Tensor network approaches for simulations of larger superconducting circuits

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Superconducting circuits are a leading platform for adiabatic quantum computing, owing to their scalability, customizability, and strong intrinsic nonlinearity. The computational capabilities of such systems are fundamentally determined by their Hamiltonian, which is given by the effective interactions among superconducting elements. Our goal is to study effective Hamiltonians of larger, more tunable, and more richly coupled systems with higher accuracy, designing circuits that fully account for residual coupling terms [1,2].

We present a tensor-network-based simulation framework that enables us to go beyond the computational limits of exact diagonalization for larger superconducting circuits. Traditional approaches scale exponentially in the number of circuit nodes, quickly saturating even high-performance computing (HPC) resources. In fact, we already encounter this limitation in simulating just two tunable, coupled persistent-current qubits (six-node lumped-element Hamiltonian). Our goal is to capture strong interactions and richer coupling mechanisms in superconducting circuits without resorting to approximations such as the Born–Oppenheimer method [3] or hierarchical diagonalization [4], both of which could fail to reproduce the rich dynamics of superconducting circuits. By representing the full lumped-element Hamiltonian as a matrix product operator and solving it with the DMRG algorithm [5,6], we obtain accurate insights into strongly coupled regimes while keeping the computational cost tractable. We have prepared our code for GPU computing, adapting it for efficient parallel execution. Preliminary results for two coupled persistent-current qubits show the expected periodic response as a function of external fluxes, validating our approach. We have quantitaive matches for single and two coupled fluxonia.

We are now refining the physical and computational parameters to match experimental data more closely. In parallel, we are applying an optimized Schrieffer–Wolf transformation within the tensor-network framework to extract effective Hamiltonians in terms of Pauli operators, likely revealing coupling terms that more approximate methods fail to capture [1]. We are currently benchmarking the methdodology also on two and three coupled fluxonia circuits in terms of computational time and accuracy vs hierahcial diagonalization. Our work paves the way for simulating larger and more complex superconducting circuits, offering deeper insights into their rich interaction landscapes.

References

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