Rethinking Quantum Network Design using a Verification-Based Quantum Transmission Protocol

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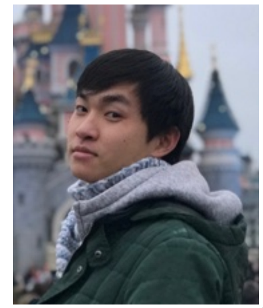

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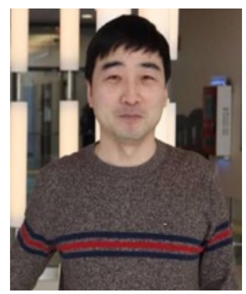

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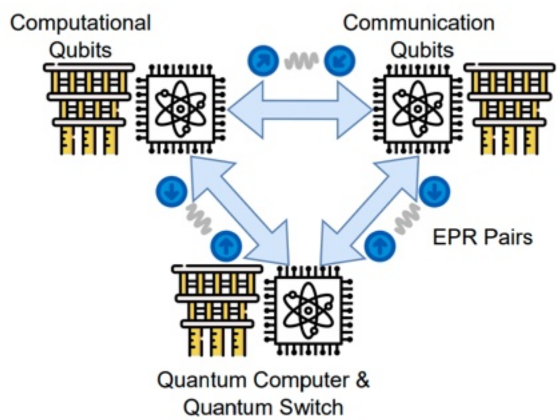
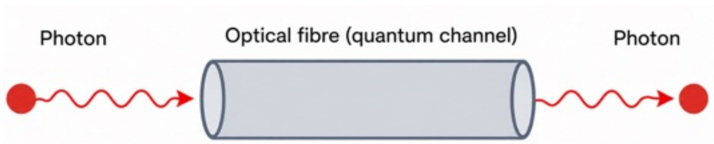
What do we need quantum networks?

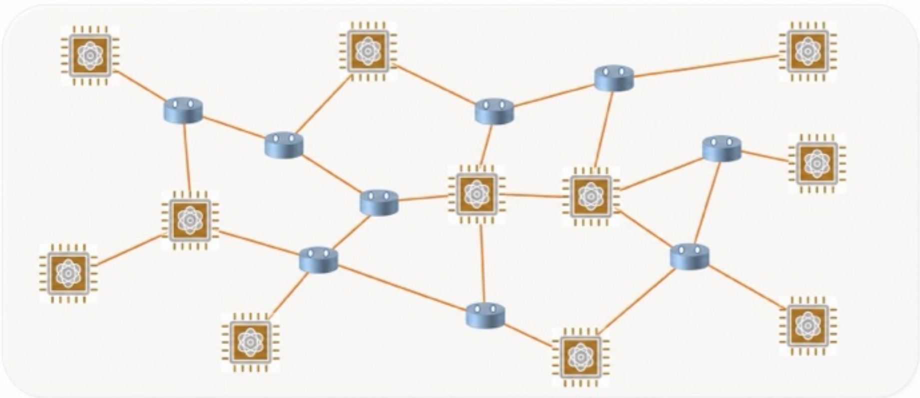
Given: Quantum computing has the potential to revolutionize computing



We need quantum networks to exchange quantum state.
Example quantum state: $|\psi\rangle = \alpha|0\rangle+\beta|1\rangle$

Quantum Networks

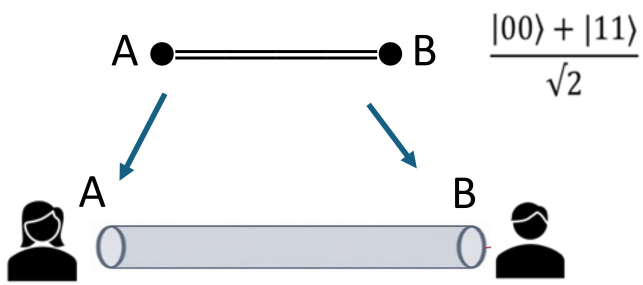




Problem: Arbitrary quantum states are extremely hard to generate, are extremely fragile, can decohere at long distances and need to be regenerated if lost (due to no cloning theorem).

