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Entanglement-Reusable Dynamic Routing for Quantum Networks

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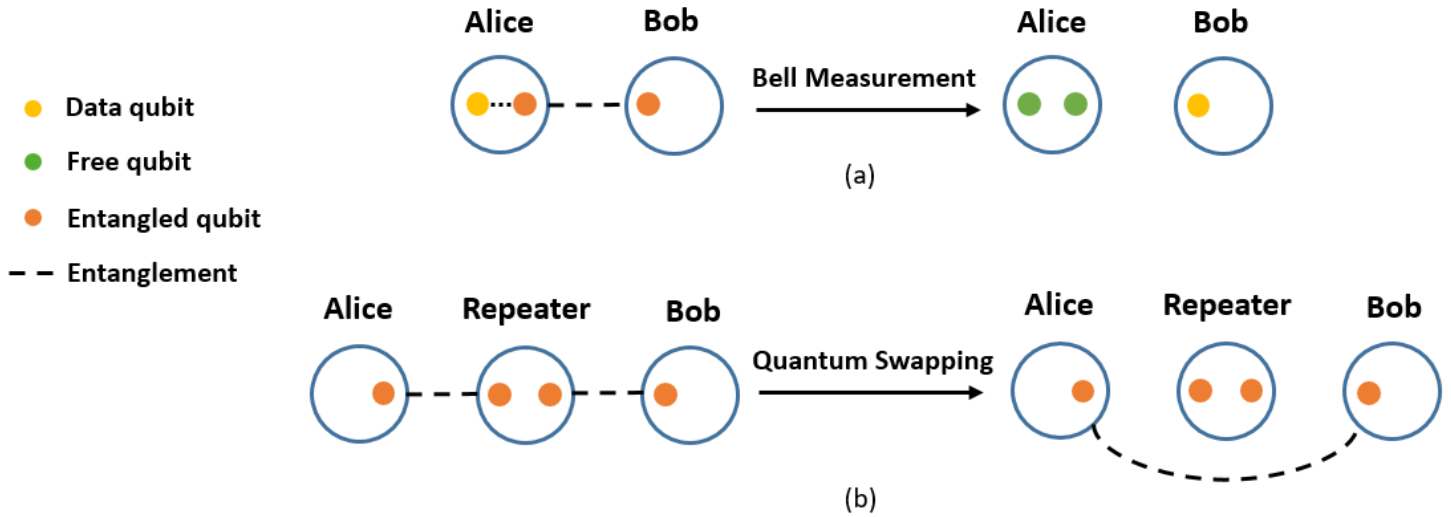
Background

- **What is a Quantum Network?**
  - Enables the transmission of *quantum bits (qubits)*.
  - Transmits information *securely* and *efficiently*.
- **Key Components**
  - Qubits: Capable of representing *multiple states simultaneously*.
  - Quantum processors: Perform *quantum computations* on qubits.
  - Communication channels: Pathways (e.g., optical fibers, satellites) that *facilitate the transfer of qubits* between processors.
- **Applications**
  - Quantum communication: Quantum key distribution (QKD).
  - Quantum computing: Powerful quantum computing cluster.

