



Contribution ID: 164

Type: **Contributed Oral**

Classical simulation of noisy quantum circuits via locally entanglement-optimal unravelings

Tuesday 2 December 2025 11:55 (15 minutes)

Classical simulations of noisy quantum circuits is instrumental to our understanding of the behavior of real world quantum systems and the identification of regimes where one expects quantum advantage. The presence of noise can decay quantum entanglement. Our work capitalizes on this idea. We employ new methods that push the boundaries of noise-induced entanglement decay, using it to significantly improve the classical simulation of noisy quantum systems. This approach makes simulating these complex circuits less computationally intensive—a crucial step for better understanding the behavior of real world quantum systems and the identification of regimes where one expects quantum advantage.

In this work, we present a highly parallelizable tensor-network-based classical algorithm – equipped with rigorous accuracy guarantees – for simulating n -qubit quantum circuits with arbitrary single-qubit noise. Our algorithm represents the state of a noisy quantum system by a particular ensemble of matrix product states from which we stochastically sample. Each single qubit noise process acting on a pure state is then represented by the ensemble of states that achieve the minimal average entanglement (the entanglement of formation) between the noisy qubit and the remainder. This approach lets us use a more compact representation of the quantum state for a given accuracy requirement and noise level. For a given maximum bond dimension and circuit, our algorithm comes with an upper bound on the simulation error, runs in poly-time and improves upon related prior work (1) in scope: by extending from the three commonly considered noise models to general single qubit noise (2) in performance: by employing a state-dependent locally-entanglement-optimal unraveling and (3) in conceptual contribution: by showing that the fixed unraveling used in prior work becomes equivalent to our choice of unraveling in the special case of depolarizing and dephasing noise acting on a maximally entangled state.

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Session Classification: Quantum Science and Technology

Track Classification: Topical Groups: Quantum Science and Technology