The bridge to possible

Packet Switching in Quantum Networks: A Path to Quantum Internet

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Introduction

- Stephen DiAdamo
- Research scientist, Cisco Quantum Lab
- Research Interest:
  - Quantum networks
  - Quantum information theory
  - Distributed quantum computing
  - Simulation

Overview of Presentation

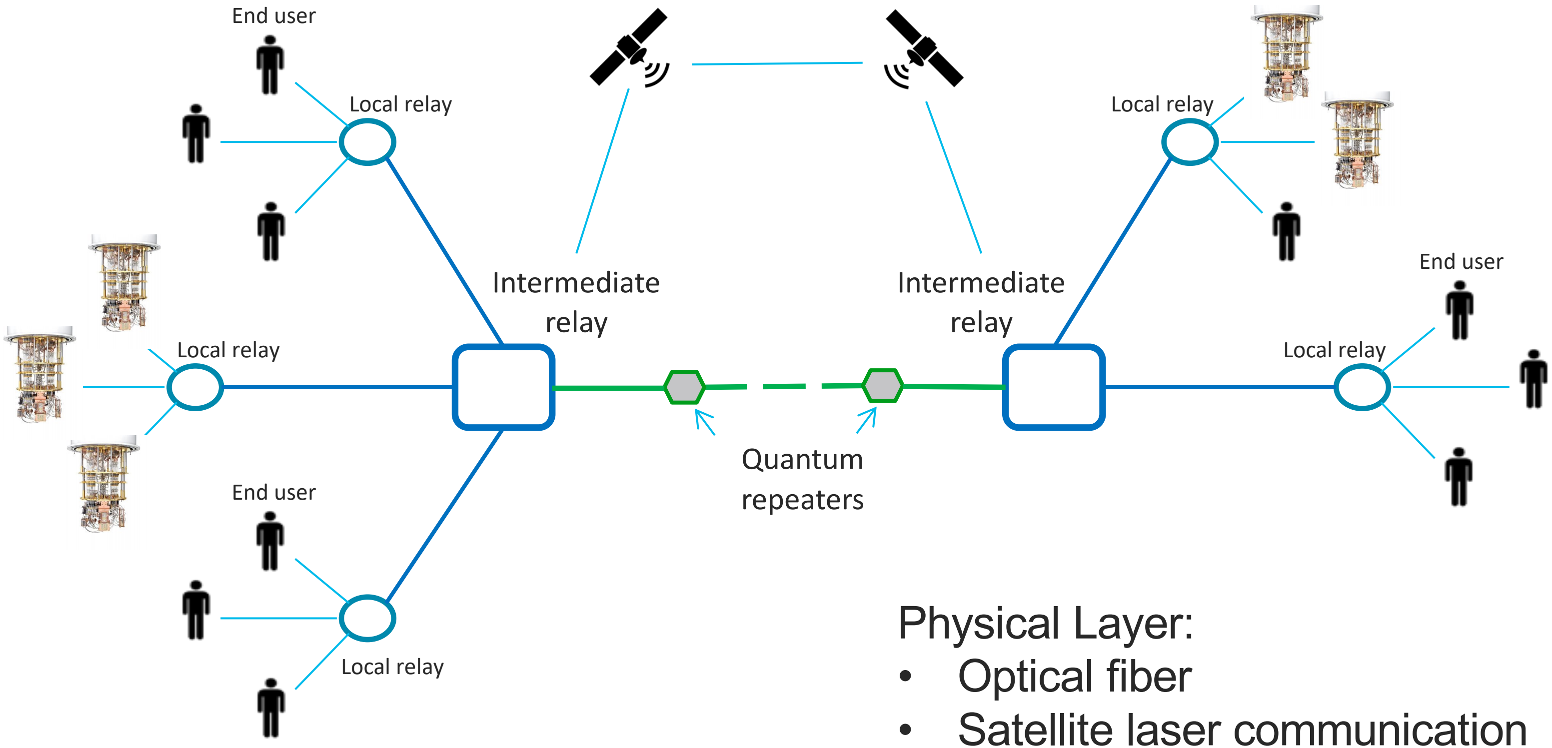
1. What is a quantum network? What does a quantum network do?
2. Existing architectures of quantum networks and shortcomings
3. Our vision of future (and distant future) quantum networks
4. Compromises and challenges for near(er)-term quantum networks
5. Applications for near-term quantum networks
6. Outlook and Summary

Disclosure: Some of this material is under patent consideration. Contact me for further details (sdiadamo@cisco.com).