Preliminaries

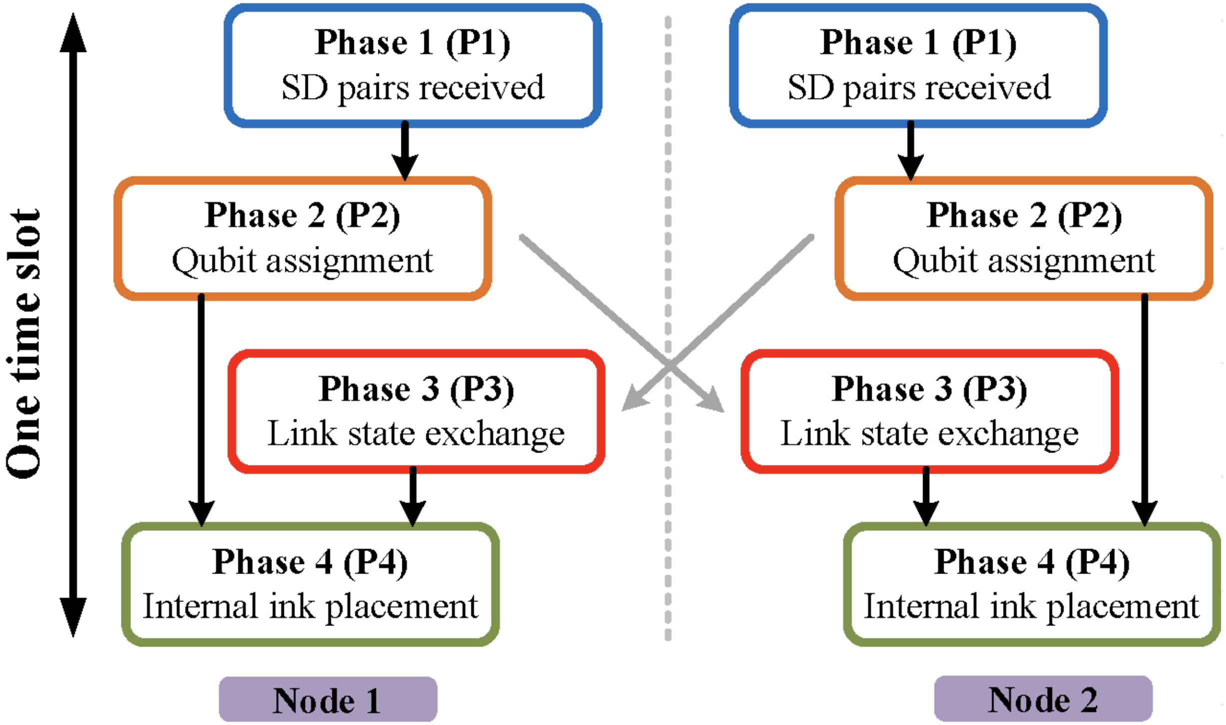
- **Quantum Entanglement**
  - Two particles become *interconnected*.
  - The state of one *instantly influences* the state of the other.
- **Quantum Swapping**
  - *Entanglement is transferred* from one pair of particles to another pair.



Examples of quantum entanglement and quantum swapping.

