Code-Assisted Entanglement Distillation for Quantum Memory Applications

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양자 메모리 응용을 위한 부호 기반 얽힘 정제 기법

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Abstract

We study code-assisted entanglement distillation protocols for quantum memory applications, focusing on repetition and [[4,2,2]] code-based schemes. Both one-way and two-way modes are analyzed under depolarizing noise. Results show that the [[4,2,2]] code achieves higher fidelity and success probability compared to the repetition code, especially when entangled states are stored for long durations. This highlights the advantage of error-detecting codes in realistic quantum memory settings.

Ⅰ. Introduction

Entanglement is a key resource in quantum communication and distributed quantum computing. However, noise in quantum channels often degrades the fidelity of shared entangled states. To mitigate this, entanglement distillation protocols (EDPs) extract high-fidelity pairs using local operations and classical communication (LOCC) [1][2].

Classical protocols such as BBPSSW laid the foundation for distillation by showing how moderate-fidelity Bell pairs can be improved. Many schemes have since extended this idea using varied classical communication and purification strategies [3].

More recently, code-assisted EDPs have gained attention. By incorporating quantum codes [4], these protocols can detect or correct errors during distillation. In this work, we compare two such schemes: one using the repetition code and another the [[4,2,2]] code. We analyze both one-way and two-way modes under depolarizing noise to assess fidelity and success probability.

Ⅱ. Code-Assisted Entanglement Distillation

A. Entanglement Distillation Protocol

Entanglement distillation is a crucial technique that enables the generation of high-fidelity entangled states from imperfect ones. Traditional protocols such as BBPSSW and DEJMPS rely on simple two-qubit operations and post-selection based on measurement outcomes. These protocols typically operate on pairs of Bell states and are effective under moderate noise conditions.

However, as the requirements for entanglement fidelity and resource efficiency increase, there has been a growing interest in generalized frameworks where multiple entangled pairs are used in a structured way to improve the purification outcome. Code-assisted approaches belong to this category, allowing the use of quantum codes to either detect or correct errors during the distillation process

B. Quantum Memory

In the broader context of quantum networks, purified entangled pairs are often required to support operations between spatially separated nodes. Although this paper does not focus on long-term storage, the ability to reliably distill high-fidelity entanglement remains foundational to any architecture involving quantum repeaters or modular quantum computation, where entanglement acts as a carrier of quantum correlations.

C. Entanglement Distillation with Quantum Codes

In this study, we consider two code-assisted EDP schemes: one utilizing the repetition code, and the other based on the [[4,2,2]] quantum error-detecting code. The repetition code encodes a single logical qubit into multiple physical qubits (e.g., $|0_L\rangle = |000\rangle$), and is capable of detecting and rejecting certain types of bit-flip errors.

On the other hand, the [[4,2,2]] code is a stabilizer code that encodes two logical qubits into four physical qubits, providing the ability to detect single-qubit Pauli errors. In our protocol, multiple noisy Bell pairs are encoded into a logical entangled state, stabilizer measurements are performed to identify valid subspaces, and successful rounds are post-selected based on syndromes.

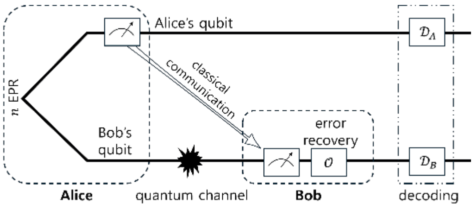

Fig. 1. Entanglement distillation protocol with 1-way classical communication

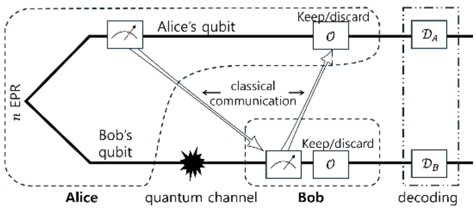

Fig. 2. Entanglement distillation protocol with 2-way classical communication

By comparing these two schemes in both one-way and two-way classical communication settings, we aim to evaluate how encoding structure and error detection capability impact the overall distillation performance.

Ⅲ. Simulation and Results

We simulate the output fidelity F' of three EDP schemes under depolarizing noise: the [[4,2,2]] code, repetition code (detection mode), and repetition code (correction mode).

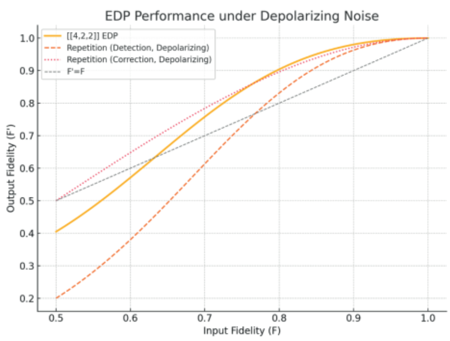

Fig. 3. Performance of entanglement distillation protocols

As shown in Fig. 3, the [[4,2,2]] code achieves higher fidelity when $F < 0.75$, while the correction-mode repetition code performs consistently across a wide range. The detection-mode scheme shows limited improvement under depolarizing errors due to its error sensitivity. These results support the effectiveness of error-detecting codes in realistic noise environments.

Ⅳ. Conclusion

We compared code-assisted entanglement distillation protocols using the repetition code and the [[4,2,2]] code under depolarizing noise. Simulation results show that the [[4,2,2]] scheme offers better output fidelity in low to intermediate input fidelity regions, while repetition-based correction provides stable performance. This suggests that structured quantum codes can enhance distillation in realistic settings, especially when multiple error types are present.

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