What are Quantum Networks?

- Networks that connect quantum-capable devices
- The transmission channels are usually free-space and fiber optics cables
- The quantum transport mediums are usually photons
- Proposed quantum network stacks have been OSI-layers-like models

Quantum Networks



Physical Layer:
- Optical fiber
- Satellite laser communication
- Potentially radio frequency

What Can Quantum Networks Do?

Quantum Key Distribution

- Transmission of perfectly secret keys for classical message encryption

Blind Quantum Computing

- Performing quantum computational tasks remotely without giving away the algorithm

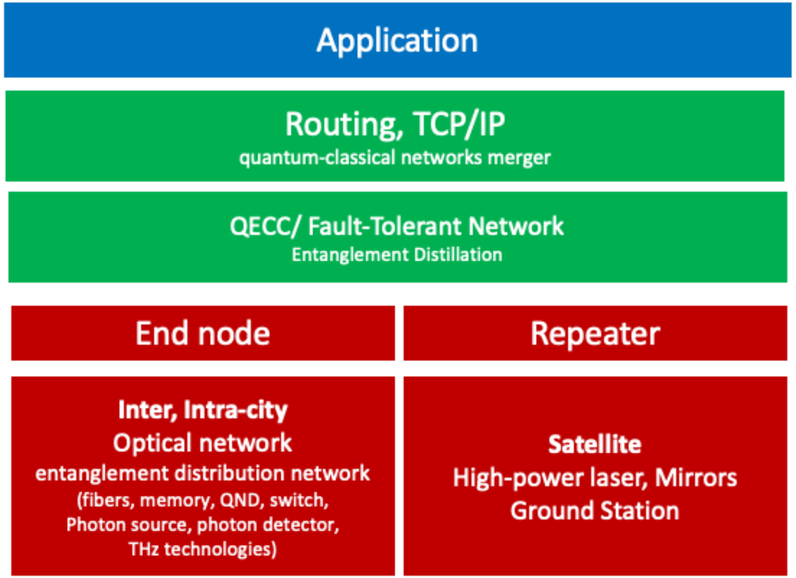
Distributed quantum computing

- Scaling quantum computers up by networking them together

Networked quantum sensors

- Can be used to measure time, magnetic fields, gravity and other phenomena with higher-than-classical sensitivity

Quantum Networking Technology Stack at Cisco



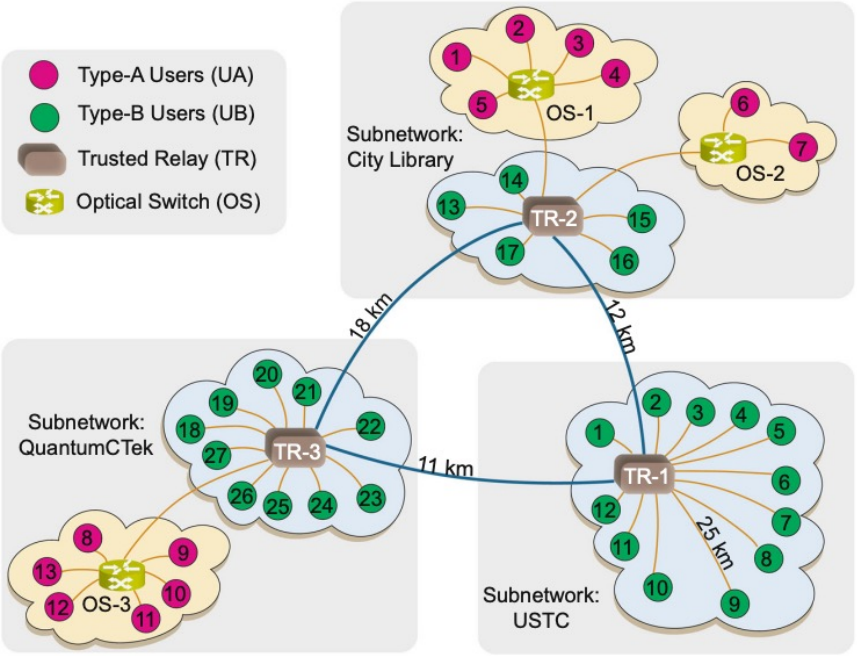
Networking: Protocols and standards, simulation, network control, security