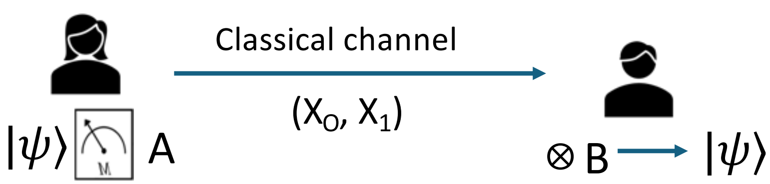
Teleportation

This magic is achieved using entanglements



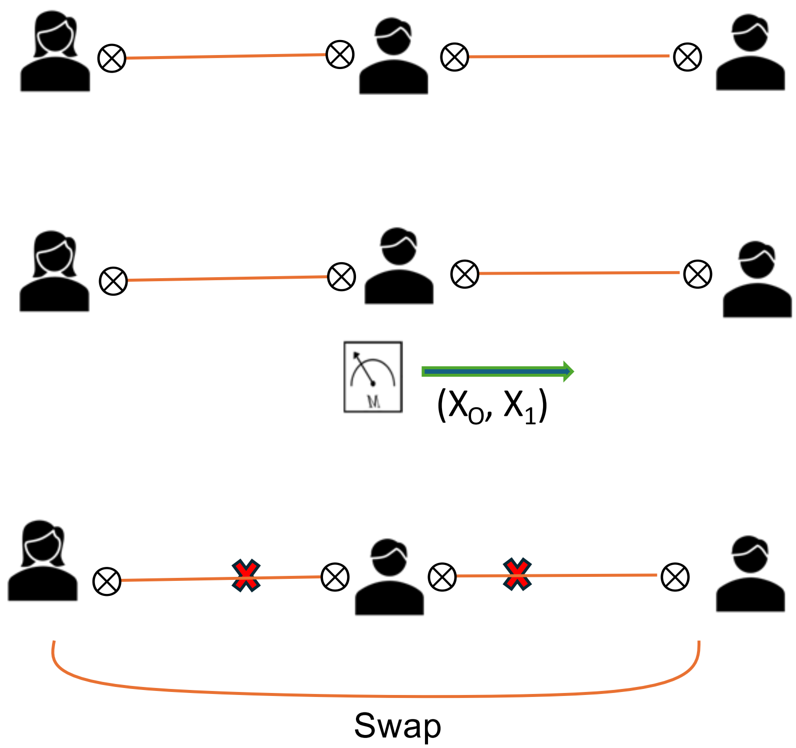
Step 1: Generate an entanglement pair of qubits

Step 2: Distribute entangled pair (Control plane)



Step 3: In data plane, use correlated qubits for teleportation

End-to-End Entanglement



Analogous to circuit switching

End-to-end entanglement is the cornerstone of existing quantum network stack

End Application	
Transport	Classic information transmission
Network	**End-to-End entanglement/teleportation**
Link	Successful entanglement generation
Physical	Attempted entanglement generation

Dahlberg et al. SIGCOMM 2019

Series of works use this idea for communication

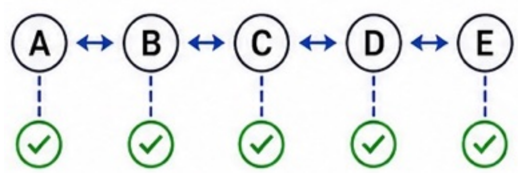
- Wojciech Kozlowski, Axel Dahlberg, and Stephanie Wehner. Designing a quantum network protocol. CoNEXT 2020
- S. Shi and C. Qian, "Concurrent entanglement routing for quantum networks: Model and designs," SIGCOMM, 2020, pp. 62–75.
- A. Farahbakhsh and C. Feng, "Opportunistic routing in quantum networks," in IEEE INFOCOM 2022,
- Y. Zhao, G. Zhao, and C. Qiao, "E2e fidelity aware routing and purification for throughput maximization in quantum networks," in IEEE INFOCOM 2022

Problem: Extremely low goodput especially as the number of repeaters increase

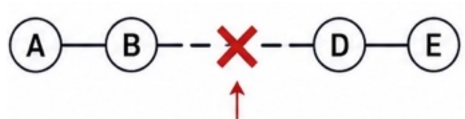
Challenges in using end-to-end entanglements

