The Quantum Internet: A Classical Perspective

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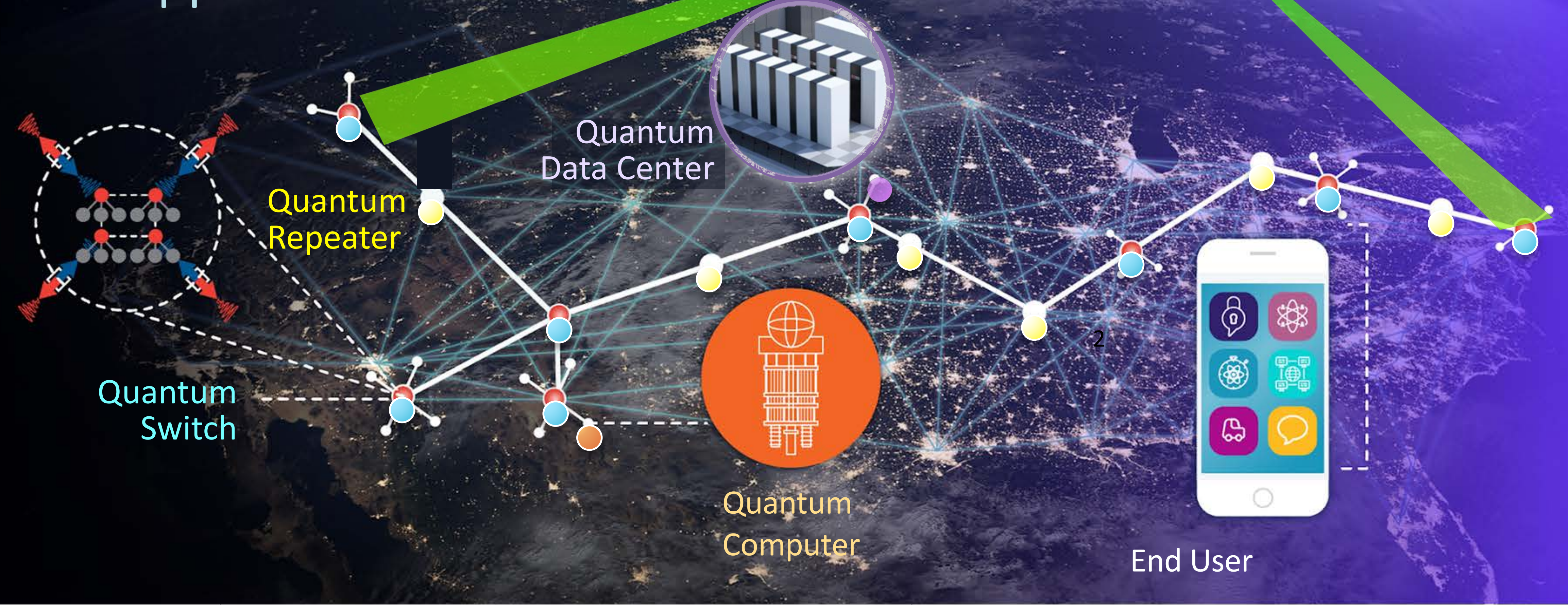
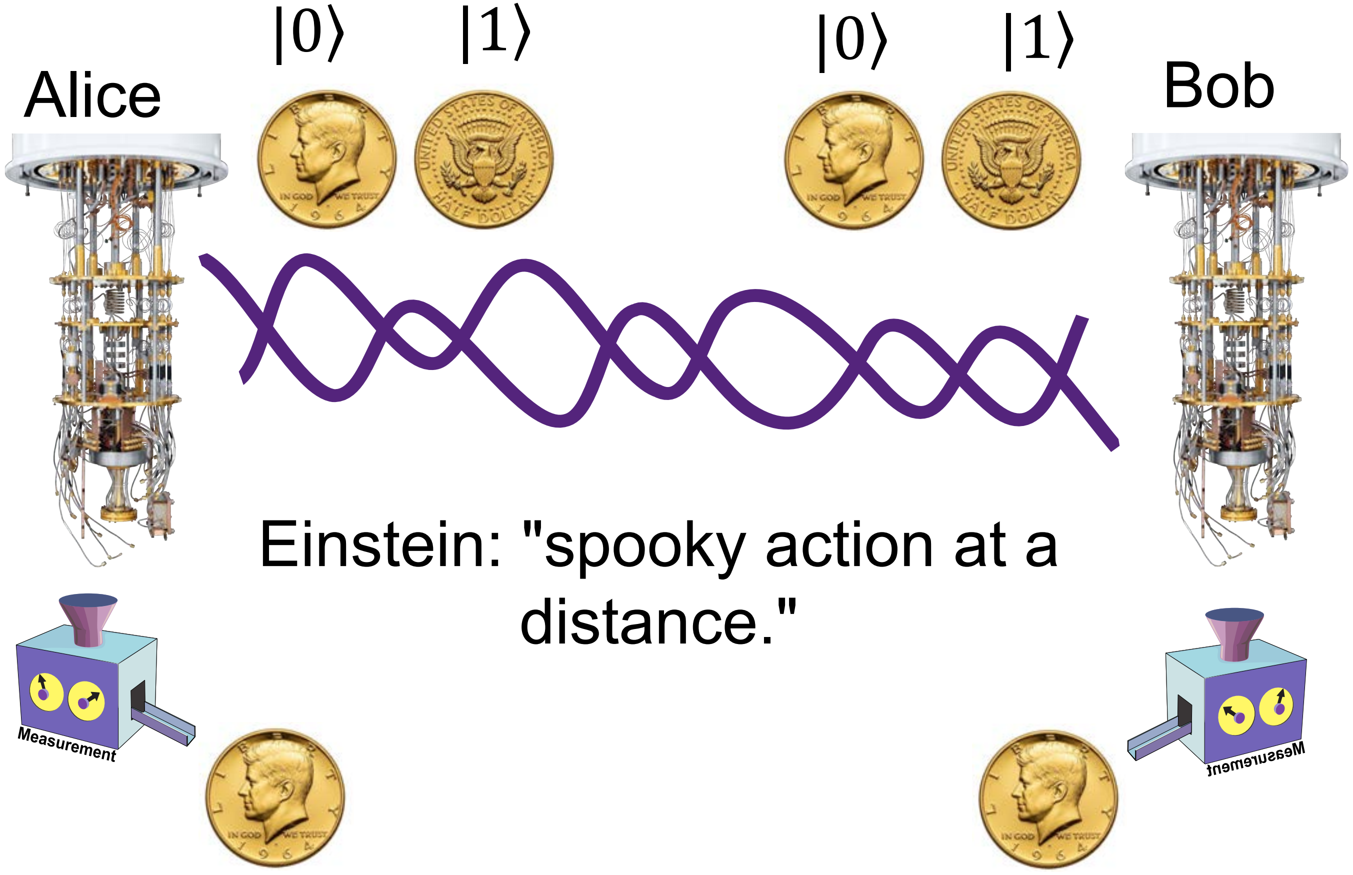
The Quantum Internet

Vision: Global network capable of high rate high quality quantum communication sessions over long distances, serving diverse applications.



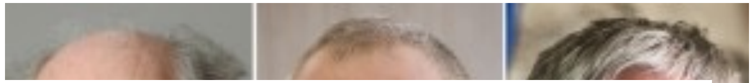
Key ingredient

Quantum entanglement, *aka Bell state*, between pair of remote quantum processors



Einstein: "spooky action at a distance."

Nobel prize, Physics, 2025:
J. Clarke, M. Devoret, J. Martinis



Turing Award, 2026:
C. Bennett, G. Brassard

Nobel prize, Physics, 2022: A. Aspect, F. Clauser, A. Zeilinger

https://pubs.acs.org/doi/10.1021/cen-10036-scicon3

Why Quantum Internet?

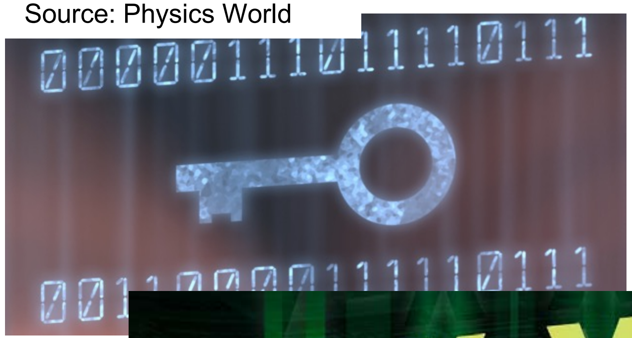
Cryptography, security – quantum key distribution (QKD)

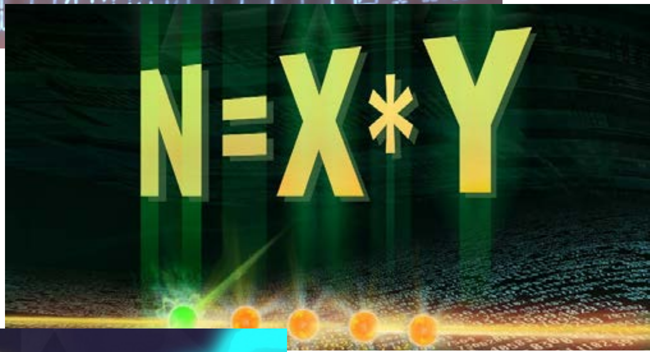
Distributed quantum computing – breaking web security, solving hard problems

