NQSTI
National Quantum Science and Technology Institute

Adaptive Quantum Error Correction for Quantum Communications

Andrea Talarico, Lorenzo Valentini, Diego Forlivesi, Marco Chiani

CNIT/WiLab, DEI, University of Bologna, Italy

Abstract: Adaptive quantum error correction leverages channel parameters estimated from entanglement distillation to optimize code selection. The proposed scheme improves reliability or reduces EPR resource consumption by adapting to channel asymmetry and fidelity.

Quantum communication is a key enabler of the emerging quantum Internet, where quantum states are transmitted across distributed nodes using protocols such as quantum teleportation. However, practical implementations face significant challenges due to noise and imperfections affecting both transmitted quantum states and shared entangled resources. These impairments reduce fidelity and reliability, making robust error mitigation strategies essential.

In this work, we propose an adaptive framework for quantum error correction (QEC) that dynamically selects the most suitable quantum code based on channel conditions inferred during entanglement distillation [1]. Specifically, we exploit information obtained through a combined distillation and distimation process to estimate key channel parameters, including fidelity and asymmetry of the effective Pauli channel induced by imperfect Einstein–Podolsky–Rosen (EPR) pairs. These parameters provide insight into the dominant error mechanisms affecting the system.

Based on these estimates, the proposed scheme (Fig. 1) adaptively modifies the encoding strategy prior to quantum teleportation. Two approaches are considered. First, code switching transforms standard surface codes into asymmetric variants [2], such as ZZZY [3] codes, which are better suited for channels dominated by phase-flip errors. Second, code deformation reduces code size while preserving error-correction performance under specific asymmetry conditions. This enables a trade-off between resource consumption and reliability, allowing either improved performance without increasing qubit overhead or reduced EPR pair consumption without degrading performance.

An analytical framework is developed to evaluate the benefits of adaptive coding as a function of channel asymmetry and physical error rates. Results show that, beyond certain asymmetry thresholds, asymmetric codes outperform conventional surface codes. In particular, ZZZY codes improve reliability under moderate asymmetry, while deformed surface codes reduce resource requirements in highly asymmetric regimes.

Overall, this work highlights the importance of leveraging channel state information in quantum communication. By integrating entanglement distillation, channel estimation, and adaptive QEC, the proposed framework provides a flexible and efficient approach to improving the performance and scalability of quantum networks. A promising extension involves incorporating quantum low-density parity-check (QLDPC) codes and advanced decoding strategies, such as the restart belief decoder [4], to further enhance performance.

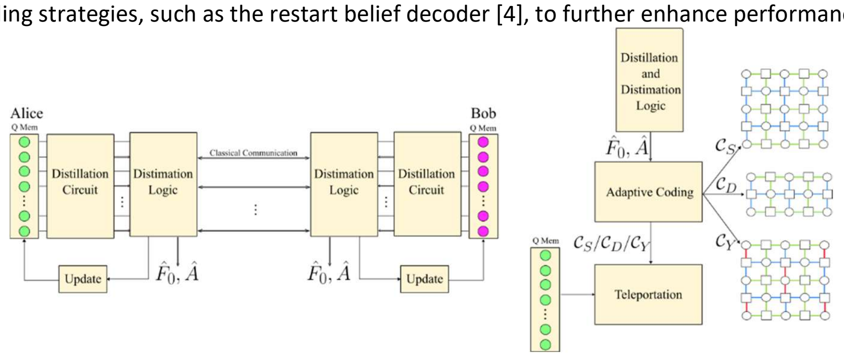

Fig. 1 Block diagram of the adaptive quantum communication scheme, where distillation and distimation is used to estimate channel parameters, enabling adaptive quantum error correction before teleportation.

Example References

[1] L. Valentini, R. B. Christensen, P. Popovski, and M. Chiani, “Reliable quantum communications based on asymmetry in distillation and coding,” IEEE Transactions on Quantum Engineering, vol. 5, pp. 1–13, 2024.

[2] D. Forlivesi, L. Valentini, and M. Chiani, “Logical error rates of XZZX and rotated quantum surface codes,” IEEE J. Sel. Areas Commun., vol. 42, no. 7, pp. 1808–1817, 2024.

[3] D. Forlivesi, L. Valentini, and M. Chiani, “Quantum codes for asymmetric channels: ZZZY surface codes,” IEEE Communications Letters, vol. 28, no. 10, pp. 2233–2237, 2024.

[4] L. Valentini, D. Forlivesi, A. Talarico and M. Chiani, “Restart Belief: A General Quantum LDPC Decoder,” *IEEE Communications Letters* (2026)