Hardware: Optical routers and switches, repeaters, memory

Existing Quantum Network Designs

Quantum Key Distribution Networks

- Already exist with available optical technology
- Commonly designed to work side-by-side with a classical network
- Used only for quantum key distribution, not a general-purpose network

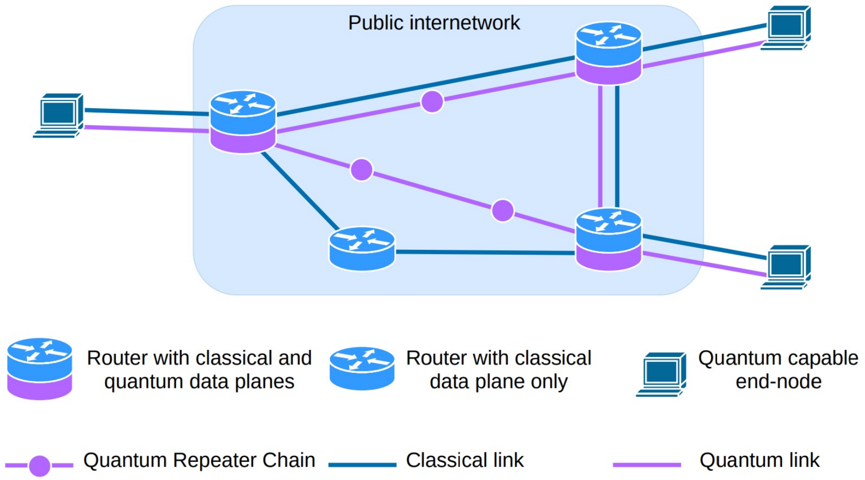


Chen, Teng-Yun, et al. "Implementation of a 46-node quantum metropolitan area network." *npj Quantum Information* 7.1 (2021): 1-6.

Existing Quantum Network Designs

Entanglement-Based Quantum Networks

- Establish an entanglement connection between communication nodes to teleport qubits
- Commonly designed to work side-by-side with a classical network
- Are general-purpose, but require robust entanglement distribution and quantum memory technology (potentially slow rates)



Kozlowski, Wojciech, et al. "Designing a quantum network protocol." *Proceedings of the 16th International Conference on emerging Networking EXperiments and Technologies*. 2020.

Current Quantum Networks

- Seem to be on a road that will not lead to scalability
- Are designed to use static or circuit switching
- Neglect supporting a variety quantum network applications simultaneously in the near(er) term

Design Vision for Quantum Networks

Future quantum networks will integrate with the classical Internet, and should be designed accordingly to "co-exist"

Our Vision of Future Quantum Networks

Universality	Should serve all quantum network applications
Transparency	Should integrate the classical Internet with quantum internet as much as possible
Scalability	Protocols should allow for scalability

Shortcomings of Current Quantum Network Designs

Application Specific

- Quantum key distribution networks only perform quantum key distribution
- Entanglement-based networks are general purpose, but not well suited for direct-transmission-based protocols

Not user-scalable

- Deployed QKD networks rely on static or circuit switching methods that may not be well suited for many users
- Entanglement-based networks work off entanglement distribution and current proposals rely on connection-based transmission protocols

Not integrable enough

- Both QKD and entanglement-based networks are currently not designed to co-exist with classical infrastructure
- Current quantum networks are designed with independent network stacks