Preliminaries

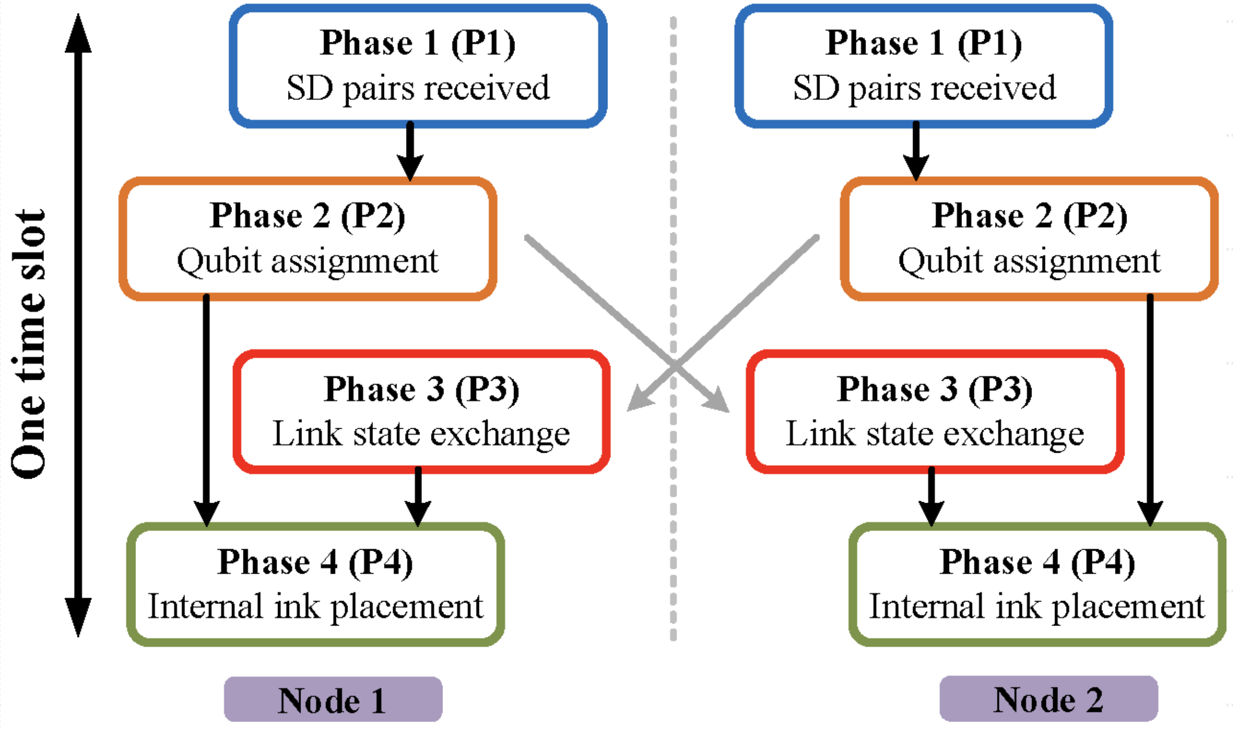
- **Procedure of Entanglement Distribution**
  - Phase 1 (P1)
    - Received the source-destination pairs with the communication request.
  - Phase 2 (P2)
    - Perform routing calculations for *path selection* and *resource assignment*.
    - *Broadcast* the routing output to every node.



The procedure of entanglement distribution.

Preliminaries

- **Procedure of Entanglement Distribution**
  - Phase 3 (P3)
    - Each node *exchanges its link states* (entanglement results).
    - Only the *nearest K-hop*.
  - Phase 4 (P4)
    - Perform quantum swapping to *distribute entanglements*.



The procedure of entanglement distribution.

Preliminaries

- **Metric: Expected Throughput (EXT) -** E_t
  - For a path P of h hops with width W:
    - Q_k^i: Probability that the k-th hop on path P can establish exactly i new successful entanglements.

$$Q_k^i = \binom{W}{i} p_k^i (1 - p_k)^{W-i}$$

    - P_k^i: Probability that each of the first k hops of P can establish at least i new successful entanglements.

$$P_1^k = Q_1^i, \qquad P_k^i = p_{k-1}^i \times \sum_{l=i}^{W} Q_k^l + Q_k^l \times \sum_{l=i+1}^{W} P_{k-1}^l$$

    - E_t: The weighted probability sum of path P in width from W to 1.

$$E_t = q^h \times \sum_{i=1}^{W} i \times P_h^i$$

Existing Works and Limitations

- **Existing Routing Strategies**
  - Q-CAST[1] and FER[2].
  - Can be categorized as *Contention-Free policies*.
  - One entanglement *can only be assigned to one path* for the teleportation of one qubit.
- **Their Limitations**
  - Quantum resources to specific paths are *strictly reserved*.
  - *Limit the EXT* of quantum networks.
  - The quantum resources are *not fully utilized*.

[1] S. Shi and C. Qian, "Concurrent entanglement routing for quantum networks: Model and designs," in Proc. of the ACM SIGCOMM, 2020.
[2] S. Zhang, S. Shi, C. Qian, and K. L. Yeung, "Fragmentation-aware entanglement routing for quantum networks," Journal of Lightwave Technology, vol. 39, no. 14, pp. 4584–4591, 2021.

