Advancing Scalable Quantum Algorithms for Simulating Multi-Qubit Systems With Colored Noise

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Ultra-sensitive, scalable quantum computing relies on the precise control of open quantum systems, where environmental memory effects lead to non-Markovian noise. As quantum systems continue to develop, inaccuracies from memoryless approximations heavily limit hardware reliability and lead to measurement error. Non-Markovian dynamics arise in realistic environments and pose a challenge for accurately modeling qubit evolution, including decoherence and disentanglement. This research develops a novel, complete operator-based framework for simulating non-Markovian dynamics in multi-qubit systems, enabling clear analysis beyond specific noise models. The environment interactions were modeled using the stochastic Quantum State Diffusion approach, allowing for memory effects to be incorporated through propagator functions. To separate the noise, the dynamics were expressed as separate quantum channels in Kraus operator form, allowing for the construction of the density matrix and analysis of population, coherence, and entanglement. Python was used to simulate dissipative and dephasing channels, demonstrating expected physical behavior. Furthermore, the model was shown to accurately compute key physical properties such as entanglement and superposition. Algorithms were implemented across multiple circuits on IBM quantum processors to compare model predictions with experimental results. It was shown that the novel non-Markovian model achieved a 3x smaller fidelity error rate compared to the standard Lindblad model. These results demonstrate that our algorithmic modeling provides more accurate descriptions of open quantum systems, alongside a scalable framework for analyzing larger noisy systems.

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