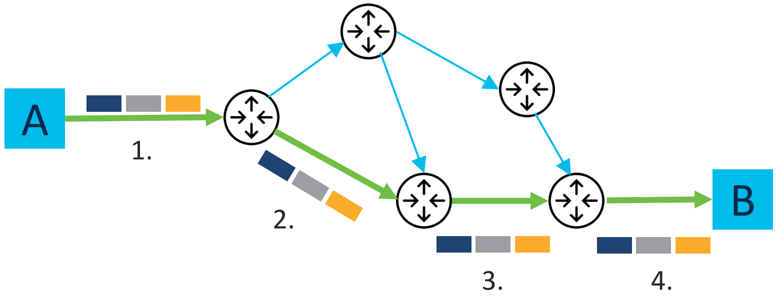
Packet-Switched Quantum Networks

- As a first step, we explore the possibility of performing packet switching in quantum networks and bring to light some of the main challenges for doing so.

- Deploying packet-switched quantum networks is a **long-term vision** with many challenges to firstly overcome. In the near term we will have to make compromises.

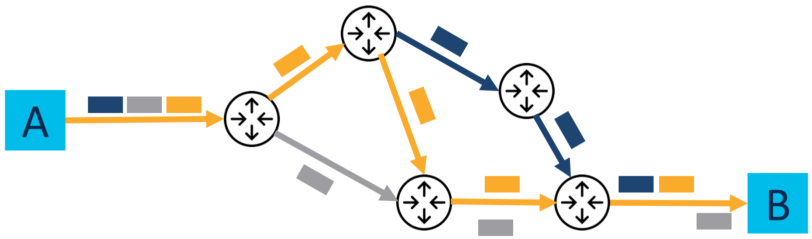
Switching in Communication Networks

Circuit Switching



- Route is reserved
- Frames arrive in order

Packet Switching

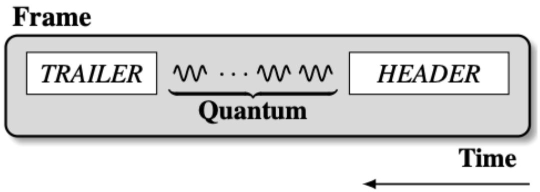


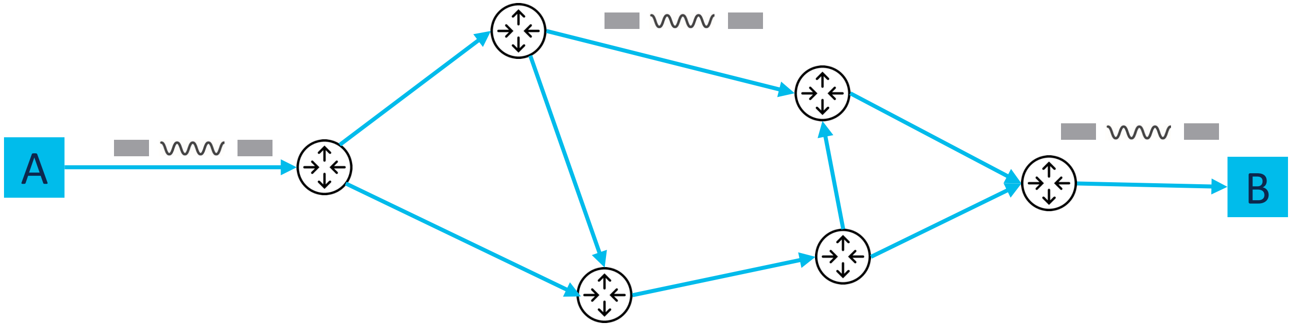
- Route is dynamic
- Frames can arrive out of order

Future Quantum Networks

Packet-Switched Quantum Network

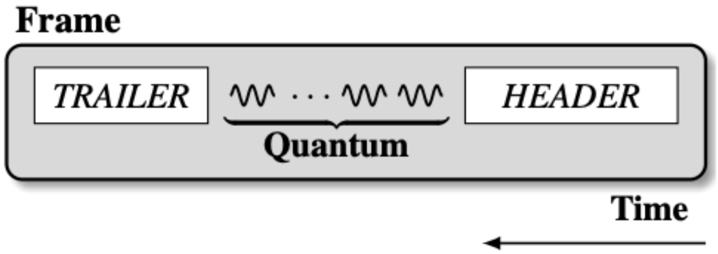
- We propose a quantum network design based on packet switching
- The frames are hybrid classical-quantum data frames