- Extremely short-lived entanglement

- Requires strict end-to-end synchronization



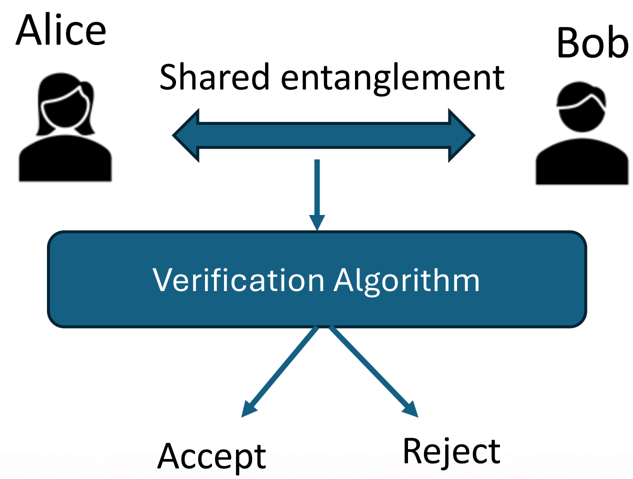
- Lack of flexibility



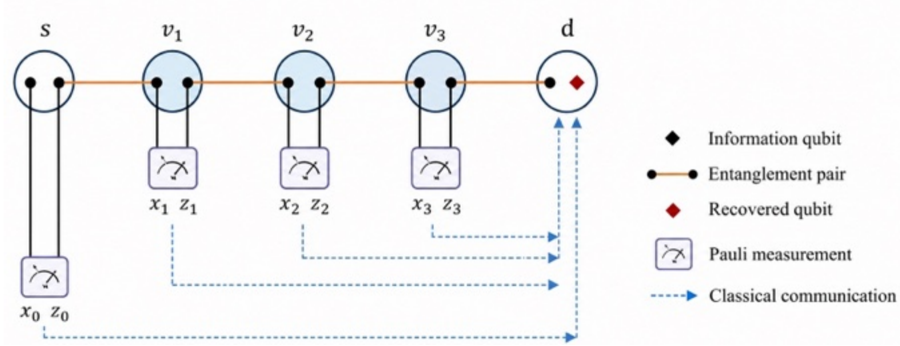
More fundamental problem: it is not possible to infer the fidelity of entanglement **before** using it for teleportation

This work: Reimagine the quantum network stack

Entanglement verification as the fundamental building block of quantum communication



Alternate (packet-switched) teleportation to avoid challenges of end-to-end entanglement



Re-imagining the quantum network stack

End Application	
Transport	Classic information transmission
Network	End-to-End entanglement
Link	Successful entanglement generation
Physical	Attempted entanglement generation

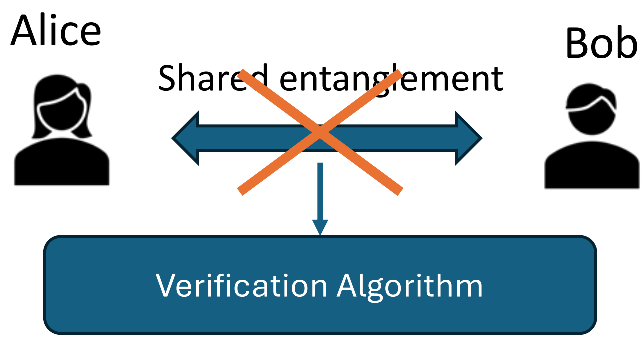
Dahlberg et al. SIGCOMM 2019

Redesigning Layer →

End Application	
Transport	Classic information transmission
Network	**Alternate (packet-switched) multi-hop communication**
Link	**Verified, successful, entanglement generation**
Physical	Attempt entanglement generation

Why existing verification techniques are insufficient?