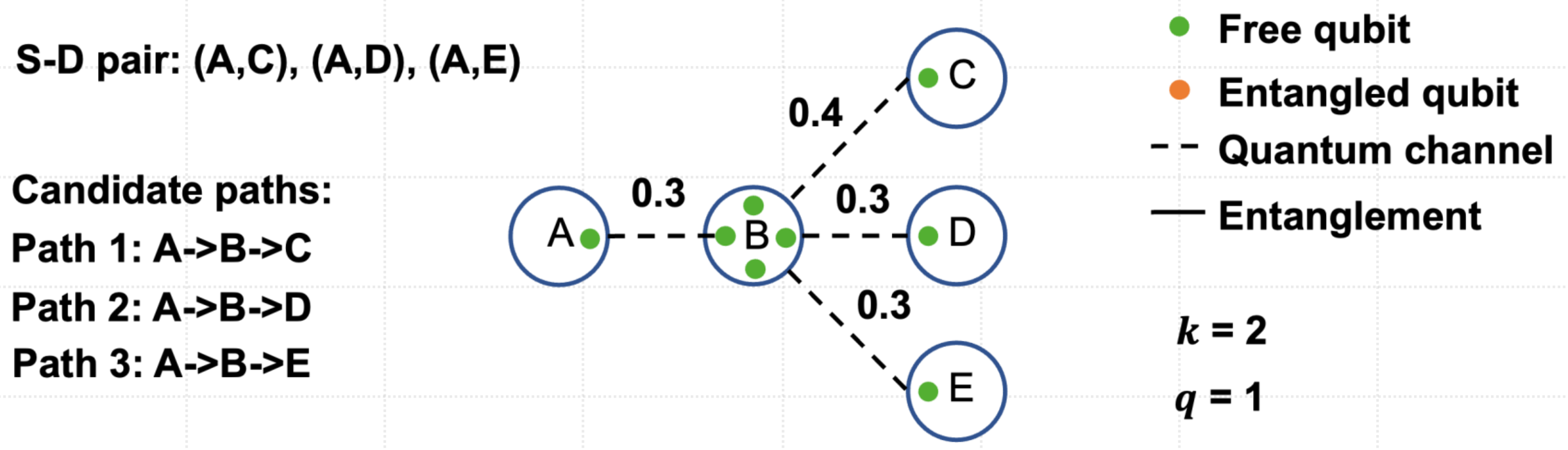
Our Key Idea

- **Over-Subscription Policy**
  - One entanglement *can be assigned to multiple paths* for the potential teleportation choices of multiple qubits.

- **Advantages of Over-Subscription Policy**
  - Utilize quantum resources more efficiently.
  - Allow the construction of more potential paths.
  - Improve the performance of network throughput.

Motivation Example

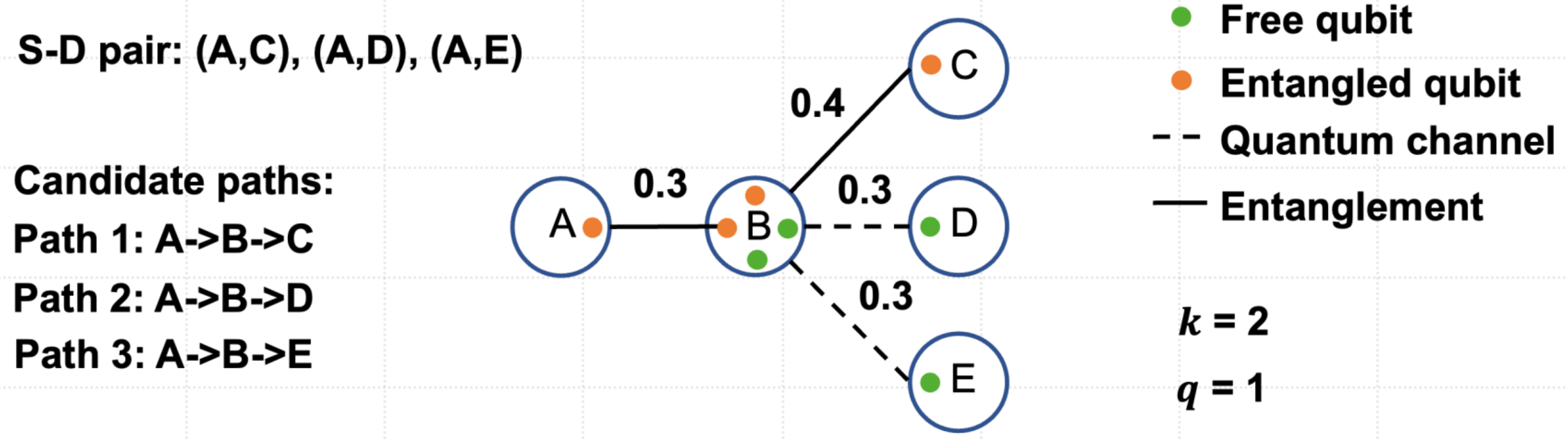
- **Metrics**
  - **Total EXT**: The *sum of EXT values* of all selected paths in quantum work
  - **Entanglement Utilization Rate (EUR)**: The *conditional probability* that one entanglement can be used in quantum teleportation when the entanglement is successfully established.