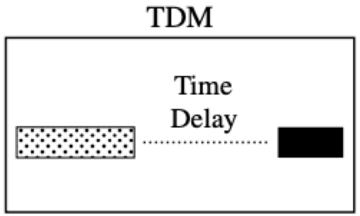
Packet-Switched Quantum Networks

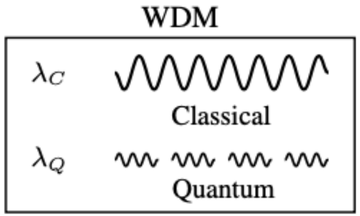
Classical-Quantum Data Frame



- Classical header & trailer
- Quantum payload
- Structured similarly to Ethernet frames

Modulation

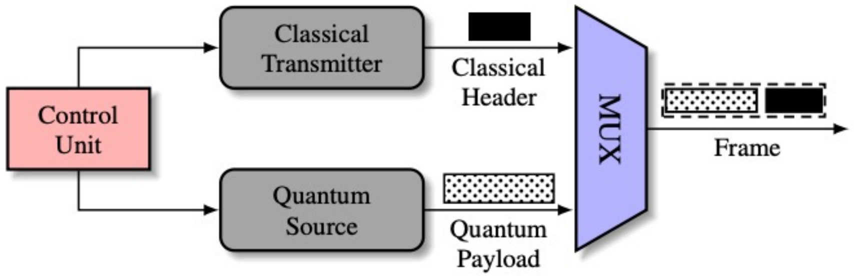




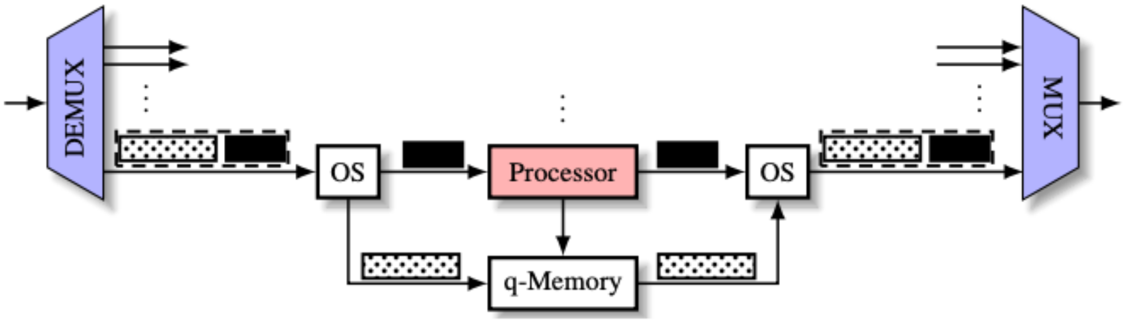
- Multiplexed with time, wavelength, etc.

