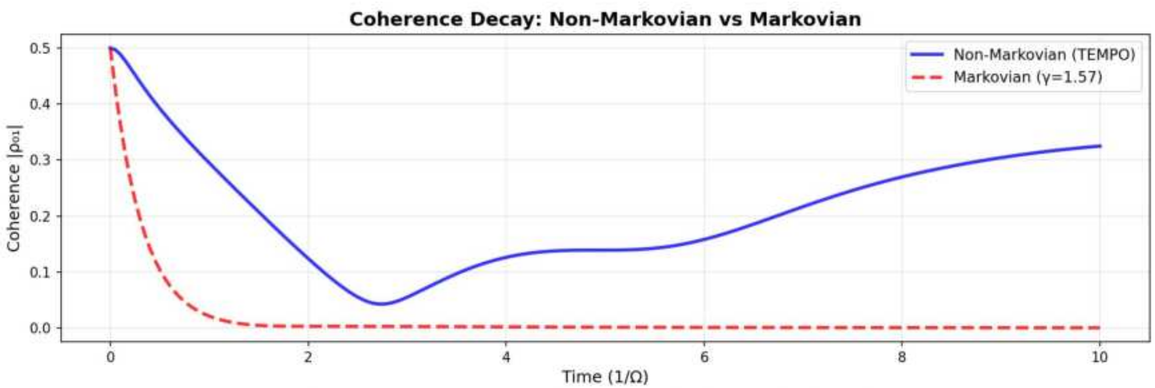
$$|\rho'\rangle\rangle = S_U\, |\rho\rangle\rangle,$$

Results

$$H = H_S + H_B + H_{\text{int}} = \frac{\Omega}{2}\sigma_z + \sum_k \omega_k \, b_k^\dagger b_k + \sigma_z \otimes B.$$

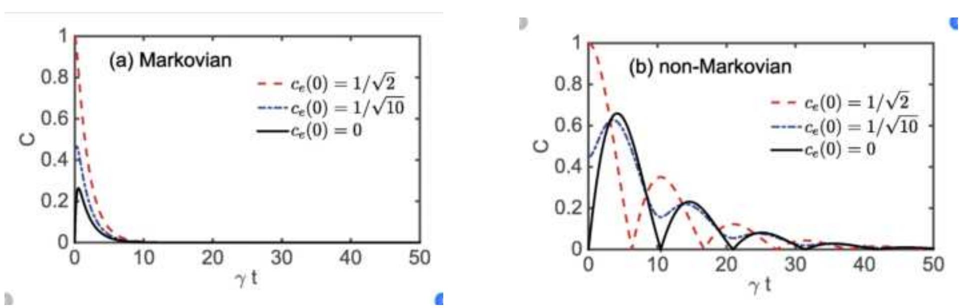
Successful recreation of the process tensor for Non-Markov processes

My Implementation



Literature

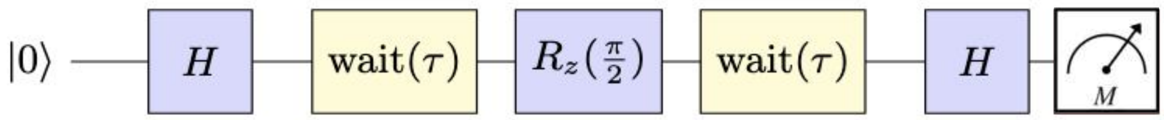
[2]