- Many verification algorithms are destructive

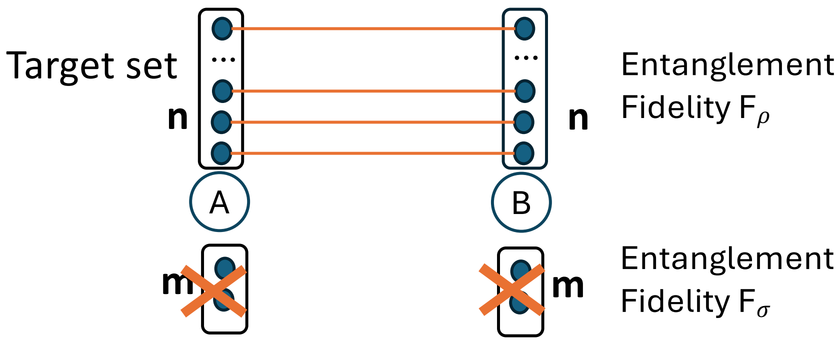


- Other techniques assume perfect entanglements and perfectly noiseless environment

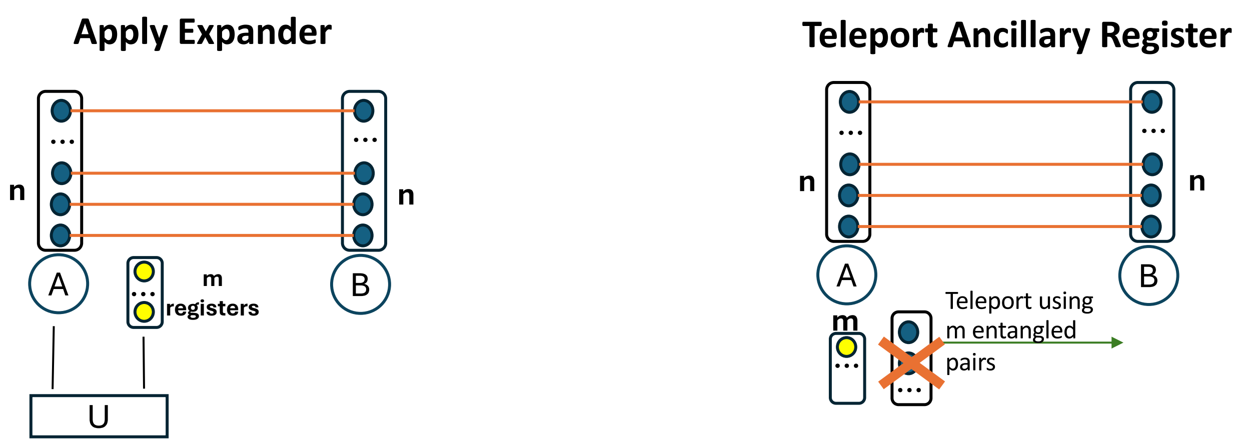
Our verification algorithm

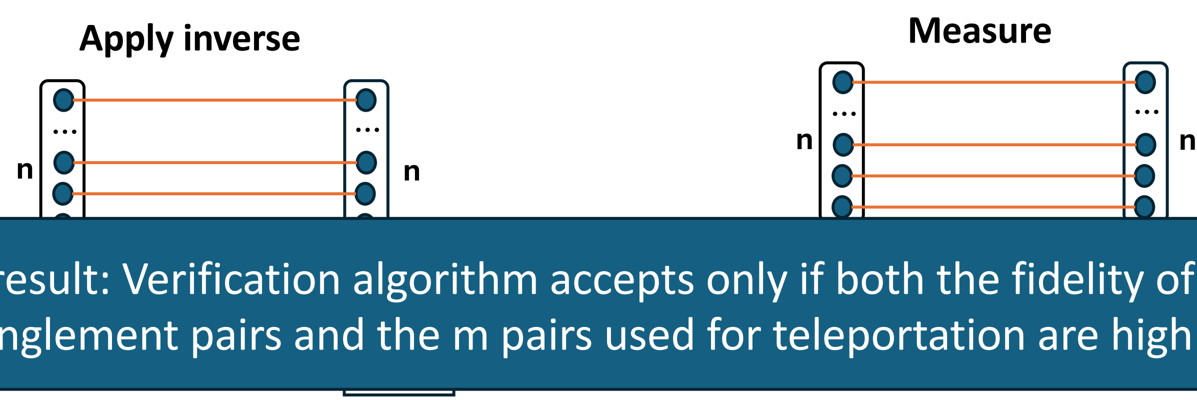
- Non-destructive
- Will accept even if entanglement is not perfect
- Does not assume communication is noiseless