High resolution sensing – exploring the universe

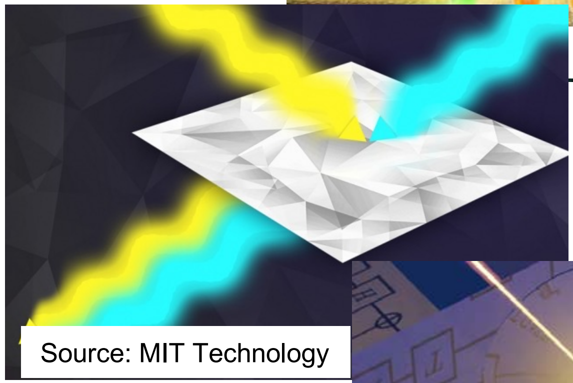
Teleportation of quantum data

Source: Physics World

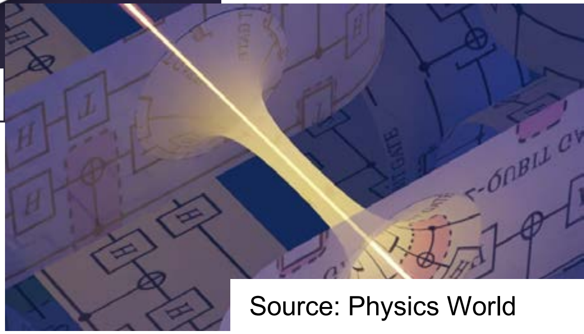




Source: IQOQI, H. Ritsch



Source: MIT Technology



Source: Physics World

Outline

Some basics

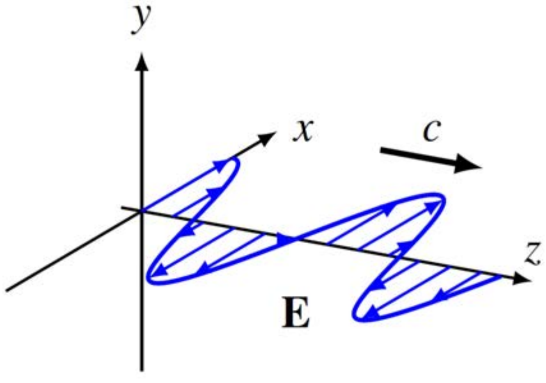
Quantum networks

A classical perspective

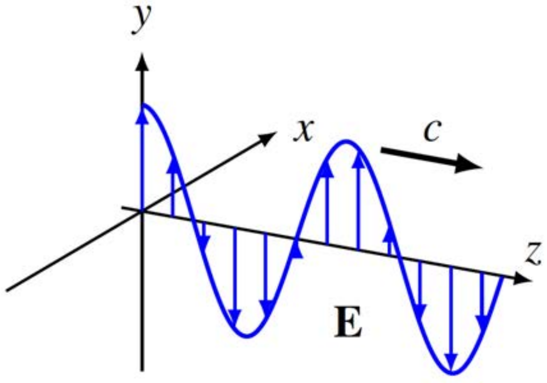
Summary

Quantum states

Qubit - two-state quantum-mechanical system



$|0\rangle$

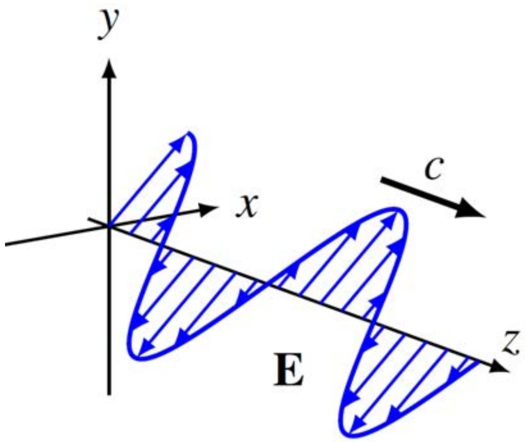


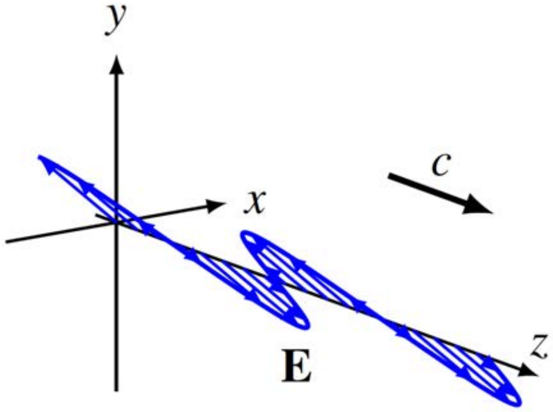
$|1\rangle$

Superposition of states

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

$$\alpha, \beta \in \mathbb{C}, \quad |\alpha|^2 + |\beta|^2 = 1$$





Entanglement

- two qubit state

$$|\psi\rangle = \alpha_{00}|00\rangle + \alpha_{01}|01\rangle + \alpha_{10}|10\rangle + \alpha_{11}|11\rangle$$

- two qubits entangled when state of one cannot be described independent of state of the other
- Bell state:

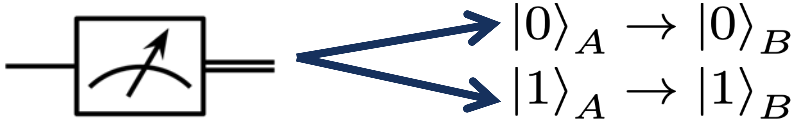
$$\frac{|00\rangle + |11\rangle}{\sqrt{2}}$$

Bell state

- Bell state

$$\frac{|0_A 0_B\rangle + |1_A 1_B\rangle}{\sqrt{2}}$$

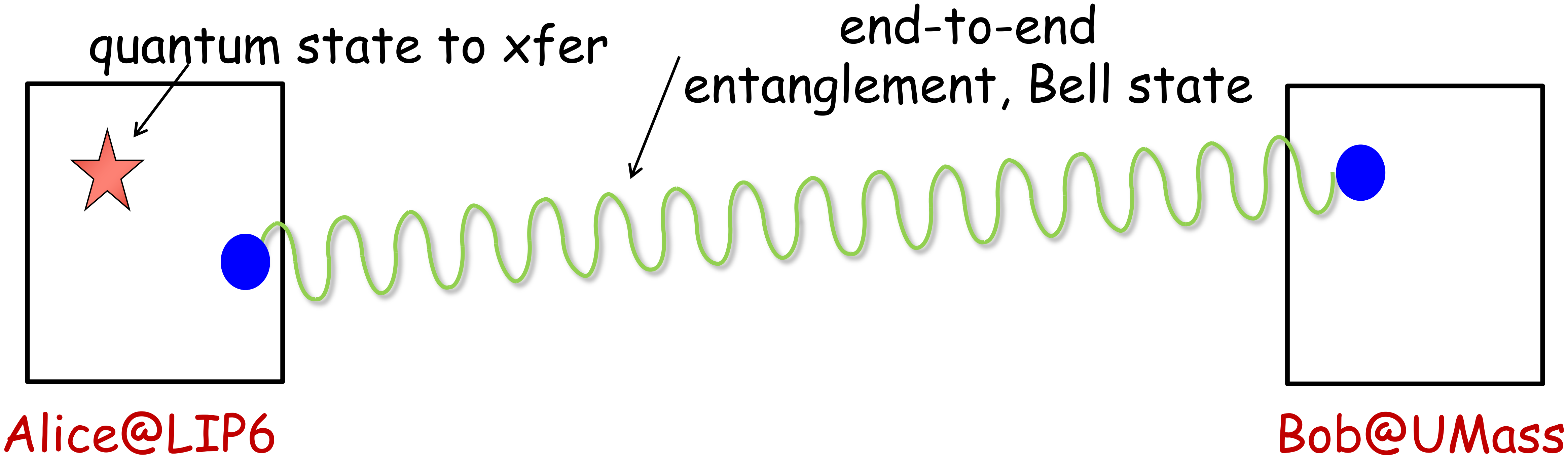
- measuring Alice's qubit yields 0,1
  - if 0, measuring Bob's qubit yields 0
  - if 1, measuring Bob's qubit yields 1
  - can generate shared randomness across distances



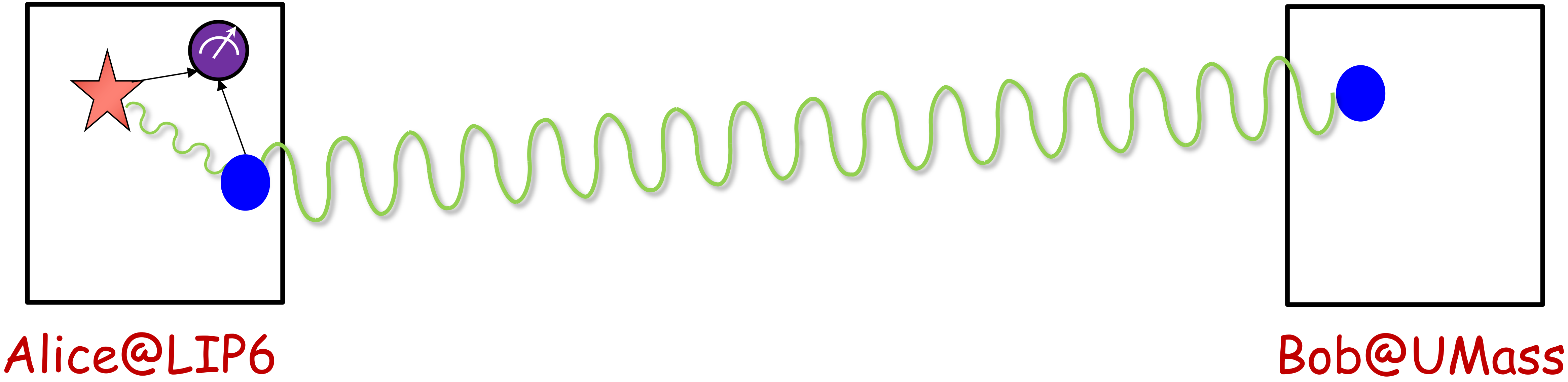
- key ingredient of quantum communications, quantum computing, quantum key distribution

