Routing Strategies for Multiplexed, High-Fidelity Quantum Networks

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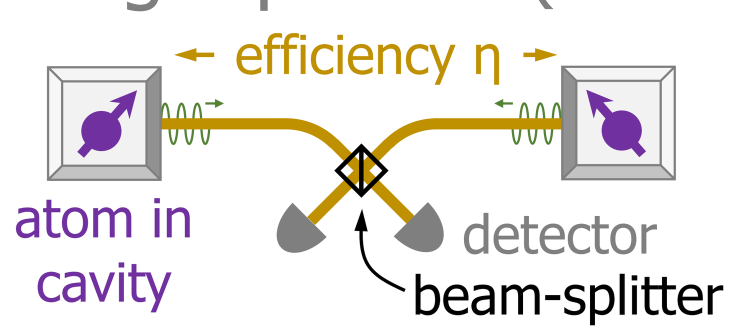
Background

Quantum networks distribute entanglement between users for communication / sensing.

Near-term entanglement protocols are heralded and probabilistic.

e.g. single-photon (Cabrillo *et al.*, 1999) protocol



Entanglement heralded with probability $p_{link} \leq 0.5\,\eta$.

∴ Near-term ("1st gen") quantum networks need **two-way classical communication**.

Difficulties:

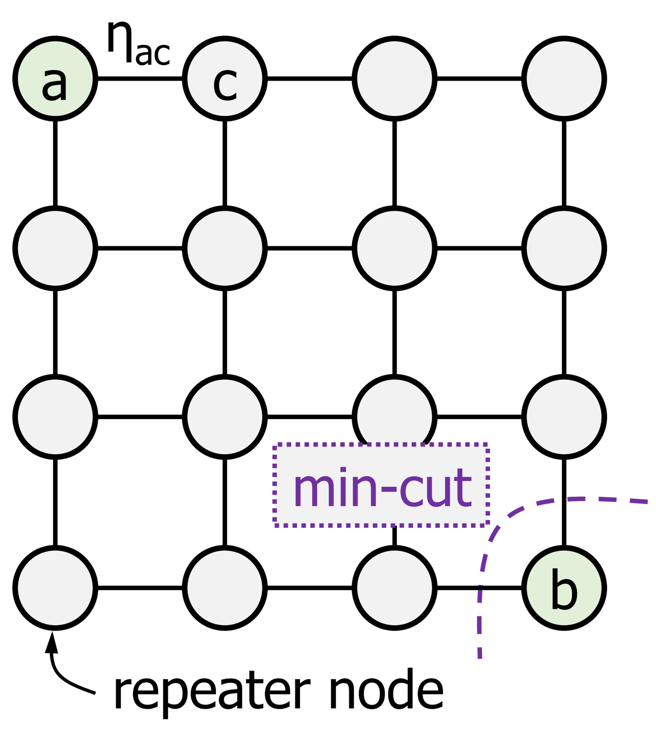
- Time needed for 2-way cc ⇒ decoherence
- Probabilistic ⇒ uncertain routing decision

Min-cut bound

Quantum network capacity = $-\log_2(1 - \eta_{min\text{-}cut})$ ebits per network use

where $\eta_{min\text{-}cut} = 1 - \max_{C\,=\,cut} \prod_{e \in C} (1 - \eta_e)$

(PLOB, 2017; Pirandola, 2019)



But 1st gen networks do not achieve single-link capacities, so the maximum achievable rate is the **min-cut bound**:

$$\text{end-to-end rate} \leq p_{min\text{-}cut} \equiv \max_{C\,=\,cut} \sum_{link \in C} p_{link}$$

Local routing

Consider **minimum-latency** networks: make routing decisions using only local link state info, to **minimize decoherence** & increase fidelity.

Also, previous work (Pant *et al.* 2019) showed that (local) **multi-path routing** raises rates.

Role of multiplexing

If repeaters have all-to-all local connectivity, (arXiv:2005.01852)

↑ multiplexing ⇒ more than linear ↑ in rate ⇒ closer to min-cut bound.

e.g. length-N repeater chain, m modes per link:

$$\text{Rate} \approx m p_{link} \left(1 - [2 \log N / m p_{link}]^{0.5}\right)$$

$\rightarrow p_{min\text{-}cut} = m p_{link}$ when multiplexing $m \rightarrow \infty$.

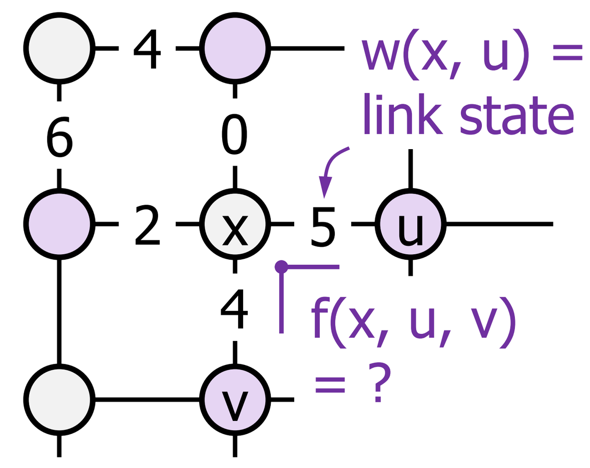
Integer program framework

Approach:

At each node, maximize expected end-to-end entanglements conditional on local link state

(assuming optimal routing at other nodes).

Objective function: $f(x, u, v)$ = number of swaps between (x, u) and (x, v)



Under this approach,

- $f(x, u, v)$ is determined separately from how modes at (x, u) and (x, v) are matched;
- the objective function can be approximated by a linear function of $f(x, \cdot, \cdot)$.

Choose other weights $g(x, u, v)$ for the linear objective function in $f(x, u, v)$ ⇒ get a collection of routing strategies based on integer programs:

$$\max_{f(x,\,\cdot,\,\cdot)} \sum_{(u,\,v)\,\sim\,x} g(x, u, v) \times f(x, u, v).$$

Possible weights:

- Original expected rate maximization weights

$g_{ERM}(x, u, v) = P(u, v \text{ separated by link state's min-cut})$

- Distance weights

$g_{distance}(x, u, v) = \exp(-\,\text{dist}(\text{Alice}, u) - \text{dist}(\text{Bob}, v))$

Results

4 × 4 square grid

Naive mode matching →

- The achievable rate with global link state information (max flow) approaches the min-cut bound as $m \rightarrow \infty$.
- Int. programs (ERM, distance weights) do better than fixed path algorithms.
- Int. programs outperform the multiplexed extension of Pant *et al.* (2019)'s greedy multi-path routing algorithm.

Optimal mode matching →