High level idea: Sacrifice a set of entanglements (m) to verify a larger target set of entanglements (n)



Verification algorithm based on quantum expanders



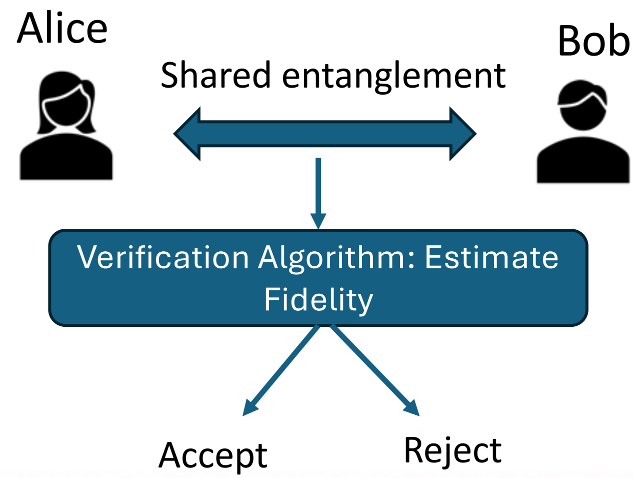


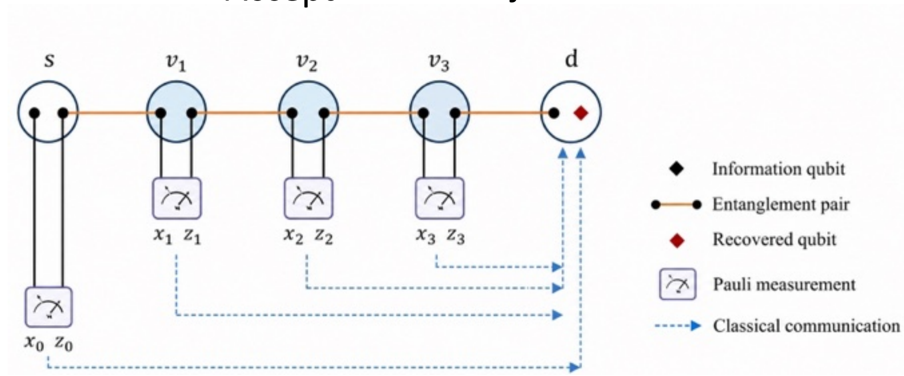
Key result: Verification algorithm accepts only if both the fidelity of n entanglement pairs and the m pairs used for teleportation are high

Our idea

Entanglement verification as the fundamental building block of quantum communication

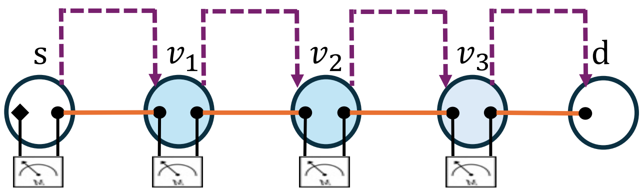
Alternate (packet-switched) communication protocol to avoid challenges of end-to-end entanglement





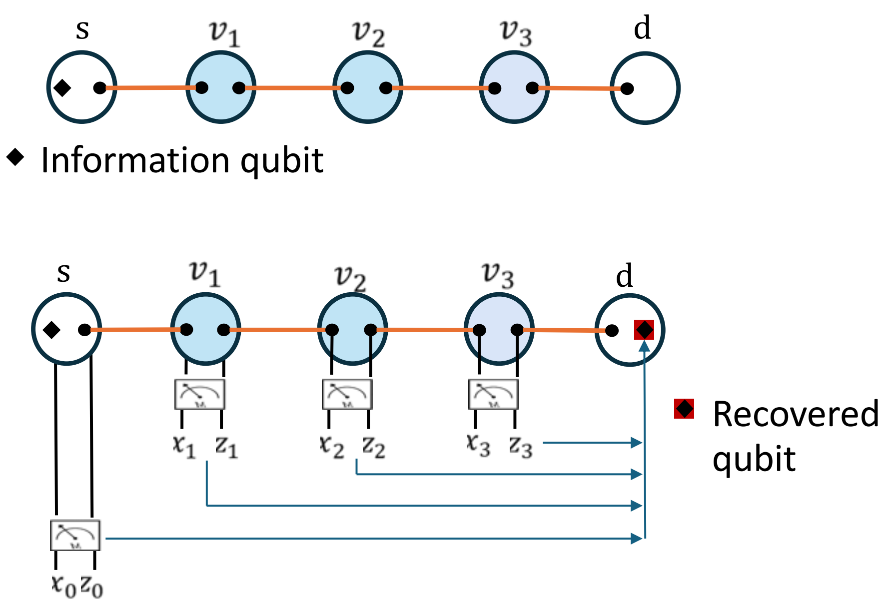
What is the alternative to end-to-end entanglement?

