Quantum Repeater with Encoding

Objective: Distribute an encoded Bell state

Bell state: $|00⟩ + |11⟩$

$|00⟩|00⟩ + |11⟩|11⟩$

Encoded Bell state with 3-qubit repetition code

Benefit: We can potentially correct for error at each entanglement swapping stage

Challenge: error propagation due to imperfect gates (error prob $p$); imperfect initial states (w/ fidelity $F_1$); and measurement errors (w/p $δ$)

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Quantum Repeaters (QRs): An enabling technology for future quantum networks that allows efficient distribution of entanglement over long distances.

Main idea: first distribute and store entanglement between short segments and then to use entanglement swapping (ES) and entanglement distillation at intermediate stations to establish entanglement at long distances.

This work: Focuses on a scheme where entanglement distillation is achieved by using deterministic quantum error correction codes (QECCs) [1]; Studies the performance of a QKD system that is run over a QR with three and five-qubit repetition codes by accounting for various sources of errors in the setup; Specifies the requirements of such systems in practice for near-term implementation.

Challenge: Simulating erroneous quantum circuits on a classical computer and obtaining the analytical form of the final entangled states after several nesting levels. The complexity of the analysis grows exponentially with the number of qubits involved. How to minimize the required approximations while still getting a rather accurate result within reasonable simulation times.

Method: Employing a novel hybrid numerical-analytical approach that relies on the linearity of the employed quantum circuits, and the transversality of the code employed.

Results: New post-selection techniques based on error detection; New efficient QKD decoders; New repeater architectures for NV-centre platforms.

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Simple Efficient QKD Decoders

- 3-qubit codes allow for a wider range of parameters before losing to probabilistic quantum repeaters
- Take-home message: For moderately long distances, we may not need complicated codes to get some advantage

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Error Detection As an Effective Post-Selection Tool

- BBM92 protocol

- Benchmarking question: Considering typical sources of error in the system, what can realistically be achieved and under what conditions?

- Sources of error:
  - Error in CNOT gates with prob $β$
  - Error in single-qubit measurements, with prob $δ$
  - Error in the initial entangled states, with fidelity $F_2$

- Figure of merit: Secret fraction (secret key rate/distributed state)

$R ≥ 1 - h(φ) - h(β)$

- Different QKD protocols possible:
  - (i) You let the service provider to do all necessary corrections and just give you the final decoded states; the users do not know m and d
  - (ii) The users know m, but not d
  - (iii) The users know d, but not m
  - (iv) The users know both d and m → our case of interest

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QR with Encoding on NV Centre Platforms

- In protocol (iv), for each pair of m and d, we effectively post-process the corresponding data together

- Question: what values of m and d result in higher key rates?

- We identify three important categories of states
  - Good states: when we detect no error at ES stage
  - Bad states: when we detect at least one error at ES stage
  - Golden states: When we detect no error neither at ES nor at decoding stage

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Key finding: In most practical cases, the secret key rate is dominated by that of the golden states → We can use error detection, rather than error correction, as a postselection tool

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