Quantum teleportation

Transfer arbitrary quantum state using Bell state as resource



Teleportation



Teleportation

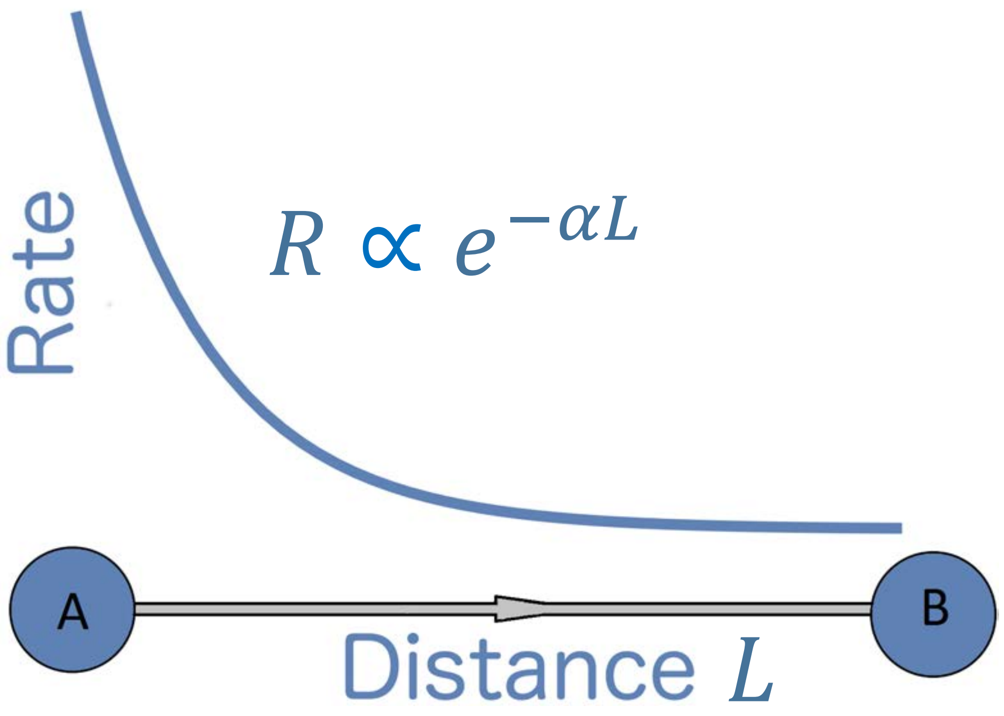
Why don’t we have a quantum Internet yet?

It’s hard!

Why?

Loss & noise

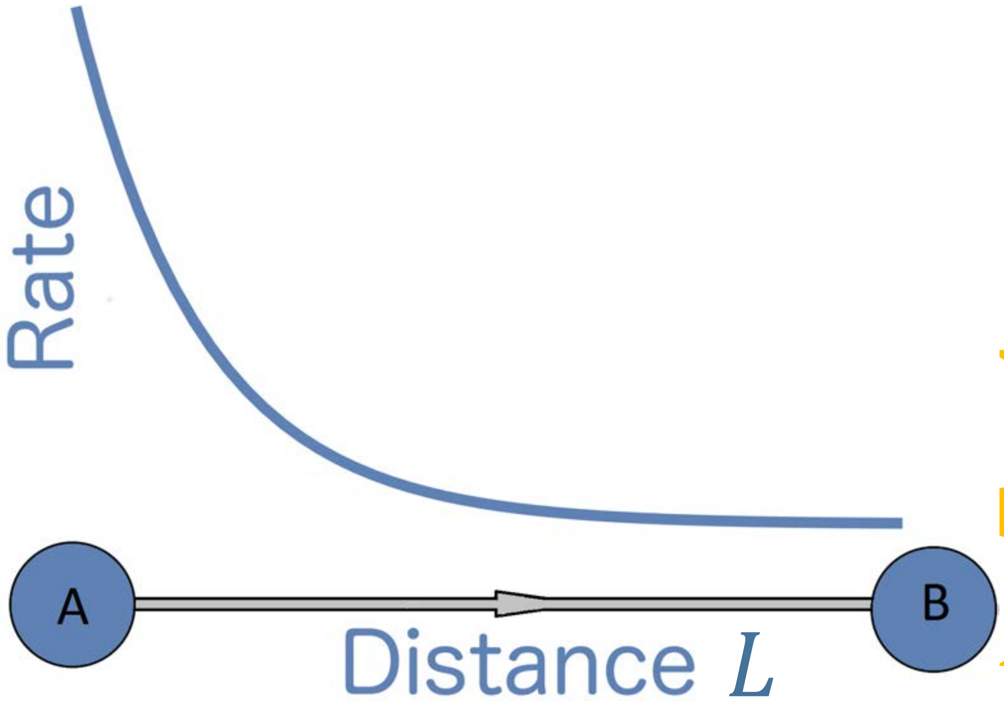
Loss



Rate decays exponentially with distance

Can we amplify signal?

Loss



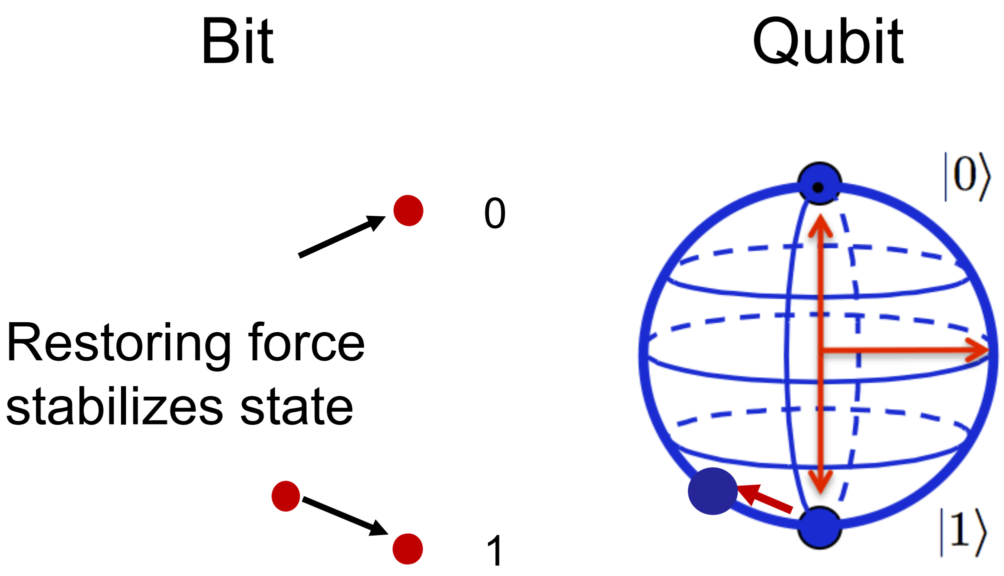
No cloning theorem!
Quantum signals
cannot be copied

Rate decays exponentially
with distance

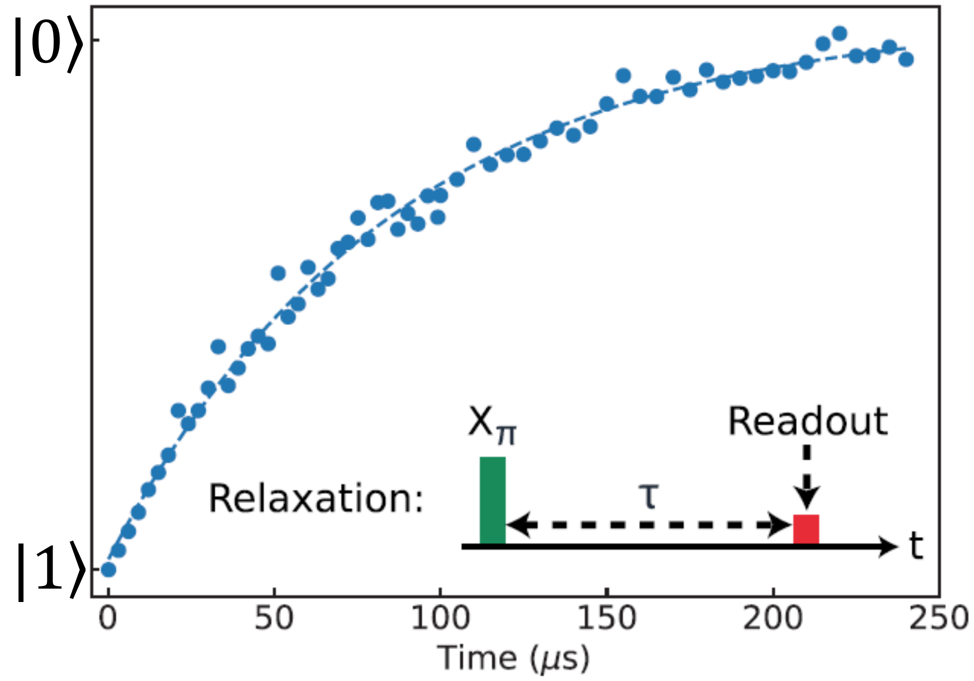
Noise?

Qubits not self protected against smallest perturbation

Qubits have limited coherence times



Restoring force towards 0 or 1 not allowed



P. Krantz, etal, Appl. Phys. Rev. 6, 021318 (2019)

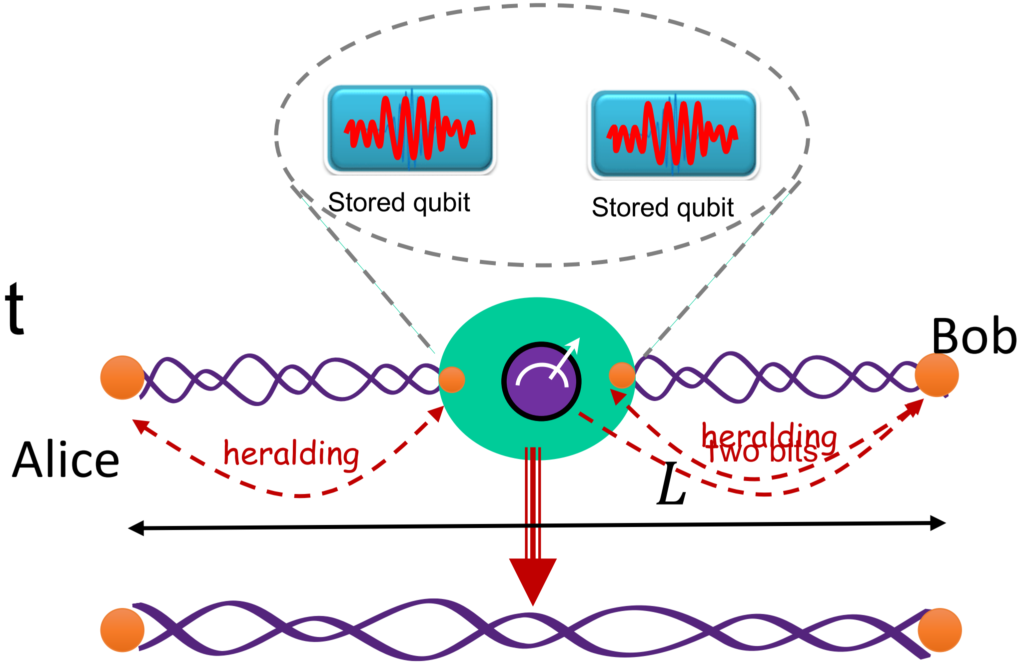
Handling loss in a quantum network

Two-way quantum repeaters

Quantum memories store entanglement

Phase I: generate link level entanglement (Bell states)

