Hybrid Tree Tensor Networks for Quantum Simulation

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Hybrid Tensor Networks (hTN) offer a promising solution for encoding variational quantum states beyond the capabilities of efficient classical methods or noisy quantum computers alone [1]. However, their practical usefulness and many operational aspects, including their scalable optimization and tailoring to specific applications, have not been thoroughly investigated yet.

In our contribution [2], we fill this gap and pinpoint instances where hTNs have the potential to outperform their classical counterparts. We propose a new hierarchically-structured hybrid ansatz, inspired by classical Tree Tensor Networks (TTNs), where we replace the topmost tensors -- namely the ones with larger bond dimensions -- with quantum states (see Fig.1). In order to characterize the advantages and limitations of this ansatz, we introduce a scalable optimization procedure based on the DMRG-inspired algorithm for classical TTNs. Therefore, we establish for the first time a complete workflow for preparing and optimizing hybrid TTNs.

We benchmark our approach on two paradigmatic models, namely the Transverse Field Ising model (see Fig.2) at the critical point and the Toric code Hamiltonian. In both cases, we successfully demonstrate that hybrid TTNs can improve upon classical equivalents with equal bond dimension in the classical part.

References

[1] Yuan et al, Phys. Rev. Lett. 127 (2021), 040501
[2] Schuhmacher et al, PRX Quantum 6.1 (2025), 010320.

Figures

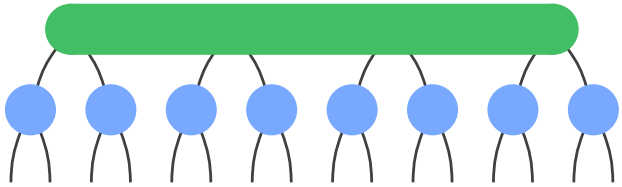

Figure 1: Illustration of the Hybrid TTN Ansatz. Classical tensors are highlighted in blue. Quantum tensors are highlighted in green.

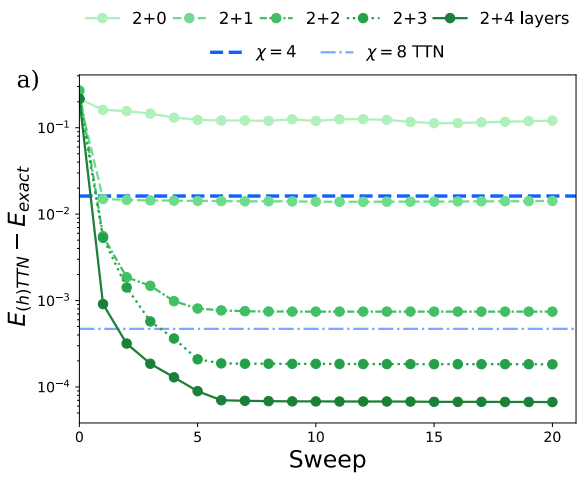

Figure 2: Ground state energy optimization for 1-dim 16-site Transverse Field Ising model using the hybrid TTN ansatz illustrated in Fig.1. The optimization is shown for different number of layers in the quantum circuit representing the quantum tensor.