Channel capacity of small modular quantum networks in the ultrastrongly coupled regime

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Abstract: We investigate state transfer in modular quantum computer architectures exploiting ultrastrong coupling between quantum processing units and interconnects. Adiabatic coherent transport achieves near-ideal single-letter quantum capacity, suppressing leakage induced by the dynamical Casimir effect.

Developing modular architectures is recently attracting a large interest as a promising roadmap for upscaling quantum computers on solid-state platforms. Modular hardware integrates interconnected quantum processing units (QPUs), while interconnects (ICs) carry quantum information and allow quantum communication at the intercore level. We address state transfer between QPUs - a basic task of quantum communication - considering two qubits coupled to an IC modeled by a d-level system [1,2]. We study the trade off between speed, increasing when the coupling becomes ultrastrong, and fidelity affected by the Dynamical Casimir Effect producing pairs of excitations which determine leakage from the computational subspace [1,2].

We investigate state transfer by a quantum bus (QB) protocol consisting of two Rabi swaps, and a virtual QB protocol operated by coherent transport by adiabatic passage (CTAP) [1-5]. As a figure of merit for efficient state transfer we calculate the single-letter quantum channel capacity Q_1 [1,2] whose behavior is shown in Fig. 1 for ICs with different numbers of equispaced levels. While the QB performance becomes poor in the ultrastrong regime, the virtual QB achieves large Q_1 and robustness against parametric fluctuations [2].

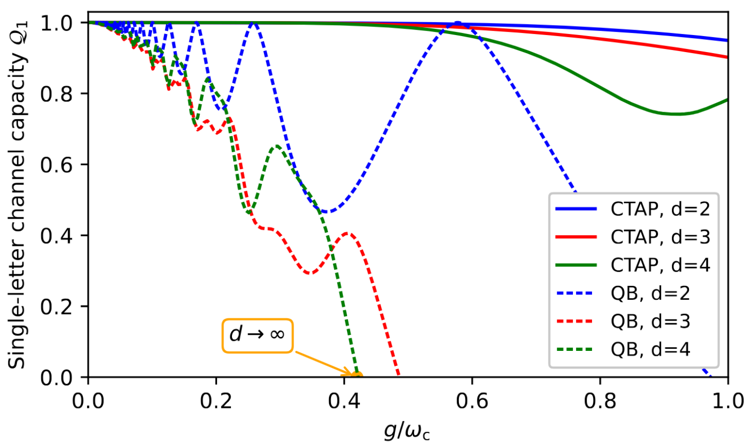

Fig. 1. Single-letter quantum channel capacity Q_1 as a function of the coupling strength g/ω_c for the QB and CTAP protocols.

References

[1] G. Benenti, A. D'Arrigo, S. Siccardi, G. Strini, "Dynamical Casimir effect in quantum-information processing", Phys. Rev. A **90**, 052313 (2014).
[2] S. A. Cordovana, L. Giannelli, N. Macrì, G. Benenti, E. Paladino, G. A. Falci, "Channel capacity of small modular quantum networks in the ultrastrongly coupled regime," *Eur. Phys. J. Spec. Top.* (2025).
[3] M. Stramacchia, A. Ridolfo, G. Benenti, E. Paladino, F.M.D. Pellegrino, D. Maccarrone, G. Falci, " Speedup of adiabatic multiqubit state-transfer by ultrastrong coupling of matter and radiation", Proceedings **12**(1) (2019).
[4] G. A. Falci, L. Giannelli, G. Benenti, S. Montangero, E. Paladino, "Ultrafast intercore computation between distant solid-state QPUs", (preprint 2026).
[5] A.D. Greentree, J.H. Cole, A.R. Hamilton, L.C.L. Hollenberg, "Coherent electronic transfer in quantum dot systems using adiabatic passage", Phys. Rev. B **70**, 235317 (2004).