Phase II: measurement (BSM, swap) propagates entanglement to ends

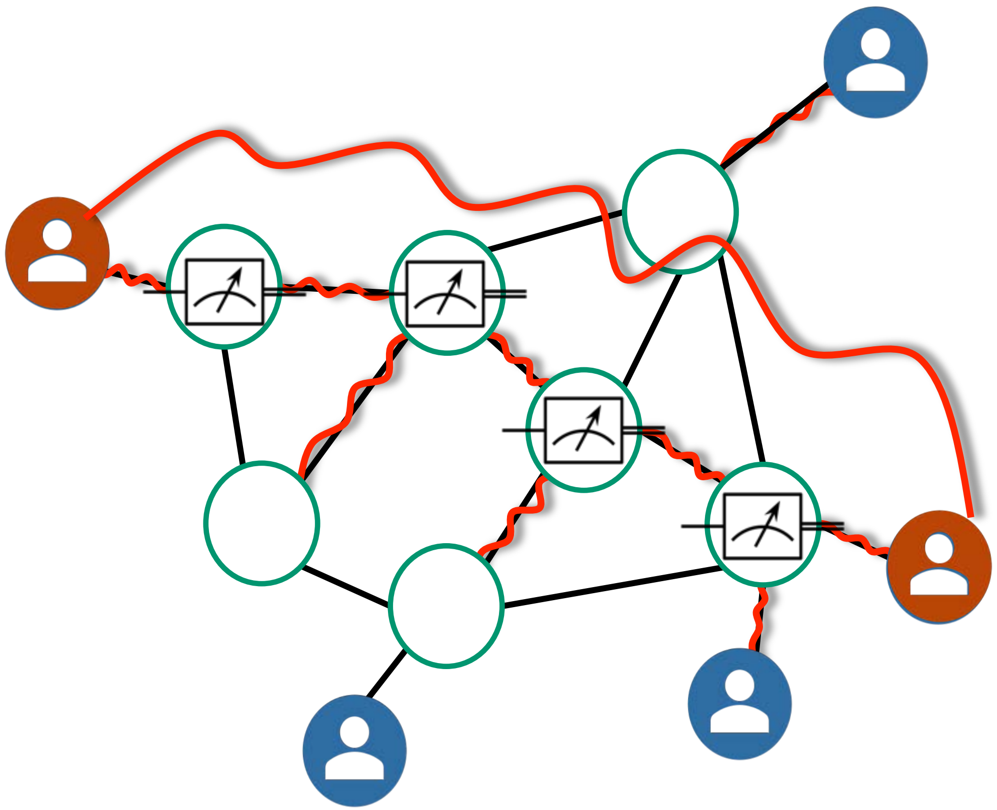


$$R = e^{-\alpha L/2}$$

$$R \propto e^{-\alpha L/N}$$

Two-way quantum entanglement network

- quantum switches/repeaters with memories connected via lossy links
- links generate entanglement
- noisy switches swap to realize end-to-end entanglement between end nodes

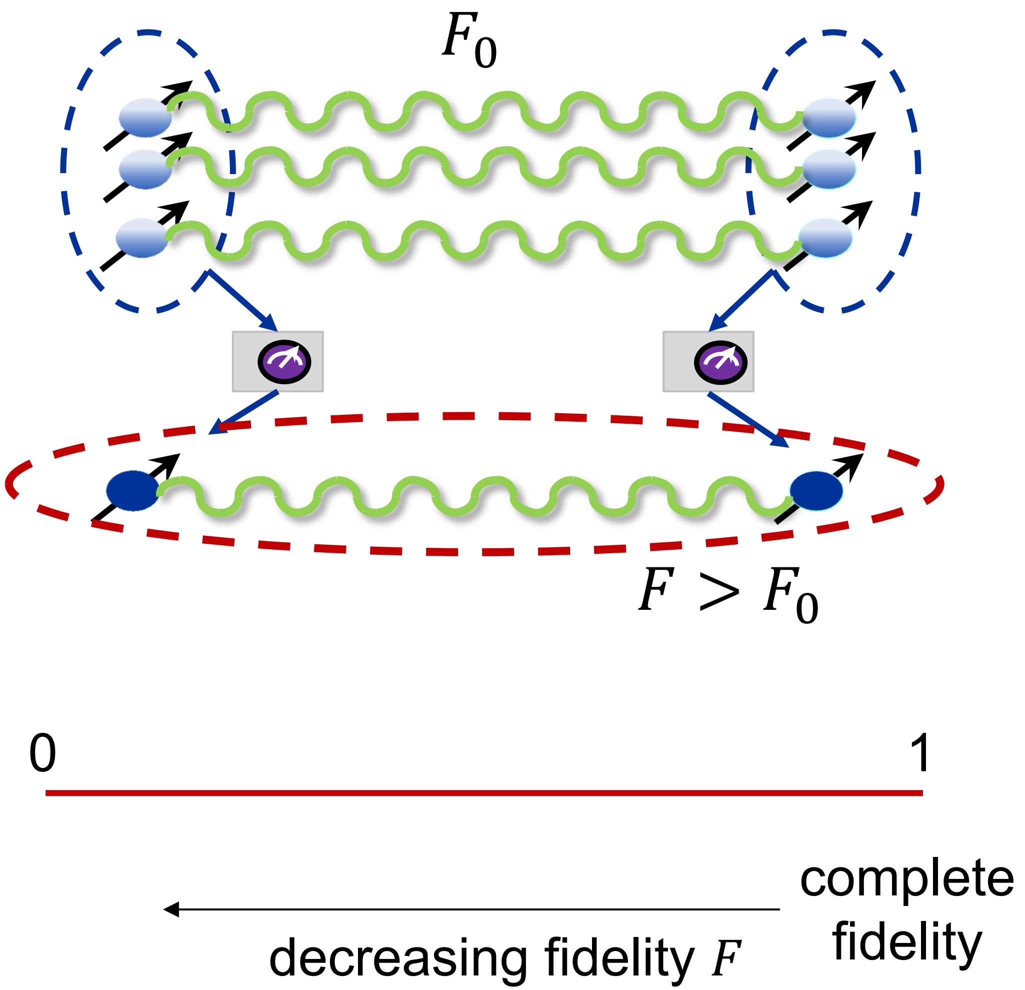


Handling noise in a quantum network

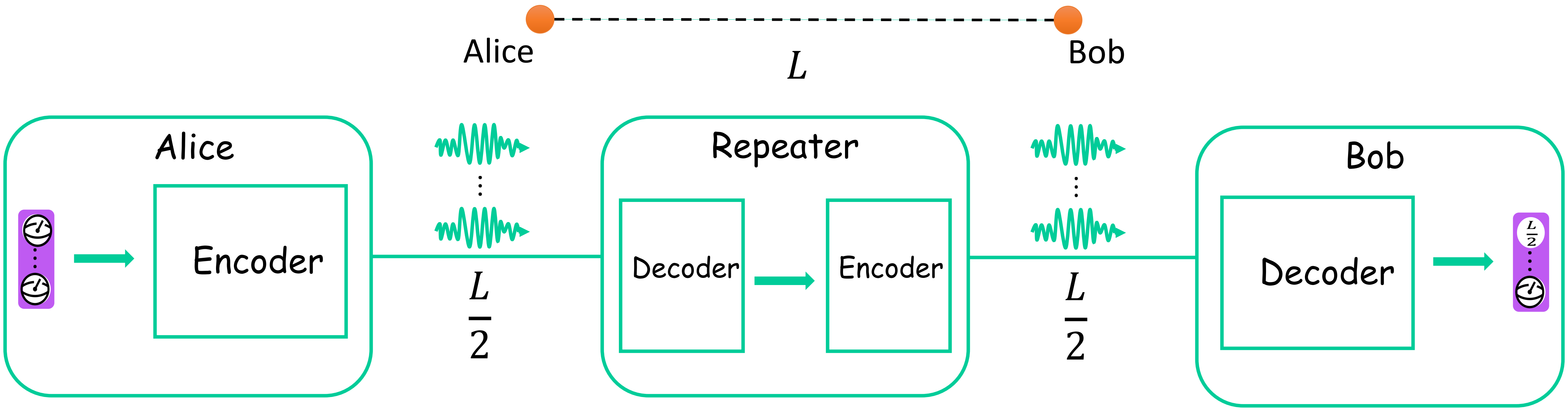
Entanglement distillation

Probabilistically convert multiple noisy entangled pairs into single strongly entangled pair (larger fidelity)!