Hop-by-hop entanglement



But…
Extreme noise due to frequent measurement and reconstruction

Our idea: deferred recovery

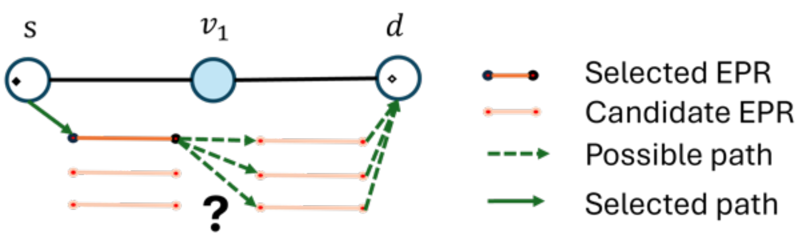


No end-to-end entanglement needed, each repeater independently performs operation

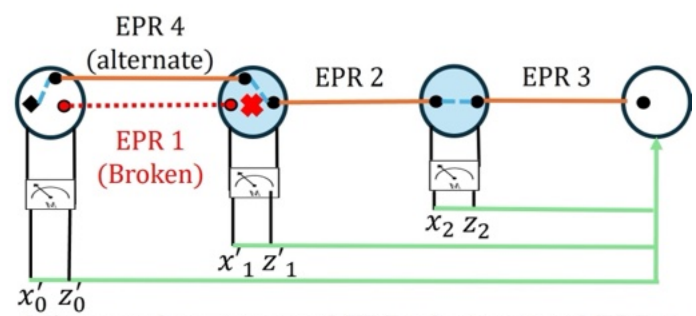
Does not have disadvantage of hop-by-hop qubit reconstruction at each repeater

But…deferred recovery over verification is challenging

Challenge 1: Which entanglement pairs to pick?



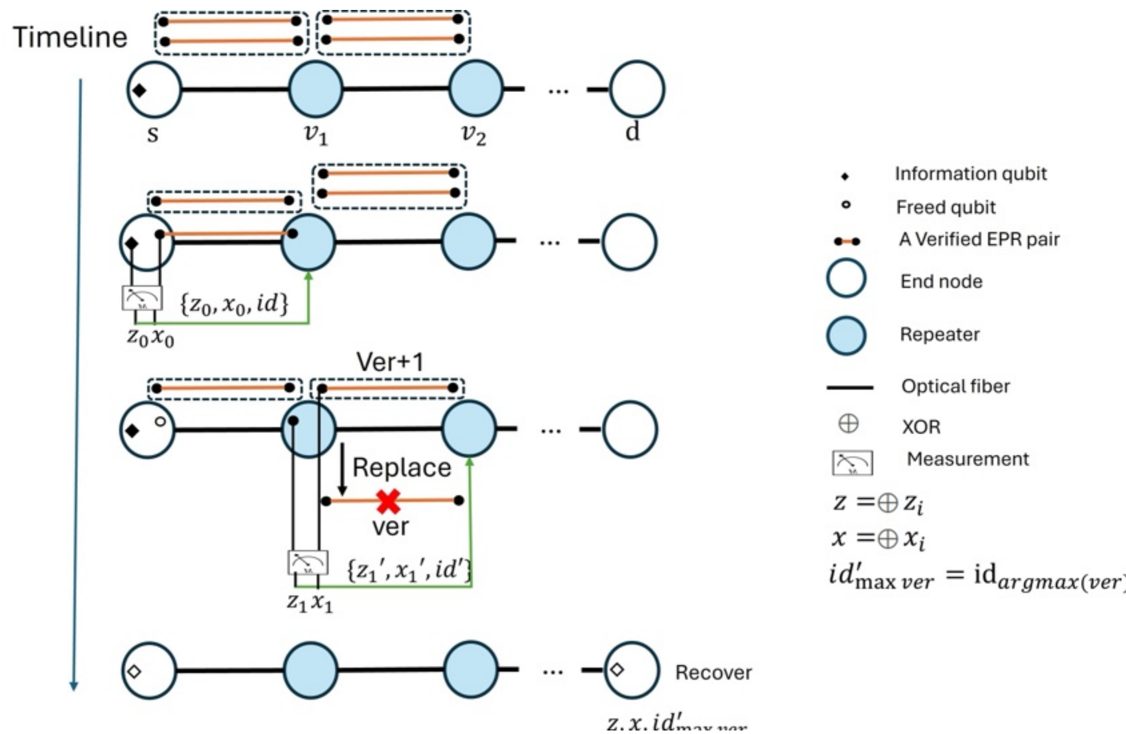
Challenge 2: What happens if an entanglement breaks