Packet-Switched Quantum Networks

Frame Generation

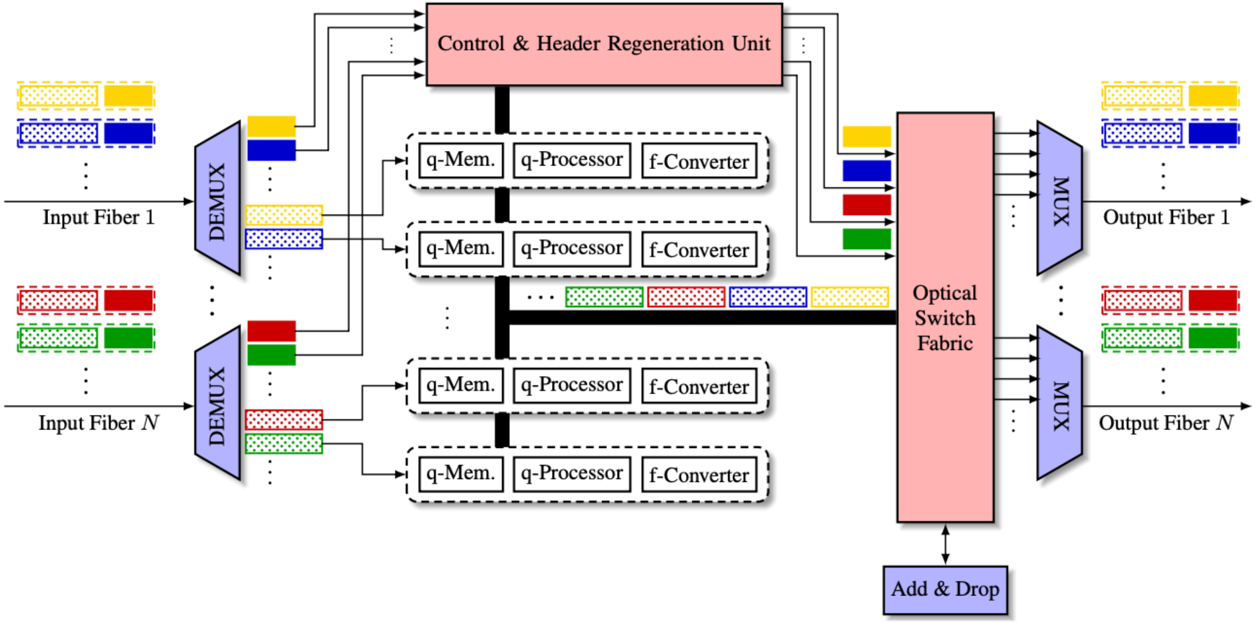


Quantum Switches



Packet-Switched Quantum Networks

Quantum Reconfigurable Optical Add/Drop Multiplexer (Q-ROADM)



Challenges to Overcome

Co-existence Challenges

- All *(deterministic)* signal amplification must be avoided for quantum signals
- Optical hardware must be very low-loss
- Distance limitations of quantum signals require geographically closer switches
- Crosstalk effects (e.g., Raman noise) between strong classical signals and weak quantum signals must be mitigated
- Switching hardware may require special containment to avoid environmental noise

Challenges to Overcome

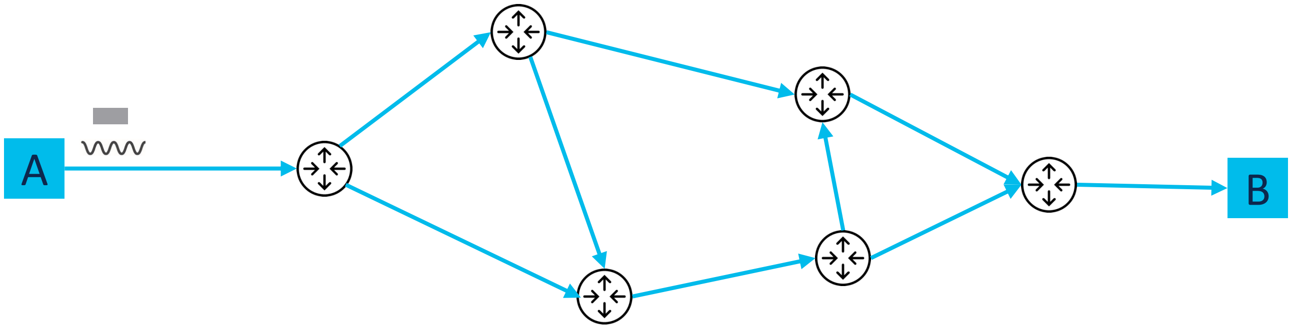
Quantum Network Challenges

- Storing quantum states robustly during classical processing time and queuing
- Quantum error correction for 2^{nd} / 3^{rd} -gen repeaters that work with direct transmission
- Quantum relay and quantum repeater designs and protocols
- Network security