A motivation example.

Motivation Example

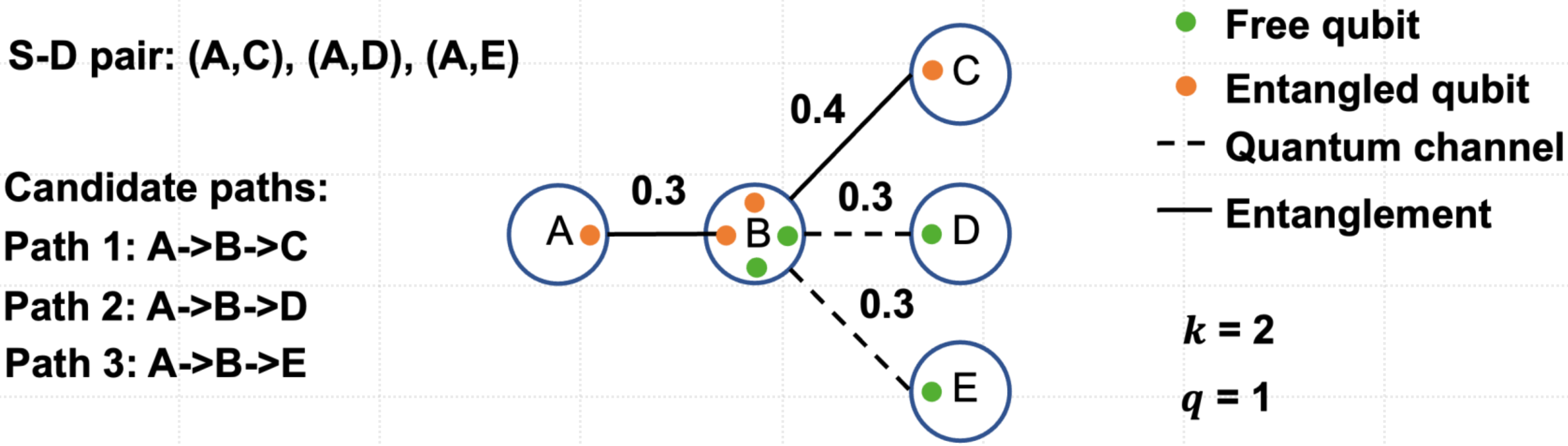
- **Under Contention-Free Policy**
  - *Only Path 1 is selected* for construction.
  - Path 2 and Path 3 can not be constructed for *lack of entanglement resources* in edge AB.
  - Entanglement resources in edge BD and edge BE would be *idle*.



A motivation example.

Motivation Example

- **Under Contention-Free Policy**
  - *Total EXT* = EXT of Path 1 = 0.3 * 0.4 = 0.12.
  - *EUR of entanglement A-B*
    - = probability that Path 1 is successfully constructed / entanglement success rate
    - = (0.3 * 0.4) / 0.3 = 0.4.