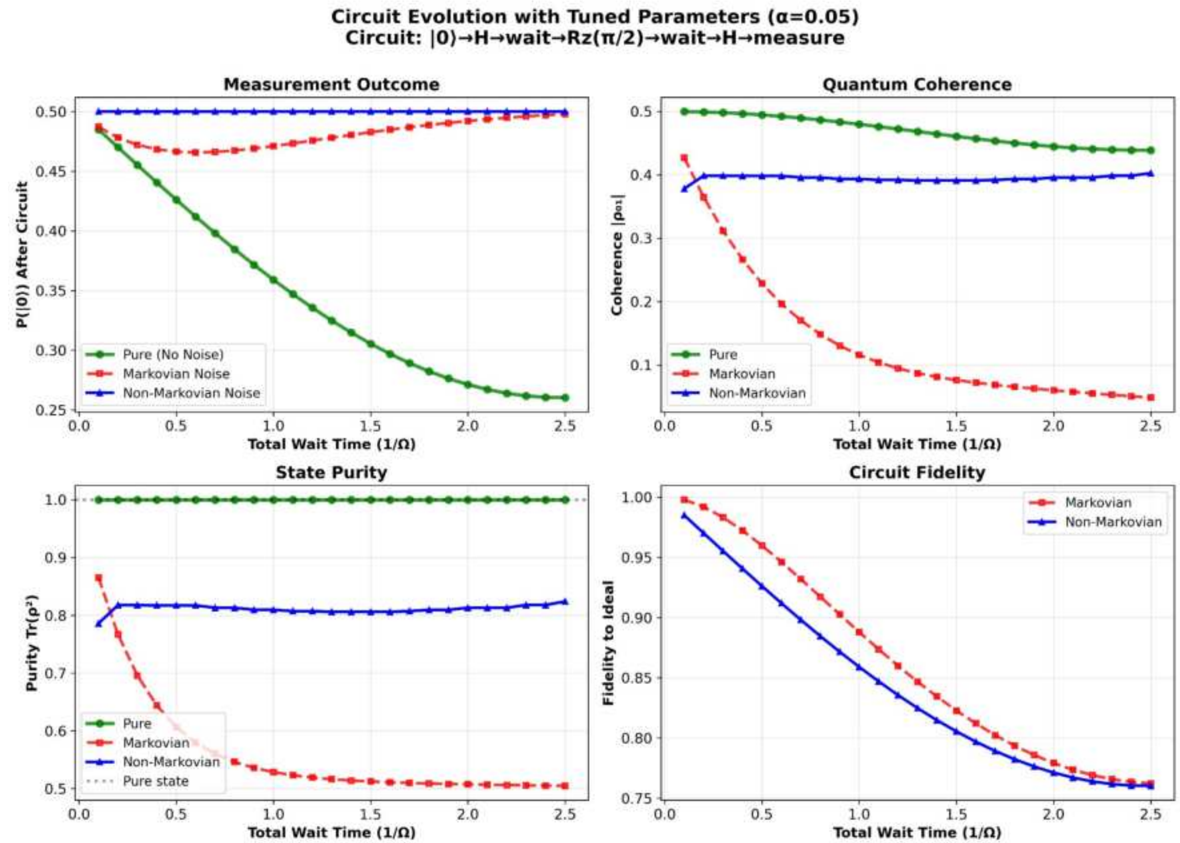


- Simulating Spin-Boson Model with Ohmic Bath
  - Dephasing Noise
- Clearly shows coherence revival
  - Expected behavior in non markov regimes

Results

Successful Simulation of Ramsey Circuit with Noise





Summary & Future Work

- Developed a framework to simulate non markovian noise in quantum simulation
  - No other libraries do this!
- Generalizable to any kind of noise
  - Process Tensors maintains CPTP maps
- Test more interesting circuits using this framework
- Integrate this with Quimb/TensorCircuit instead of doing manual contractions

References

- Pollock et al. (2018) https://arxiv.org/pdf/1512.00589
- Xiao, Xing & Lian, Yuxiang & Li, Yan-Ling. (2020). Weak Measurement-Assisted Coherence Enhancement with Initial System-Environment Correlation. International Journal of Theoretical Physics. 59. 1-7. 10.1007/s10773-019-04305-2.
- Strathearn et al. (2018) https://arxiv.org/pdf/1711.09641

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