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Quantum phase estimation with optimal confidence interval using three control qubits

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Estimating the ground state energy of a physical system is an important task in quantum algorithms. If the ground state can be prepared on a quantum computer, then its energy can be estimated using the quantum phase estimation algorithm, which involves applying multiples of a unitary to the ground state, controlled on an auxiliary state prepared on a control register. Textbook descriptions of quantum phase estimation prescribe preparing an equal superposition state on the control register, but much better performance can be achieved with more complicated, entangled states. The state which provides the optimal confidence interval for the estimate is a discrete prolate spheroidal sequence (DPSS) state, which can be difficult and costly to prepare, especially for early-generation fault-tolerant quantum computers.

In this work, we describe an efficient procedure for preparing a DPSS state by using a matrix product state (MPS) approximation and provide an explicit quantum circuit structure for its implementation. We provide numerical evidence showing that for DPSS states configured for confidence levels up to 99.99% and with dimension up to 2^{25}, an MPS approximation with bond dimension 4 achieves fidelity exceeding $1 - 10^{-7}$, inducing a negligible relative decrease in confidence level. Furthermore, we show that when the dimension is a power of two, we can combine our technique with the semi-classical quantum Fourier transform to enable quantum phase estimation with only three qubits allocated to the control register. The ability to freely adjust the dimension of the state on the control register enables the user to pick the most suitable trade-off between confidence interval width and the number of controlled unitary operations applied during the quantum phase estimation algorithm. The scaling and flexibility of our technique make it suitable for performing accurate ground state energy calculations on early-generation fault-tolerant quantum computers.

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