MIDTERM POSTER

A HEURISTIC APPROACH FOR RESOURCE GENERATION IN A QUANTUM NETWORK

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BACKGROUND

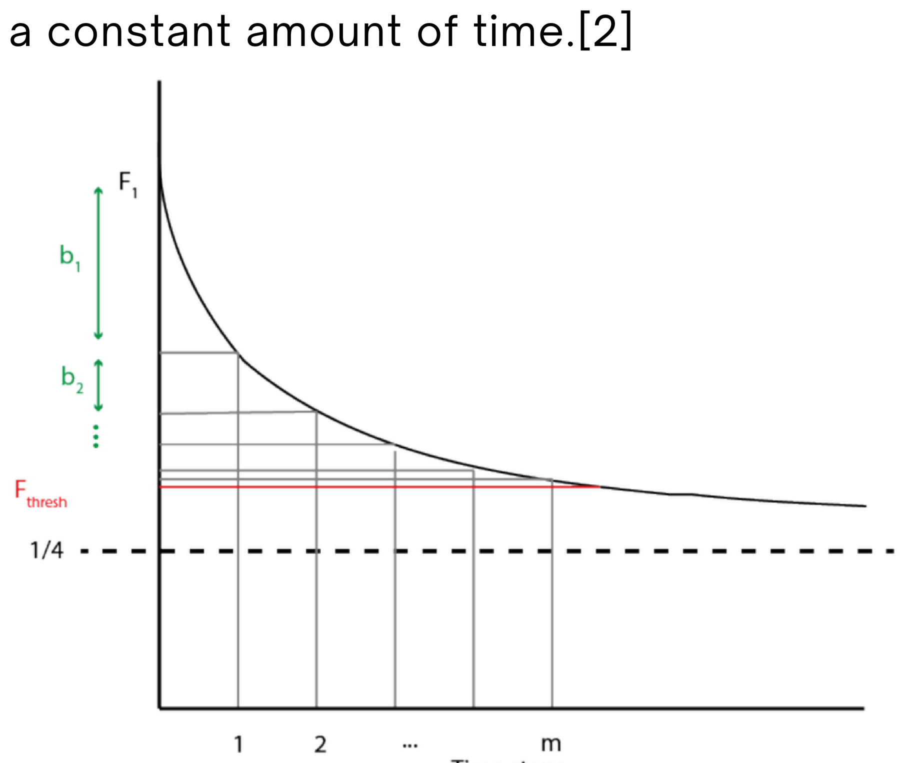
- Entanglement links are vital resources in quantum computing.
- Generating multiple entanglement links is an important stepping stone towards achieving quantum internet.[1]
- An entanglement link is always noisy, the quality of the noisy bell pair is represented by its fidelity $F = \langle \Psi_{00} | \sigma | \Psi_{00} \rangle$.
- In lab, generating a single entanglement link is handled in batches, which all cost a fixed amount of time Δt.
- Entanglement links will suffer from depolarizing noise and their fidelity will degrade exponentially overtime.
- Purification is a way to distill a high-quality link from more noisy links.
- We want to generate multiple entanglement links of which quality is higher than some threshold F_{th}.

PROBLEM SETTING

The problem is a Markov Decision Process defined as follows:

State Space

- A decoherence process with given decay rate Γ can be discretized into different fidelity bins(b1,b2,...) since each action costs a constant amount of time.[2]



- The state of all existing links is described by their corresponding fidelity bins:

$$n(F) = \left\lfloor \frac{1}{\Gamma} \ln \frac{F - \frac{1}{4}}{F_{th} - \frac{1}{4}} \right\rfloor$$

- Each timestep will degrade all existing links in the memory by one bin.
- When the bin is lower than the threshold bin, we discard that link.

Initial state and Terminal state

- Initial state will be a quantum memory without any links.
- Terminate the generation when the number of links in the memory meets the requirement.

Action Space

- Each entanglement generation protocol is an action (p_a, F_a) Specified by the success probability and the link fidelity.
- Typical Heralded entanglement generation offers a continuous action space with a linear probability-fidelity trade-off, yielding the action space.

$$\mathcal{A} = \{(p, F) : F = 1 - \lambda p, p \in (0, 1)\}$$

- Purification can be modeled as a specific action that generates less qubit.
- EPL purification scheme on top of two qubits with fidelity F will give a fidelity 1 link with probability $\frac{F^2}{2}$.