Fidelity: measure of closeness of entanglement to perfection



One-way quantum repeaters



Protect information with Quantum Error Correction (QEC)

State recovered if sufficient photons survive

Probability of delivering logical state, p, depends on encoding

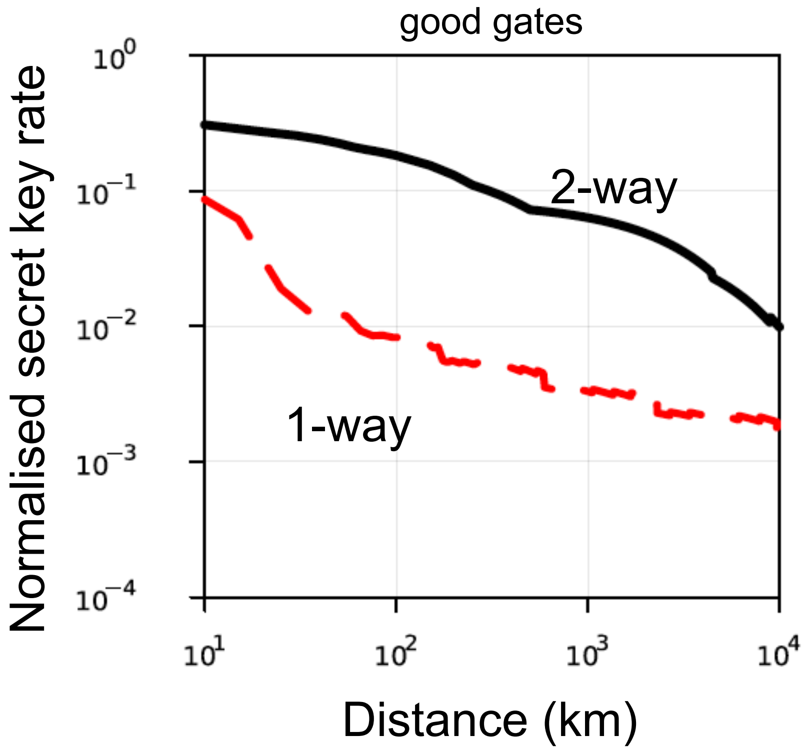
Two-way vs. one-way

One-way vs. two-way configurations for different distances (multiplexed)

- gates, memories 2-5 years out
- secret key rate, combines rate + fidelity

Two-way outperforms one-way by as much as order of magnitude at lower cost

Why? Two-way handles loss better



Mantri, et al. *Comm. Physics* 2025

A classical perspective

Connectionless 2-way Qnet architecture

Connectionless

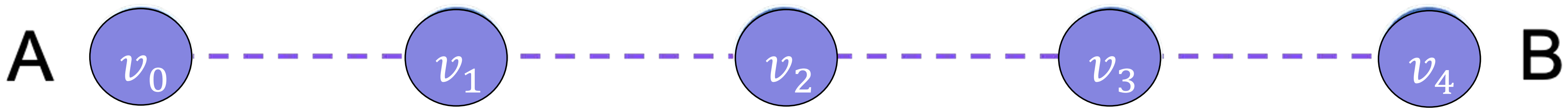
- little or no flow state at switches/repeaters
- handle each entanglement request separately

Requirements:

- support multiple entanglement request streams
  - diverse qualities of service (rates vs. fidelities)

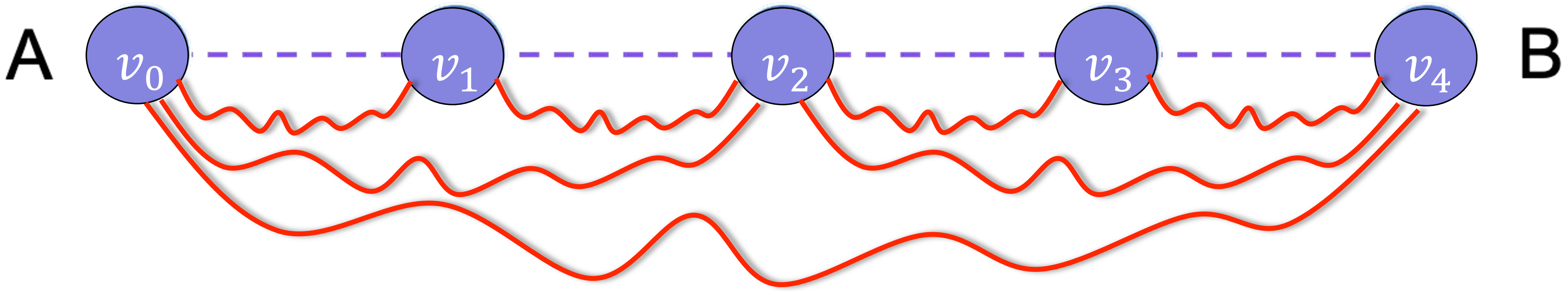
Key: sequential (cascaded) swap schedule

Swap scheduling



- nested swapping – accepted standard
- swap as soon as possible (ASAP)

Nested swaps

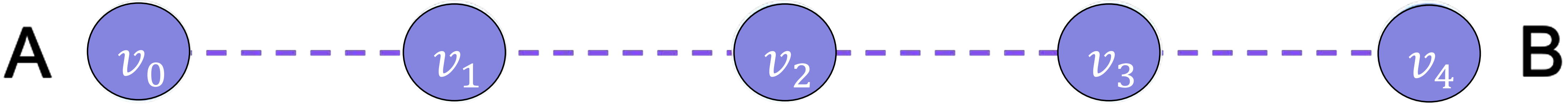


- all link resources on a path given to single session at a time
- requires careful synchronization (connection state)

  → spatial, time division multiplexing

W. Dai, etal., *IEEE JSAC*, 2020

Swap scheduling



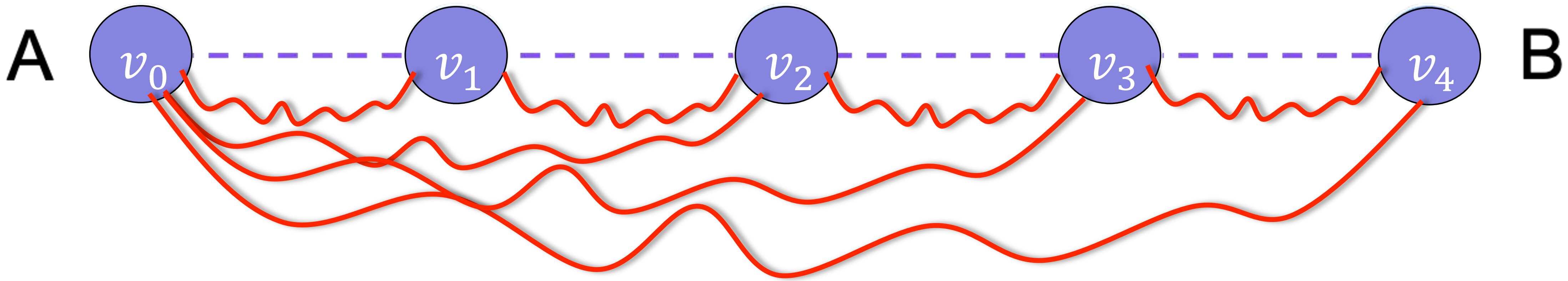
- nested swapping
- swap as soon as possible (ASAP)

requires synchronization (connection state)

- sequential (cascaded) swaps
  - only requires link-level synchronization

Sequential swaps

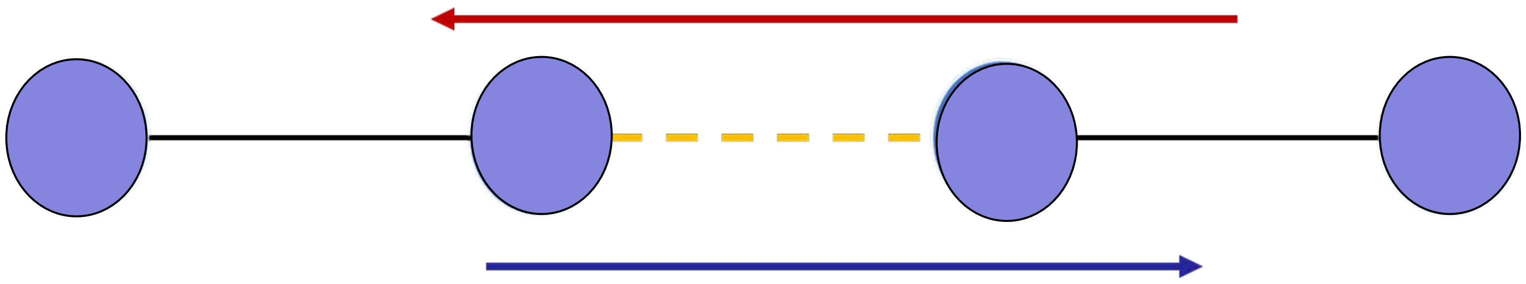
- swaps executed sequentially:



