Symmetric Clifford twirling for cost-optimal quantum error mitigation in early FTQC regime

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Twirling noise affecting quantum gates is essential in understanding and controlling errors, but applicable operations to noise are usually restricted by symmetries inherent in quantum gates. In this work, we propose symmetric Clifford twirling, a Clifford twirling utilizing only symmetric Clifford operators that commute with certain Pauli subgroups. We fully characterize how each Pauli noise is converted through the twirling and show that certain Pauli noise can be scrambled to a noise exponentially close to the global white noise. Moreover, we provide numerical demonstrations for highly structured circuits, such as Trotterized Hamiltonian simulation circuits, that noise effect on typical observables can be described by the global white noise. We further demonstrate that symmetric Clifford twirling and its hardware-efficient variant using only local symmetric Clifford operators acting on a few logical qubits can significantly accelerate the scrambling. These findings enable us to mitigate errors in non-Clifford operations with minimal sampling overhead in the early stages of fault-tolerant quantum computing.