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Low-Rank Split-Operator Propagation for Structured Open Quantum Systems

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Direct numerical simulation of open quantum systems is limited by the quadratic memory cost of storing the density matrix. We present a deterministic low-rank propagation method for time-local Markovian dynamics. The method applies to Hamiltonians composed of a time-dependent diagonal part and terms that become tridiagonal after suitable permutations of the basis, as well as to collapse operators with diagonal or narrow-banded representations. The density matrix is represented by a low-rank ensemble of state vectors. Coherent evolution is advanced using a symmetric Suzuki–Trotter decomposition: diagonal factors are applied exactly, while tridiagonal factors are evaluated using Cayley transforms that require only solving tridiagonal linear systems. Dissipation is incorporated through infinitesimal Kraus branches, after which the enlarged ensemble is compressed to a prescribed rank using a small Gram matrix. For a fixed retained rank and number of collapse channels, the memory requirement and the dominant computational operations scale linearly with the Hilbert-space dimension.

The method is benchmarked on a driven finite-spin model of an NV-center ensemble coupled to a microwave cavity. The interaction terms become tridiagonal in different basis orderings, while the cavity and collective-spin collapse operators retain a banded structure. Comparison with full-density-matrix simulations in QuTiP shows close agreement for the cavity quadrature variance in the tested regime, while the integrated errors of the monitored observables decrease systematically as the retained rank is increased from 2 to 16. Pure-propagation timing benchmarks exhibit near-linear scaling, with fitted exponents between 1.09 and 1.23. The method is therefore most effective when the density matrix remains approximately low rank; strongly mixed states and continuously pumped lasing regimes may require larger ranks and reduce the computational advantage.

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