Research Question

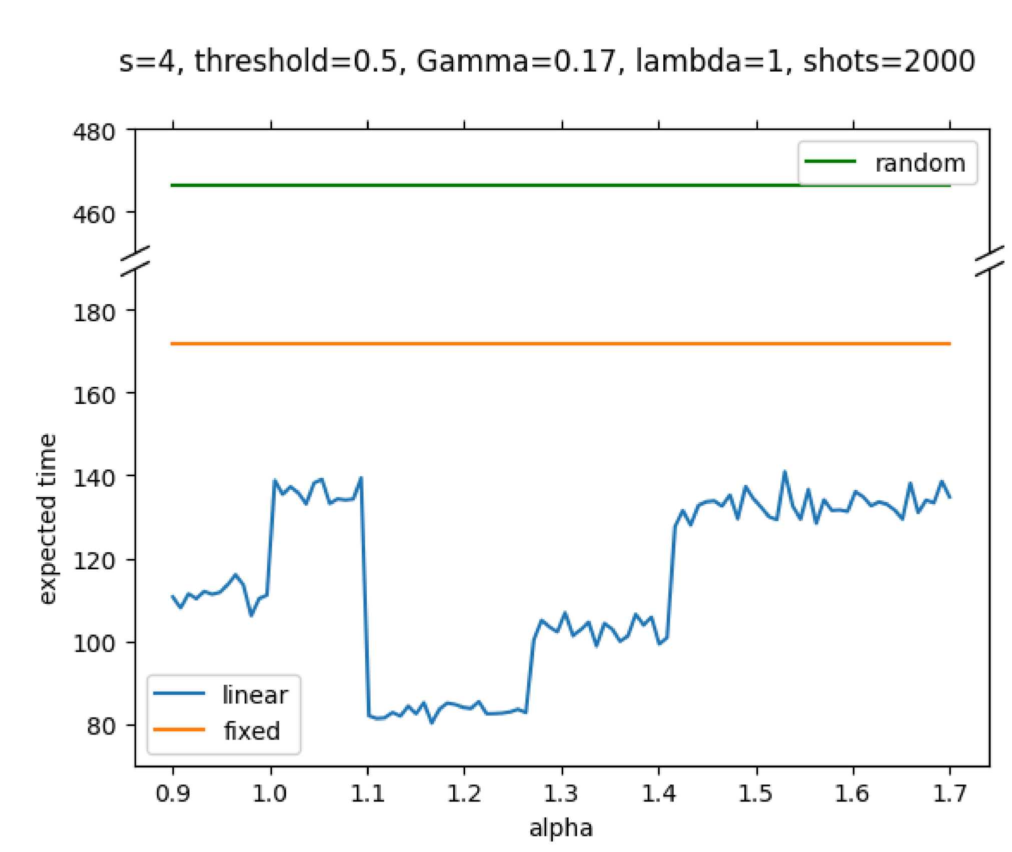
How can we find an efficient policy to minimize the time for generating s links given the model above?

