Research Plan

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Background of the research

Compared to classical communication, entanglement is a unique property in quantum communication that enables applications that are not feasible classically. In general, many of these applications consume entangled links, thus these links can be viewed as resources within a quantum network. However, these entangled links tend to degrade due to qubit decoherence over time. Thus finding an efficient protocol for sending multiple entangled links with minimized time becomes a stepping stone toward achieving a general quantum communication internet.

Research Question

In an experimental setting for entanglement generation, several actions can be chosen. This will affect two parameters: the probability of the transmission p, and the fidelity F which represents the quality of the entangled pair. The goal is to send n entangled links up to a certain quality over the communication channel. Previously, characterisation for the performance with a single action has already been conducted[2]. The research aims to search for an efficient protocol when multiple actions including purification are allowed.

Specifically, we are interested in R-states, a type of noisy entangled state commonly produced in the lab. There will be several purification schemes applicable here such as the EPL scheme, which is a type of purification scheme designed specifically for such states.

In each time slot, the system will generate two R-states with success probability q and choose to carry out some purification schemes i or not purify at all. The purification will have a success probability of p_i. If it fails, it will return nothing. If succeeds, it will return a qubit with a higher fidelity F_i. The action space can thus be characterized by a set of (probability, fidelity) tuples: $\{(q \cdot p_i, F_i)\}$ where doing nothing corresponds to the action with $i = 0$.

To solve this general question, we can break it down into three batches of subquestions:

Modelling for entanglement generation

- What is a Markov decision process(MDP)?
- How should we model this process using MDP: What will be the state space, action space and rewards for this model?
- What will be the 'optimal' policy?
- What intuition/heuristics can be derived from the outcome?

(possible variant) What are the current experimental settings and potential near-term applications? Can we optimize more based on these specific cases?

Considering the effect of purification schemes

The project will mainly focus on this specific purification protocol.[1].

- What is a purification protocol? This will mainly focus on a brief overview of the idea as well as the input-output of the protocol considered here.

- How can we incorporate the purification protocol into the model developed above?
- How different will the policy and its performance be after adopting the purification?
- When will purification improve the performance?

Further reach

This protocol can be seen as a sub-protocol for general entanglement transmission over several quantum repeaters. Thus how we can incorporate it into a larger protocol including quantum repeaters and entanglement swapping will be a meaningful thing to look into at the end of the project.

Method

Most of the project will be carried out via simulations. Heuristics and Reinforcement learning(RL) will be the main methods for searching an admissible policy. Heuristics here can be used as a policy that is inspired by assumptions, RL results, or part of the RL algorithm.

- Heuristics include protocols with limited parameter which is formulated based on certain assumptions. Analysis of the heuristic methods can help us derive fast protocols in experiments and help us gain more insights about the transmission process.
- Reinforcement learning will be more computationally intensive. The frameworks and algorithms to choose from are also worth discussing.

Planning of the research project

Indicated weekdays are the draft deadlines.

- week 1:
  1. Plan for the project;(Tuesday)
  2. install and familiarize with the needed software packages;(Tuesday)
  3. literature review on the basic ideas of MDP, RL, and purifications;(Whole week)
  4. testing the greedy heuristic;(Friday)
  5. come up with a basic model for the question.(Friday)
- week 2:
  1. further literature review toward actual implementation of the simulation;(whole week)
  2. formulate the performance of the greedy heuristic and evaluate it (Wednesday)
  3. discuss with the supervisor how to combine the purification model;(Thursday)
  4. try out some toy models via simulation and the resulting policies to gain more insight.(Friday)
- week 3:
  1. further literature review; (whole week)
  2. choose several actual models of interest and design how to code them; (Wednesday)
  3. start the actual implementation coding. (Thursday)
- week 4:
  1. continue to set up the simulation;(whole week)
  2. run simulations and analyse initial results; (Wednesday)

3. compare the results with heuristic approaches (whole week)
4. start writing for the midterm report. (Wednesday)

- week 5:
  1. midterm report; (to be settled)
  2. adjust/clarify potential project aims for the latter part of the project; (same time with midterm report)
  3. routine work on simulations, start with more advanced topics and ideas. (whole week)
- week 6:
  1. start drafting final thesis paper (maybe based on the midterm report);(Wednesday)
  2. collect further simulation results.(whole week)
- week 7:
  1. finish the first draft of the thesis; (Wednesday)
  2. draft paper review with supervisor; (Thursday)
  3. collect further simulation results.(whole week)
- week 8-9:
  1. finish the second draft of the thesis; (week 9 Tuesday)
  2. draft paper review with the responsible professor; (week 9 Thursday)
  3. prepare for the poster; (Week 9 Friday)
  4. prepare for final presentation. (Week 9)
- week 10:
  1. finish the poster (Monday)
  2. final presentation. (to be settled)
- From week 7 Further planning is only a vague outline.

For each week, I would like to work on campus for at least 4 days.

References

[1] Bethany Davies, Ãlvaro G. IÃ±*esta*, and Stephanie Wehner. *Entanglement buffering with two quantum memories.* arXiv:2311.10052 [quant-ph]. Feb. 2024. DOI: `10.48550/arXiv.2311.10052`. URL: `http://arxiv.org/abs/2311.10052` (visited on 04/25/2024).

[2] Bethany Davies et al. *Tools for the analysis of quantum protocols requiring state generation within a time window.* en. arXiv:2304.12673 [quant-ph]. Apr. 2023. URL: `http://arxiv.org/abs/2304.12673` (visited on 04/23/2024).