- link resources given to session only when request needs them

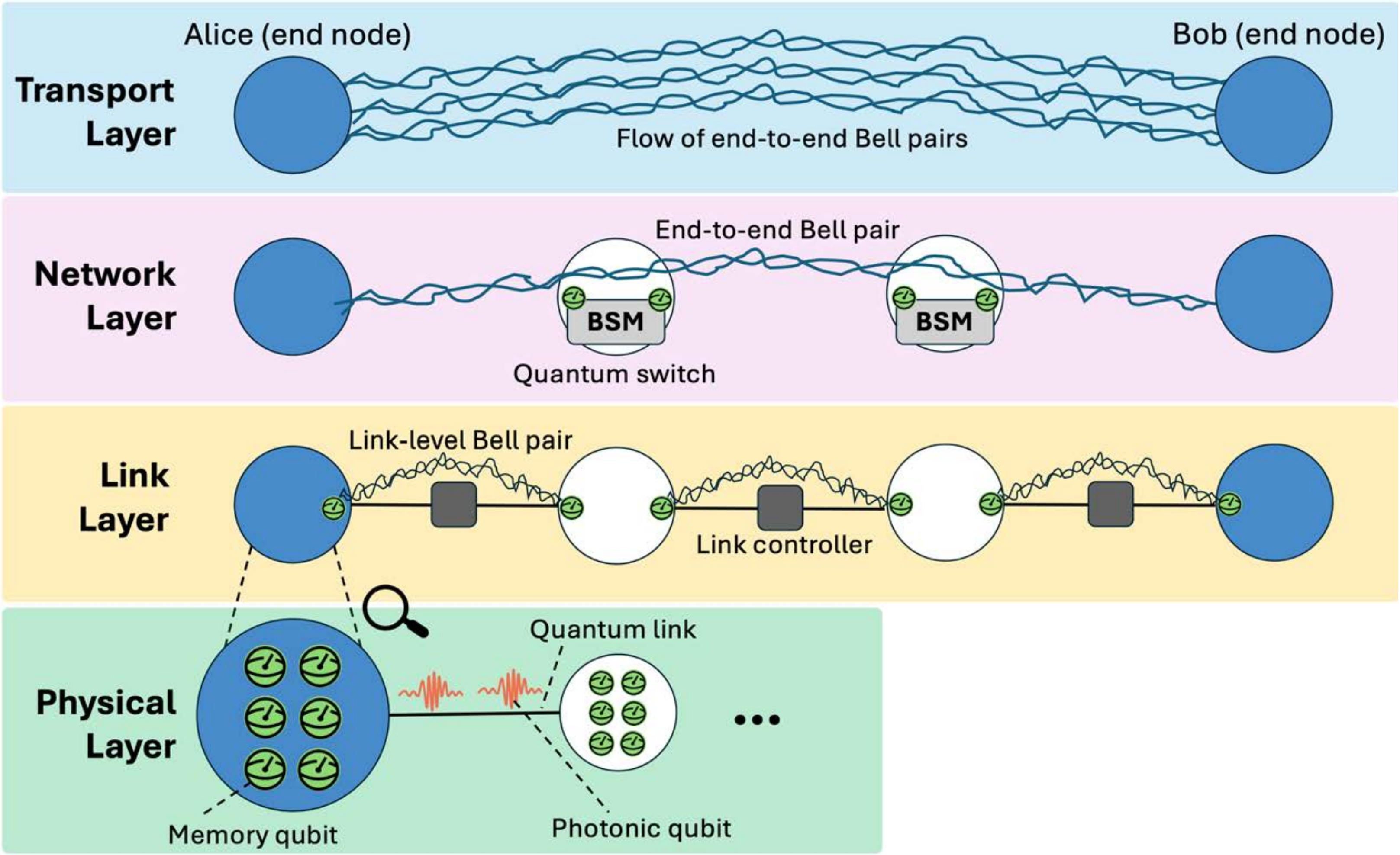
Analogous to datagram service in classical Internet

Link synchronization



- associate link controller with each link
- use information from neighboring switches
  - time multiplexing?
  - use backlog information; allocate to direction with largest backlog?

Connectionless protocol stack



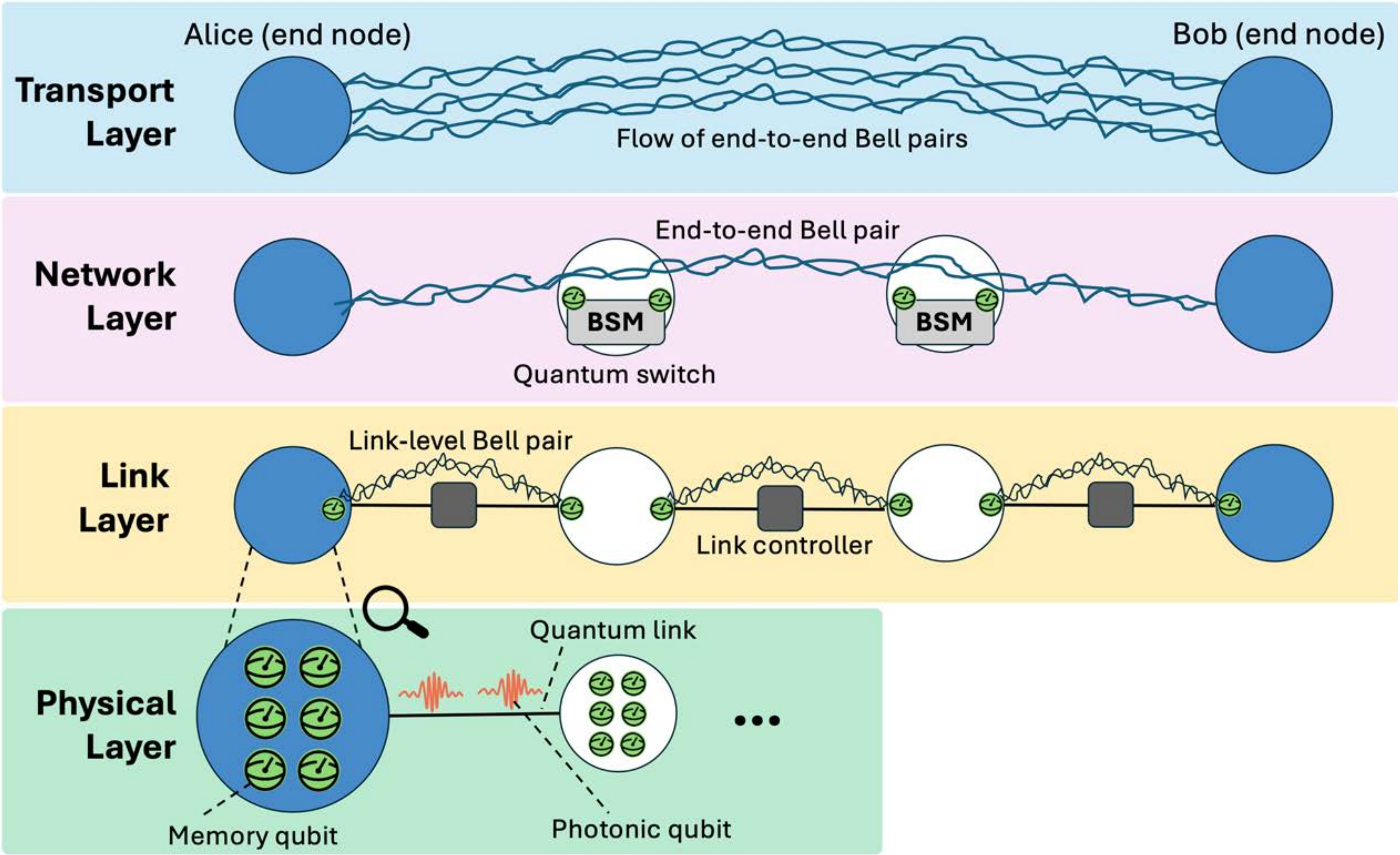
Quantum TCP

Routing and sequential swapping with store and forward

Heralded Bell pair generation (link-controller)

Quantum operations

Connectionless protocol stack



Quantum TCP

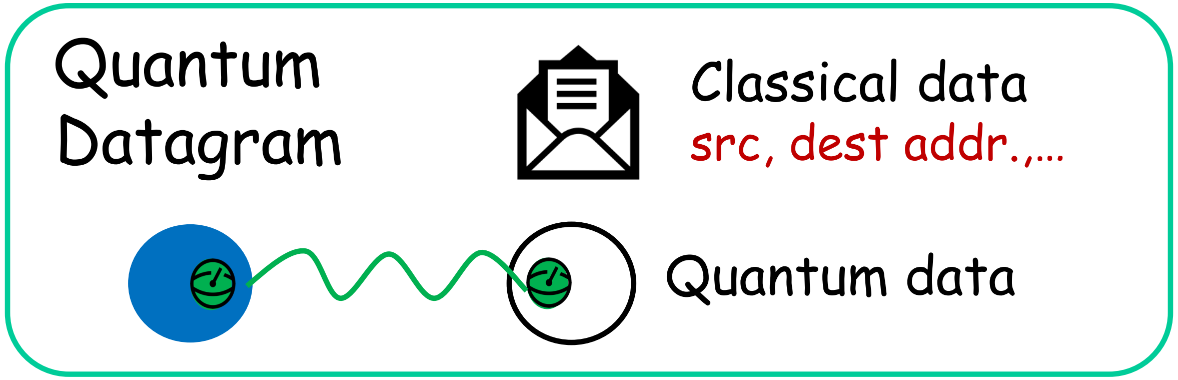
Routing and sequential swapping with store and forward

Heralded Bell pair generation (link-controller)

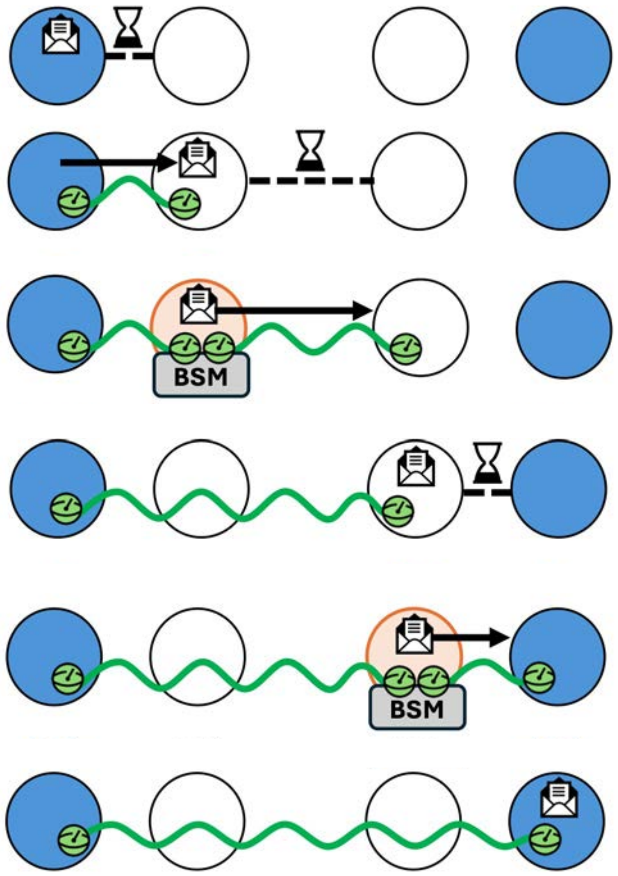
Quantum operations

Network layer

- forward quantum datagrams including Bell states like packets via sequential entanglement swapping