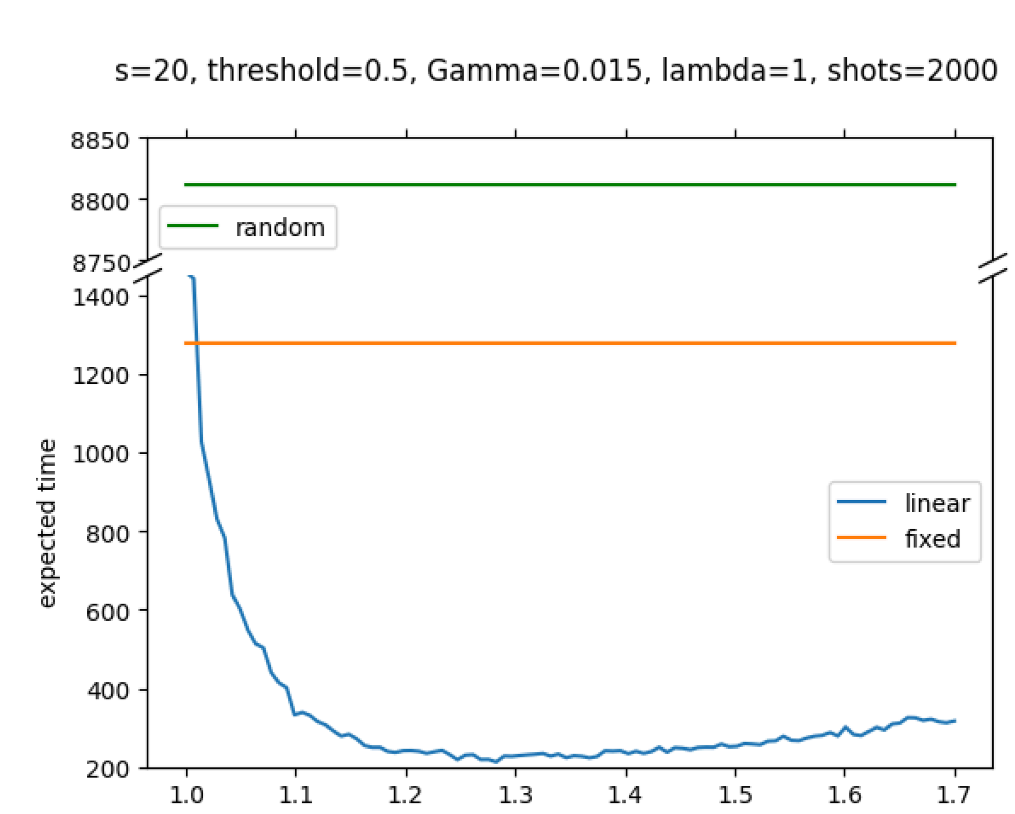
RESULTS

For comparison, we choose two baselines:

1. random action
2. single fixed action

We illustrate that under both high decay rate, little links and low gamma decay, many links the heuristic outperforms the baselines.





Results that include purification have not been obtained yet.

METHODOLOGY

Discretize actions

- Two actions that belong to the same fidelity bin n will have the same lifespan. Thus the highest probability action within the bin will be the optimal action within the bin.
- We can restrict the action space to

$$\mathcal{A} = \{(p_n, F_n)_{optimal} : n \in Bin\}$$

Look-ahead heuristics

- The current action is decided by the number of links that needs to be generated.
- The link we want to generate currently needs to survive until all the links have been established
- The fidelity bin of the current link should be proportion to the estimated time ahead

Algorithm 1 Heuristic Policy$(s, \mathcal{A}, \alpha)$

$t_{ahead} \leftarrow 0$
$\pi(s) \leftarrow \mathrm{argmax}_a \{p_a : (p_a, F_a) \in \mathcal{A}\}$
for $i = \{s-1, s-2, \ldots, 2, 1\}$ **do**
 $t_{ahead} \leftarrow t_{ahead} + \frac{1}{p_{\pi(i+1)}}$
 $\pi(i) \leftarrow \arg_a \{n(F_a) = \lfloor \alpha \cdot t_{ahead} \rfloor\}$
return π

Policy(see pseudocode above)

- We always choose the highest success probability action to generate the last link.
- The estimated time to generate a link with probability of p_a is $E[T_a] = \frac{1}{p_a}$.
- The policy can be defined recursively with an adjustable proportion factor α.
- The factor α can be optimized via actual simulations.

Algorithm that includes purifications is still being looking into for now.

DISCUSSION AND FUTURE GOAL

- Simulation shows that the heuristic can signigicantly improve the speed of entanglement generation compared to the baslines.
- Further study on how to incorporate purification schemes such as EPL scheme into the current heuristic needs to be done.
- Current heuristic only look-ahead, and does not consider the links within the memory. How to relax the condition of look-ahead can also be investigated.

REFERENCES

[1] Stephanie Wehner, David Elkouss, and Ronald Hanson. Quantum internet: A vision for the roadahead. Science, 2018.
[2] Bethany Davies, Thomas Beauchamp, Gayane Vardoyan, and Stephanie Wehner. Tools for the analysis of quantum protocols requiring state generation within a time window. IEEE Transactions on Quantum Engineering, 2024.