Routing in Quantum Networks

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Prepared for the IRTF QIRG:
Scope

- First-generation quantum repeater networks (no QEC)
- Studied routing literature since 2017
- Bi-partite entanglement
- Motivation: unified terminology, accessible to network engineers
- Protocols supported:
  - Heralded entanglement generation
  - Swapping
  - Purification
  - Teleportation

Simplified view of a first-generation repeater
Abstractions, communications, and classical processing for operating a quantum repeater network with SDN principles: Hierarchy and time-scales.
Problem Formalism: Requests

\[ r = (s, d, \delta, F) \]

- \((s, d)\) are the nodes receiving end-to-end entanglement
- \(\delta\) = desired end-to-end entanglement generation rate
- \(F\) = minimum fidelity threshold

Entanglement routing on a 2D square lattice network
Problem Formalism: Key Parameters

\( P_{u, v} = \text{probability of generating elementary entanglement on a channel between nodes } u \text{ and } v. \)

\( P_s = \text{probability of successful swap} \)

\( C_{u, v} = \text{edge capacity (i.e. max number of entanglements that can be generated in a single time slot)} \)
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Takes into account:
- Source & detector efficiencies
- Channel parameters (attenuation, distance)
- Number of attempts per time slot

Entanglement routing on a 2D square lattice network
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\( P_s = \) probability of successful swap

\( C_{u, v} = \) edge capacity (i.e. max number of entanglements that can be generated in a single time slot)

\( P_s \leq 0.5 \) for swapping based on linear optics
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Takes into account:
- Multiplexing modes (time, space, wavelength)
- Qubit capabilities at \( u \) and \( v \)

Entanglement routing on a 2D square lattice network
“Aggregate utility”

Objective: maximize the total number of end-to-end entanglements delivered for all requests.\(^1\)

Output: set of paths, schedules, and installation.

\(^1\)Other objectives may maximize fidelity support with weighted maximization
Taxonomy of Routing Strategies

Quantum Routing

Routing
- Path computation
  - Distributed
  - Centralized/SDN
- Route installation
  - Static
  - Dynamic
- Optimization algorithms
  - Path searching
  - Linear Programming
  - AI-based
- Fidelity support
- Forwarding
  - Passive
  - Purification/QEC
- Path recovery
- Swapping
  - Synchronous
  - Asynchronous
- Opportunistic
- Reactive
- Opportunistic
- Proactive
- Virtual
- E2E/Schema
- Per link
- Sequential
- Parallel
- Simultaneous
- Ad-hoc
Taxonomy of Routing Strategies

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  - AI-based
Taxonomy of Forwarding Strategies

- Forwarding
  - Fidelity support
  - Path recovery
  - Swapping
    - Synchronous
    - Asynchronous
    - Opportunistic
    - Purification/QEC
      - Passive
      - E2E/Schema
        - Per link
        - Sequential
        - Parallel
        - Simultaneous
        - Ad-hoc
Proactive Routing

Path Computation is done before any entanglements are generated.

Assumes global knowledge of physical topology.

Centralized Controller or distributed across nodes.
Reactive Routing

Generate local entanglements, report virtual topology, do path computation, continue with swapping.

Acts on virtual topology not just physical

Centralized Controller or distributed across nodes

Can be more effective for resource management and protocol scheduling
Virtual Routing

Build virtual graph where path selection is executed.

Virtual links can be combined together to create E2E entanglement.

Virtual links can be chosen deterministically or randomly.

Each virtual link can only be used once.
Opportunistic Routing

Path selection and entanglement creation are executed at the same time, hop by hop.

No preliminary path selection phase.

Next hop is selected at transmission time based on local entanglement results.
Swapping Strategies

Synchronous: all entanglements created at the same time and all swaps succeed at same time.

Asynchronous: All entanglements are ready before swapping begins (requires memory)

Opportunistic: repeaters swap as soon as possible

Example swap schedules
### Other Routing Considerations

#### Path Computation Algs.
- Dijkstra’s & variants
- Path search on graph
- Greedy algs.
- Linear Programs
- AI-Based

#### Fidelity Support
- Passive vs. active
- Purify then swap? Or swap then purify?
- Choice of purification scheme
- Link cost metrics

#### Path Recovery
- Handle decoherence, photon loss, & operational errors
- Alternate paths
- Entanglement re-generation vs. preservation (w/ purification or QEC)
Open Questions

1. Optimal topology and optimal use of topology
2. Routing schemes for 2nd- and 3rd-gen repeaters
3. How coupled should routing and forwarding be?
4. More intensive data plane overhead analysis
5. Lack of robust failure recovery in literature
6. Interoperability of heterogeneous links & hardware
Thank you!

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Stay tuned for arXiv publication!