- no resource reservation
- best-effort service

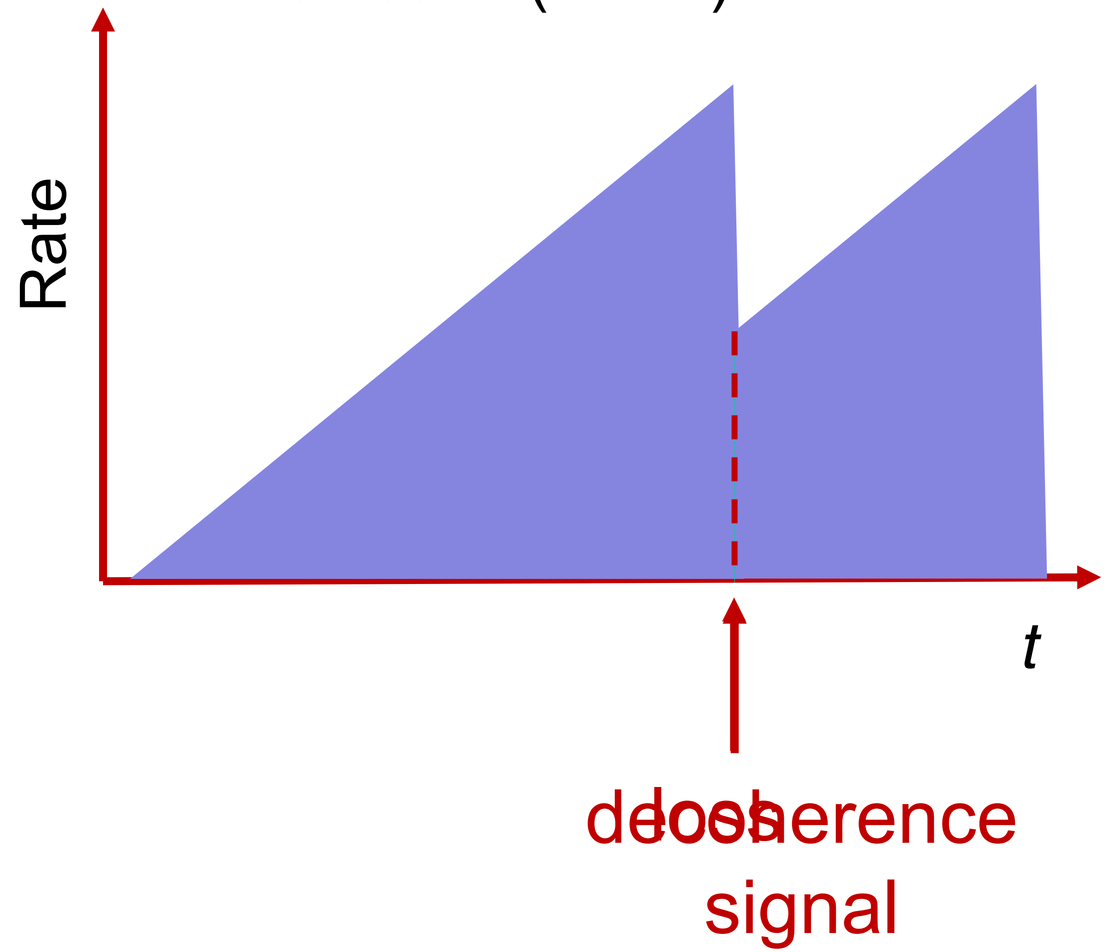


Yoo, etal, IEEE Comms (2024), Bacciottini, etal, arXiv:2410.08980

Transport layer: QTCP

- TCP-like: opening handshake, data flow, closing handshake
- Ack’s for delivered q-datagrams
- control E2E q-datagram rate (congestion control, AIMD)
- active decoherence management

Additive Increase Multiplicative Decrease (AIMD)



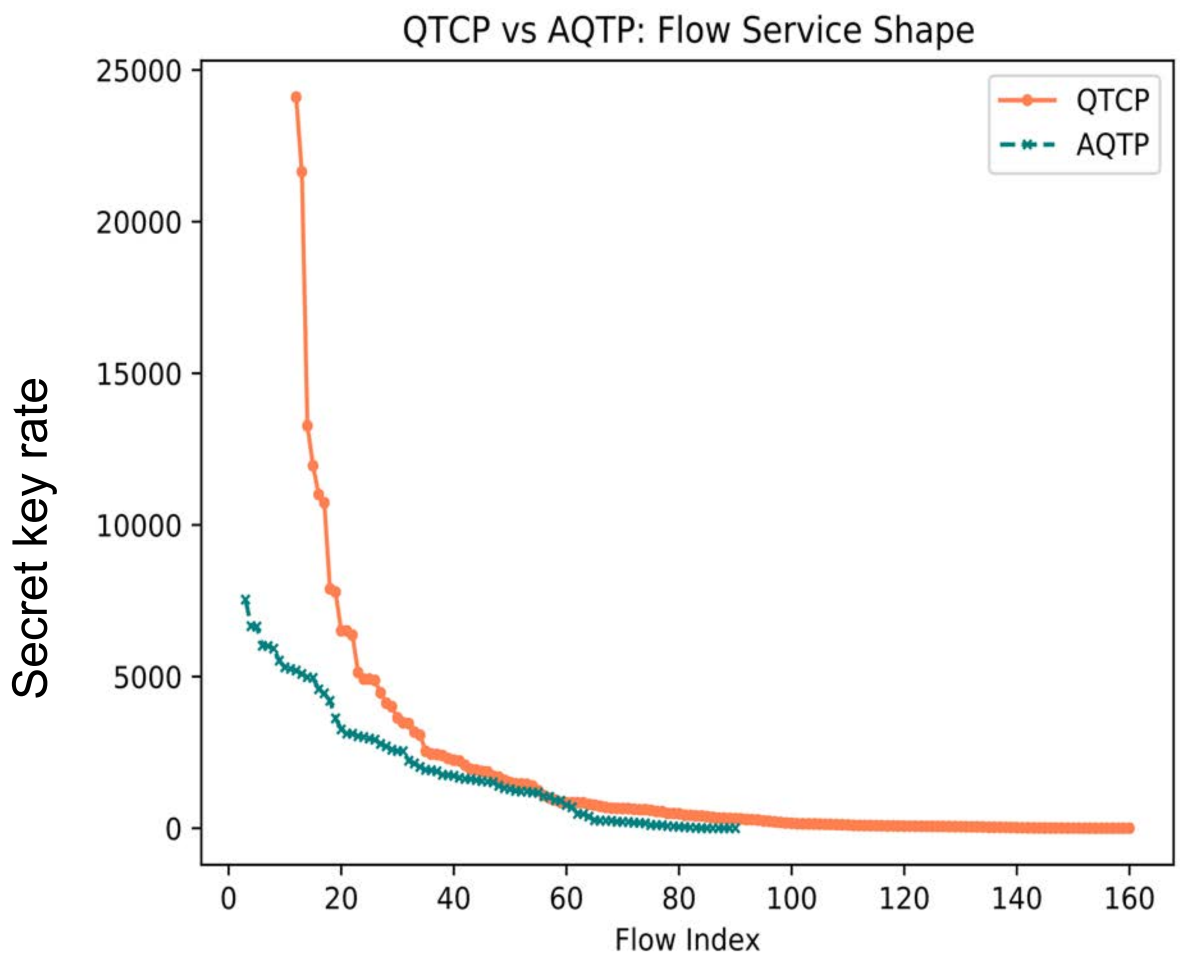
Bacciottini, etal, IEEE Network 2025;

Transport layer: QTCP

- TCP-like: opening handshake, data flow, closing handshake
- Ack's for delivered q-datagrams
- control E2E q-datagram rate (congestion control, AIMD)
- active decoherence management

Comparison:

- coherence time 100ms
- AQTP – flow/reservation-based transport protocol
- multiple flows on Dutch Surfnet network



Bacciottini, etal, IEEE Network 2025; Zhao, etal. IEEE JSAC 2024

Connectionless architecture

- simplifies synchronization; link by link classical comms
- amenable to analytics (understandability, management)

Allows deployment of classical Internet protocols

- Quantum-TCP
- destination-based routing
- multicast ↔ multipartite state distribution

But – classical Internet not sensitive to noise!

Guedes de Andrade, etal.. arXiv:2405.18252, 2024, Bacciottini, etal, IEEE Network, 2025