Mismatch: assumed EPR1 but actual EPR4

VBQT protocol

- Late binding with verification
- Identifier-based consistency
- Attempt-based local replacement



Reimagined quantum network stack

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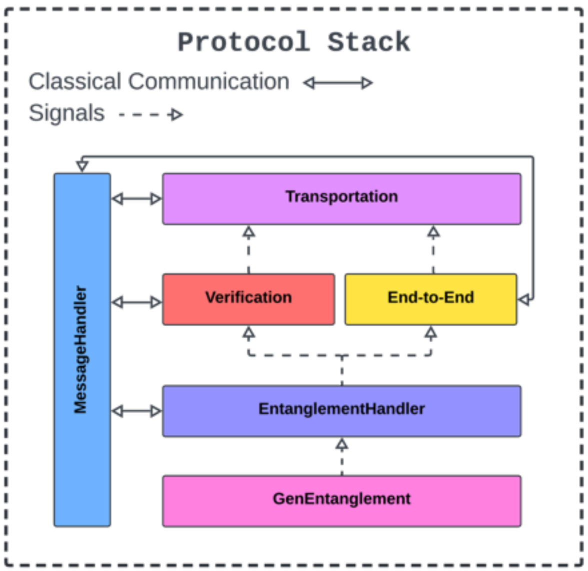
Evaluation using NetSquid

Extended NetSquid to implement multi-path protocol



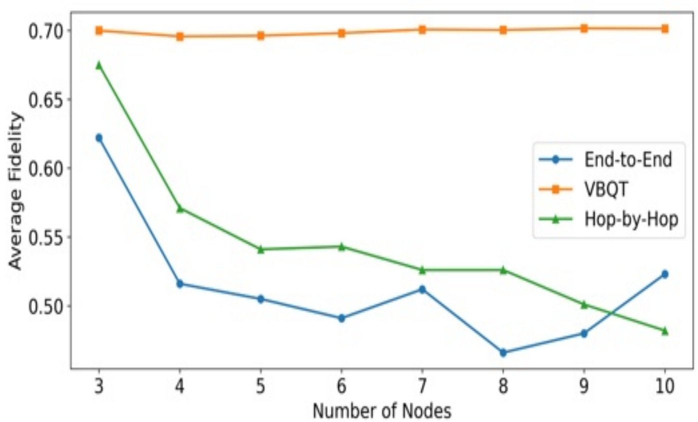
Parameters obtained from real experiments