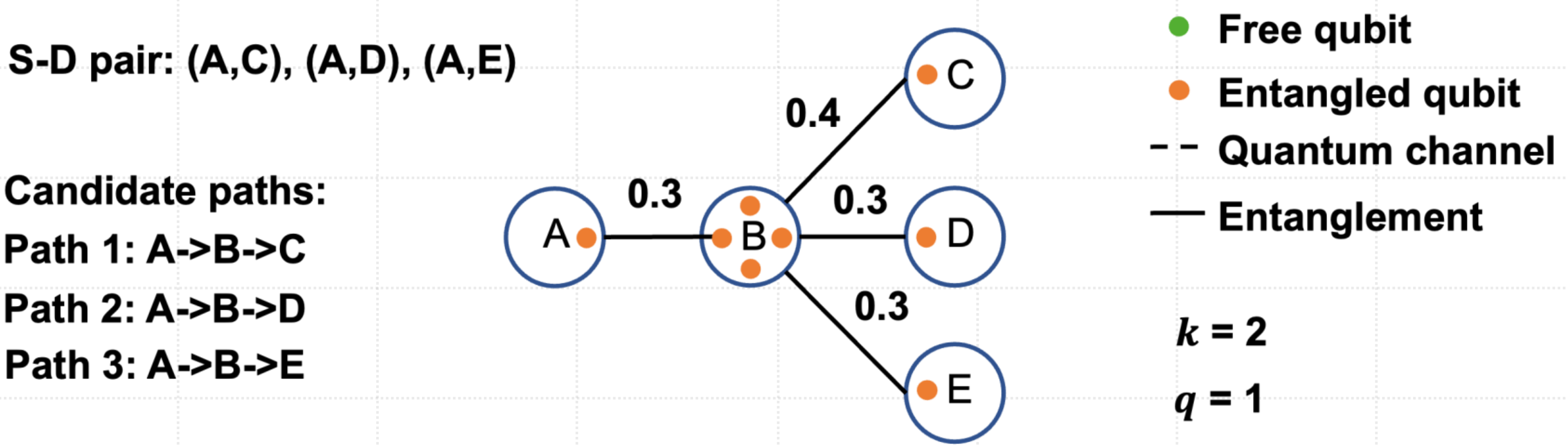


A motivation example.

Motivation Example

- **Under Over-Subscription Policy**
  - Paths 1, 2, and 3 *can all be selected* for construction.
  - *Total EXT*
    - = EXT sum of Paths 1, 2, and 3
    - = 0.3 * [0.4 + (1 - 0.4) * 0.3 + (1 - 0.4) * (1 – 0.3) * 0.3] = 0.211.