Link-level rate-fidelity tradeoff

higher fidelity → lower rate

Entanglement rate

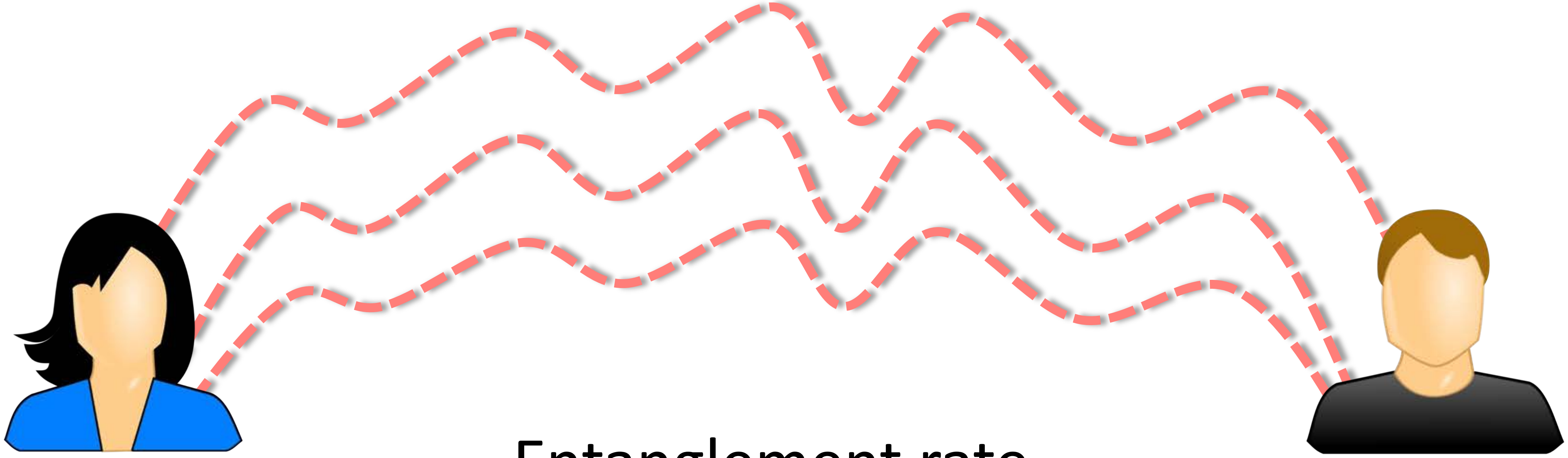
$$p \approx 2\eta\, \alpha$$

tunable brightness parameter

Fidelity: $(1-\alpha)$

Link-level rate-fidelity tradeoff

lower fidelity → higher rate



Entanglement rate

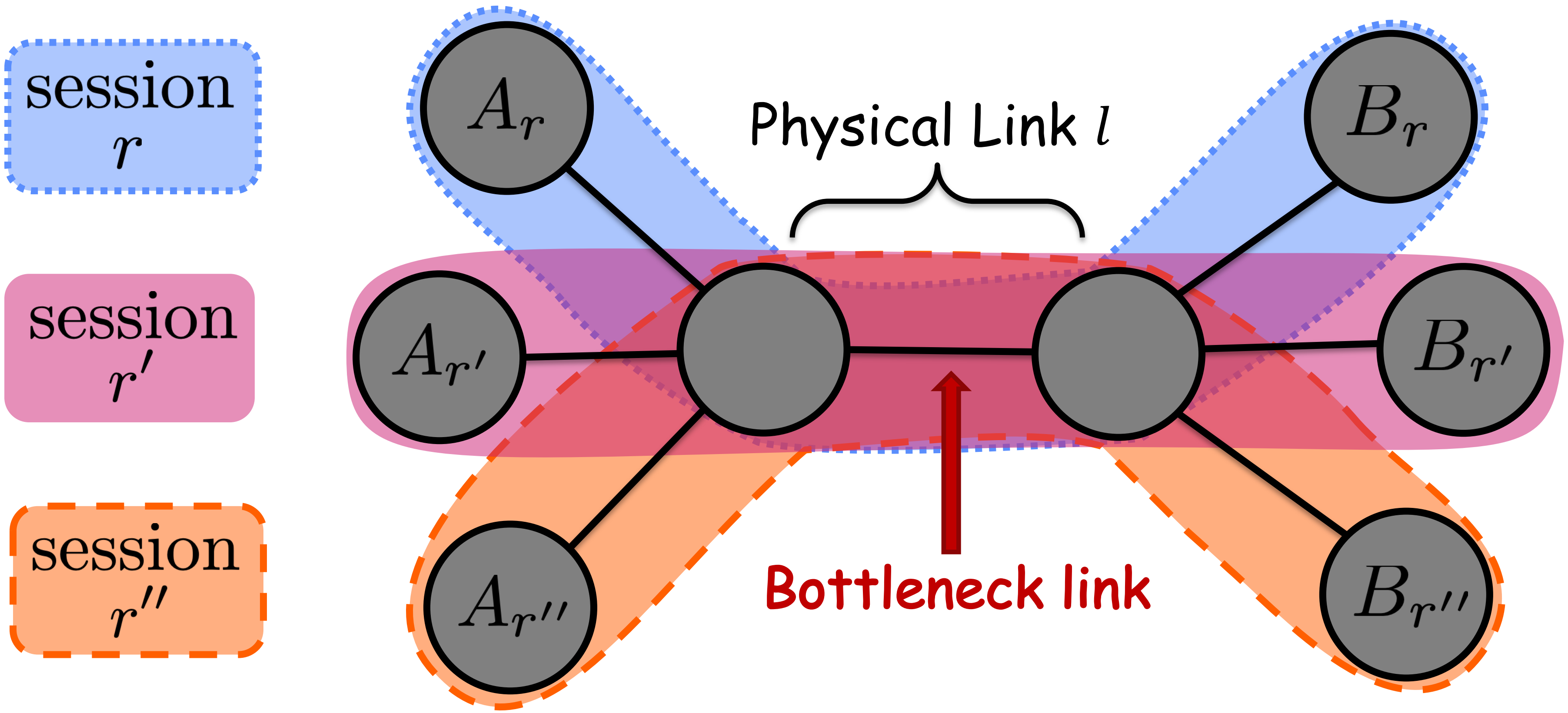
$$p \approx 2\eta\, \alpha$$

tunable brightness parameter

Fidelity: $(1-\alpha)$

Quantum Network Resource Allocation

Multiple sessions want to share Bell states



Goal: find, for each session r:

- **E2E generation rate** $\boldsymbol{R_r}$ *(pairs/s)*
- **E2E fidelity** $\boldsymbol{F_r}$ of generated states

For each link l:

- **operating parameter** $\boldsymbol{\alpha_l}$

While **maximizing session benefits**

Question: Best way to allocate limited resources?

Primal/Dual network utility optimization

Standard Formalism

Goal: $\max \sum \log \underbrace{U_r}(R_r, F_r)$

Utility function U_r : benefit of session r.
BB84: U_r is **secret key rate**

subject to:

$$\sum_{r:l\in r} R_r \leq 2\eta_l \alpha_l$$

Link rate constraints:
Session through link l must not exceed link generation rate (determined by α_l)

(plus, optionally)

$F_r > F_r^*$ *E2E fidelity constraints*

Primal/Dual approach

R_r, w_l — **Primal variables**:
- Session rates
- Link parameters

λ_l — **Dual variables**:
- Quantify "price" to use link l

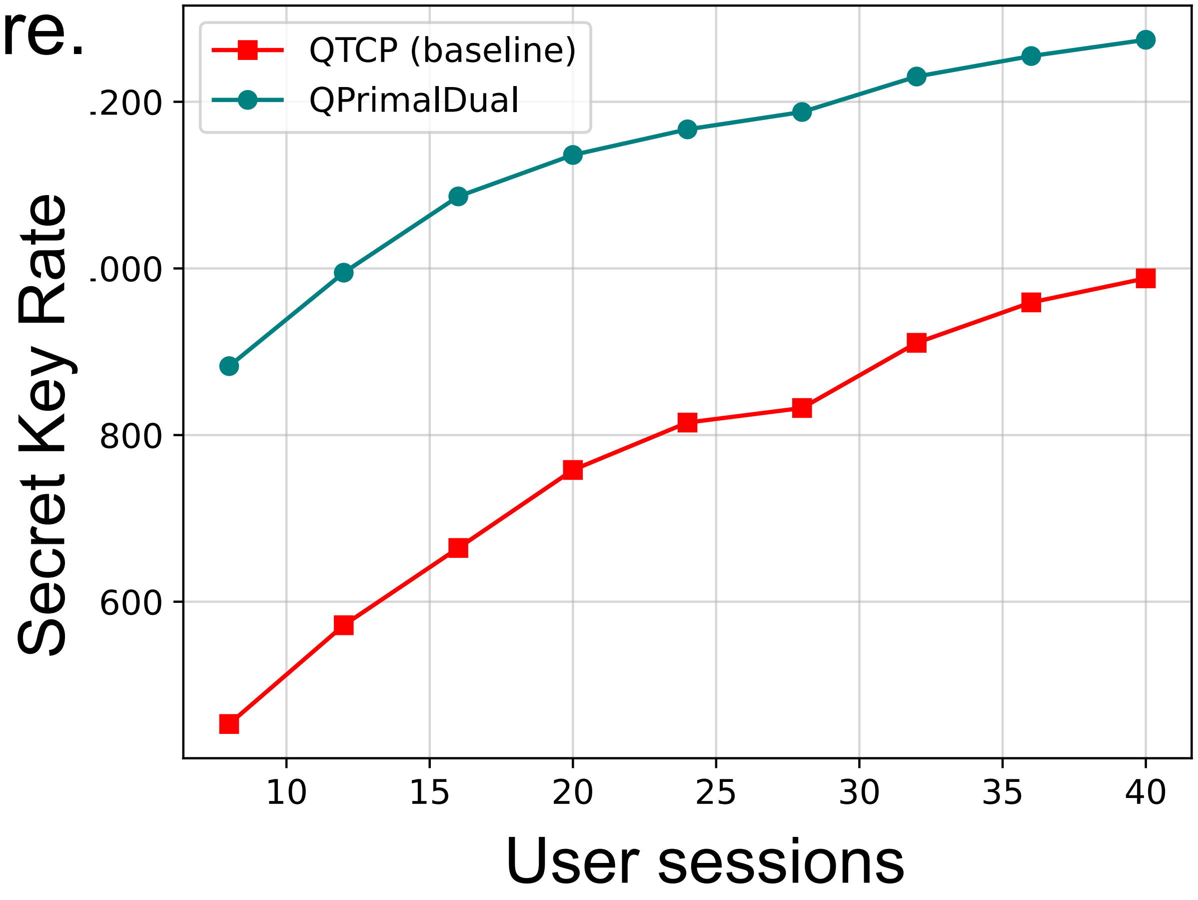
Decentralized algorithm updates variables over time; provably converges to optimal values

Vardoyan, Wehner. arXiv:2210.08135; Panigrahy, etal. arXiv:2510.09371

Transport Layer: QPrimalDual

- QPrimalDual: incorporates algorithm in sequential architecture. Replaces Quantum TCP

- NSFNet topology
- random flows
- QPrimalDual vs QTCP



QPrimalDual: scalable, decentralized, provably stable.

Panigrahy *et al.* arXiv:2510.09371

Summary

Two-way Qnet architecture very promising

- outperforms one-way architecture with error correction

At first glance two-way looks very different from classical network … but sequential swapping makes it look similar

- can borrow from classical networks
- TCP congestion control
- network utility maximization

Challenges

- entanglement fungible; can store ahead of time
- multipartite entanglement (multicast wo cloning)
- incorporate distillation – not a classical construct
- connect models to specific quantum technologies

Acknowledgments

U.S. DEPARTMENT OF ENERGY

DOE RAMSES, PiQSci: $\Pi|\mathrm{Q}|\psi\rangle$ projects

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