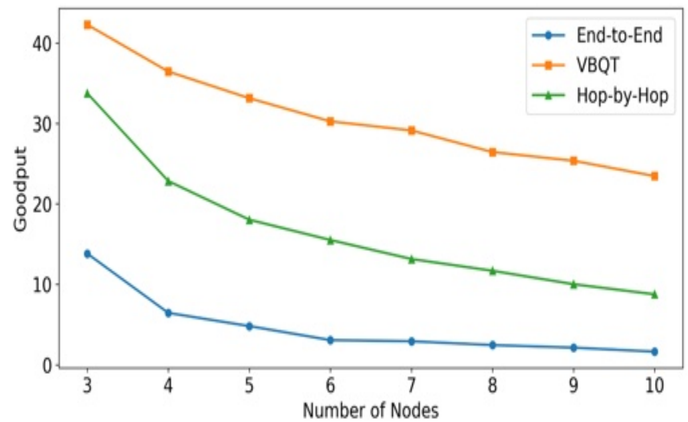
Parameter	Value
EPR Memory Depolar. Rate	8641 Hz [19]
Quantum Channel Depolar Rate	63109 Hz [19]
Measurement and Readout Time	3 μs [15]
Photon Loss Rate	0.2 dB/km [15]
Communication speed	2.06×10^8 m/s [15]

Evaluation goals

- Compare the performance of VBQT (verification + packet-switched multi-hop communication) with end-to-end and hop-by-hop approaches
  - For different number of repeaters
  - For different distances
  - For different depolar rates
- Evaluate the latency added due to verification
- Perform numerical analysis of the verification protocol

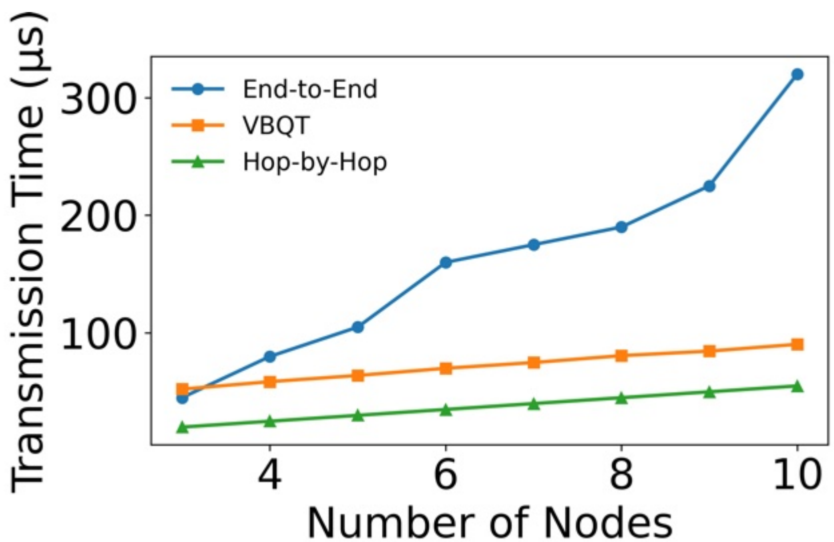
Under increasing repeaters

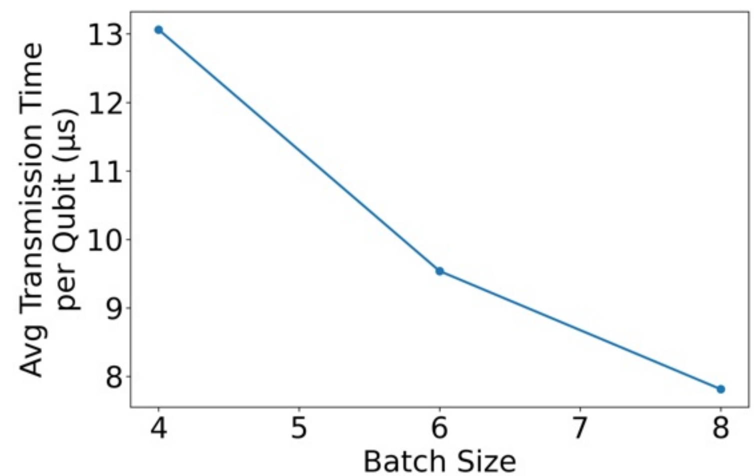




Results are similar for changing node distances and decoherence rates

Effect of verification





Conclusion and Future work

- Verification is key to successful multihop quantum communication
  - But efficient, non-destructive verification remains a challenge
- A packet-switched approach to multi-hop quantum communication provides significantly more flexibility
- Need closer collaboration with experimentalists to validate key components of the protocol on real quantum hardware