> 0.12

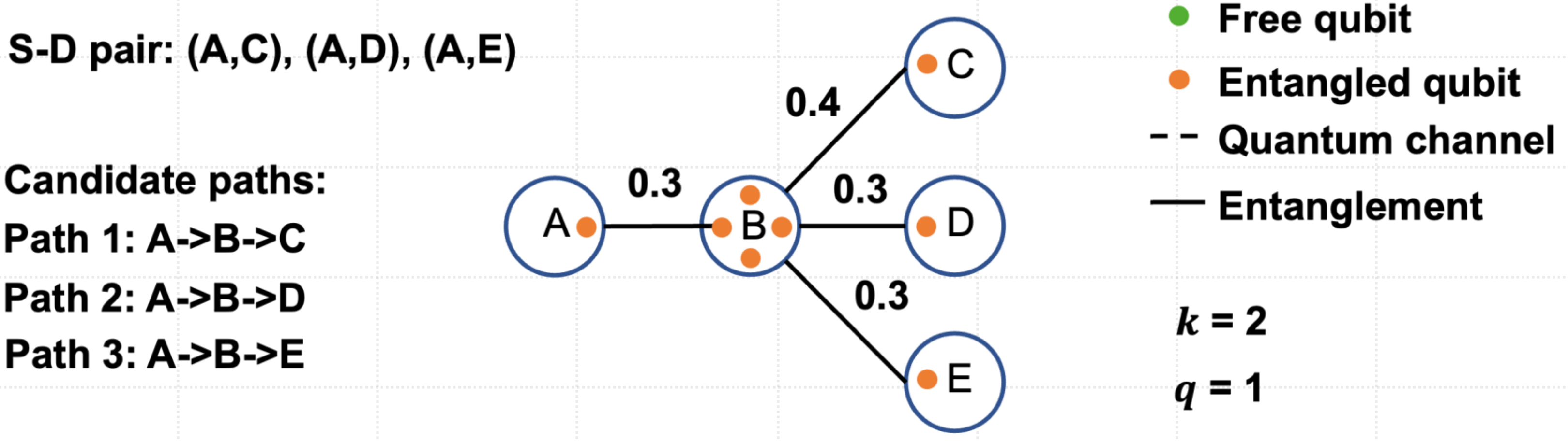


A motivation example.

Motivation Example

- **Under Over-Subscription Policy**
  - *EUR of entanglement A-B*
    - = probability that at least one path is successfully constructed / entanglement success rate
    - = 0.3 * [0.4 + (1 - 0.4) * 0.3 + (1 - 0.4) * (1 – 0.3) * 0.3] / 0.3 = 0.706.

> 0.4



A motivation example.

ERDRA Algorithm

- **Entanglement-Reusable Dynamic Routing Algorithm (ERDRA)**
  - Key features of ERDRA
    - *Reusing* pre-assigned entanglements.
    - *Activating* idle quantum resources.
  - Novel metric – Reusable Factor
    - The internal probability that the j-th hop of a candidate path can still offer exact i channels for future use even after path assignments and new generations.
  - Main steps
    - Path selection.
    - Resource assignment.
    - Network topology updates.

ERDRA Algorithm

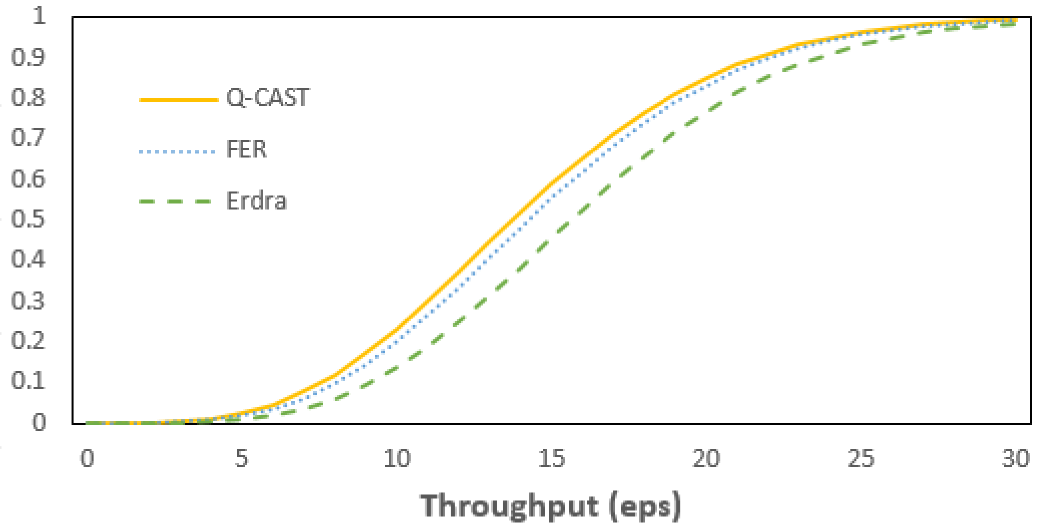
- **Detailed Algorithm**
  - **Step 1**. Search for the *best path* in terms of EXT metric between the pairs.
  - **Step 2**.
    - Only the one *with the highest EXT value* is selected as the optimal solution for every iteration.
    - All relative resources (i.e., qubits and channels) would be *reserved and assigned virtually*.
  - **Step 3**.
    - *Remove the reserved resources* from the residual graph.
    - *Add in the newly established entanglements*, with their presence quantified by the reusable factor of edges along the candidate path.
  - **Step 4**. Repeat steps 1-3.

Evaluation

- **Simulation Setup**
  - Custom-built time-based simulator.
  - An area of 100K units by 100K units square (1 unit = 1 km).
  - Nodes are randomly scattered, and the distance of any two nodes is at least $50\sqrt{n}$ units (n denotes the number of nodes).
  - Edges are generated based on the Waxman model.
  - The number of qubits available for each node is independently uniformly selected from 10 to 14.
  - The width of the edge is independently uniformly picked from 3 to 7.
  - More detailed parameter settings are introduced in [1] and [2].

Summary

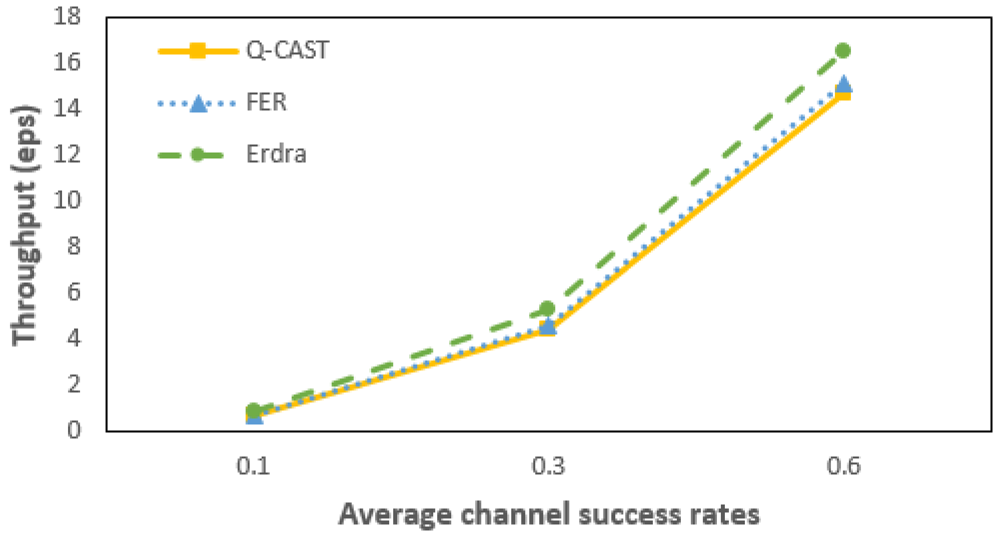
- **Simulation Results**
  - Network throughput.
    - Measured in terms of eps (*i.e.*, ebits, entangled qubits) per time slot.
      - ERDRA allows more assigned resources to be *flexibly reused*.
      - *More paths are engaged* in the construction process.
      - ERDRA can *outperform* FER by 1.4 eps.



CDF of network throughput.

Summary

- **Simulation Results**
  - Throughput under different success rates.
    - In an environment where the quantum network is much degraded.
      - ERDRA can *make the best use of the available resources* for path construction.
      - *More gain* or *less loss* would be achieved in throughput performance.



Throughput under different channel success rates.

Summary

- **Main Contributions of Our Paper**
  - **Reusable Factor Metric**
    - Introduces a *novel metric* to evaluate the probability that reserved quantum resources for a candidate path can still offer available channels for other potential paths even after path assignments.
  - **ERDRA Algorithm**
    - Proposes the ERDRA to enable the *multiple assignment* of quantum entanglement, improving the routing performance and EXT of quantum networks.
  - **Performance Gains**
    - Demonstrates through simulations that ERDRA achieves *substantial performance gains* over state-of-the-art algorithms, effectively utilizing quantum resources and enhancing network throughput.

Thanks for your attention!

Q&A