Intermediate Stage Quantum Networks

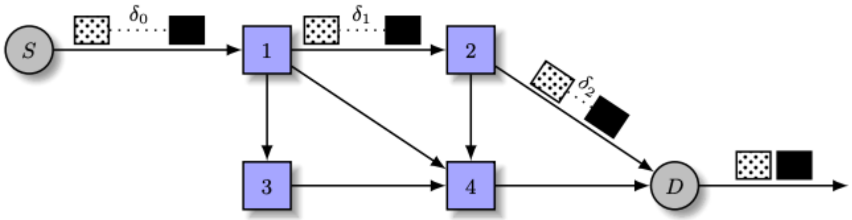
Burst-Switched Quantum Networks

- We can make compromises in an intermediate-stage to still perform some quantum networking tasks, although we lose the general-purpose attribute



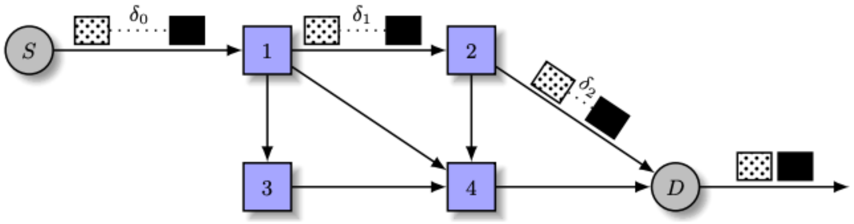
Burst Switching

- Precise classical/quantum transmission scheduling to avoid storing quantum states
- Send control information ahead of the payload “just in time”
- Switching decisions are made before the quantum payload arrives
- With robust quantum memories, transitioning to packet switching becomes possible



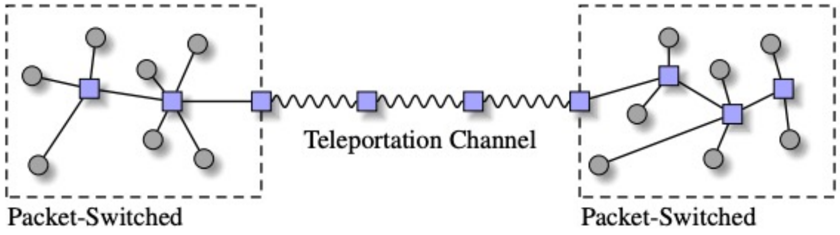
Burst Switching

- Can help to mitigate cross-talk effects
- Determining sufficient ”guard time” between classical and quantum parts can be difficult



Intermediate-Future Quantum Networks

- Dynamic switching can help to scale the number of users, but cannot alone scale distance
- At metropolitan scale, dynamic switching methods can be used with quantum relays
- Dynamic switching can be combined with (potentially first gen) quantum repeaters for long distance applications
- For inter-networking, dynamically-switched sub-networks can be connected via a "*teleportation channel*" forming a **hybrid network**



Applications for Intermediate-Stage Quantum Networks

Suitable applications for intermediate stage quantum networks are those which are loss-tolerant

Quantum key distribution and entanglement distribution meet the criteria

We simulated these two scenarios for a rough benchmark

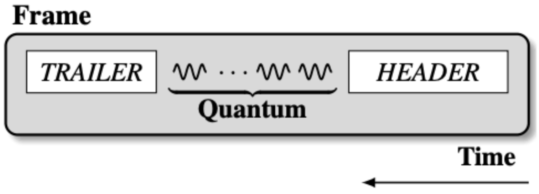
Suitable Quantum Network Applications

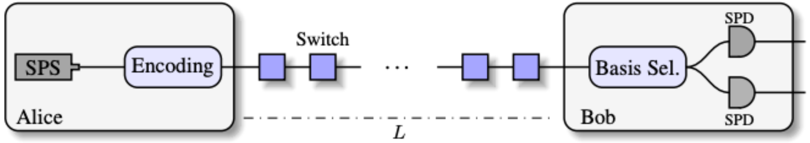
Quantum Key Distribution

- Frames are composed of BB84 states and undergo loss at each switch
- Secret Key Rate:

$$R = K \cdot Q \cdot [1 - f \cdot H_2(e_z) - H_2(e_x)]$$

- K : A node "availability" probability
- Q : The signal yield
- f : the error correction efficiency
- e_z, e_x : The error rates in Z and X basis



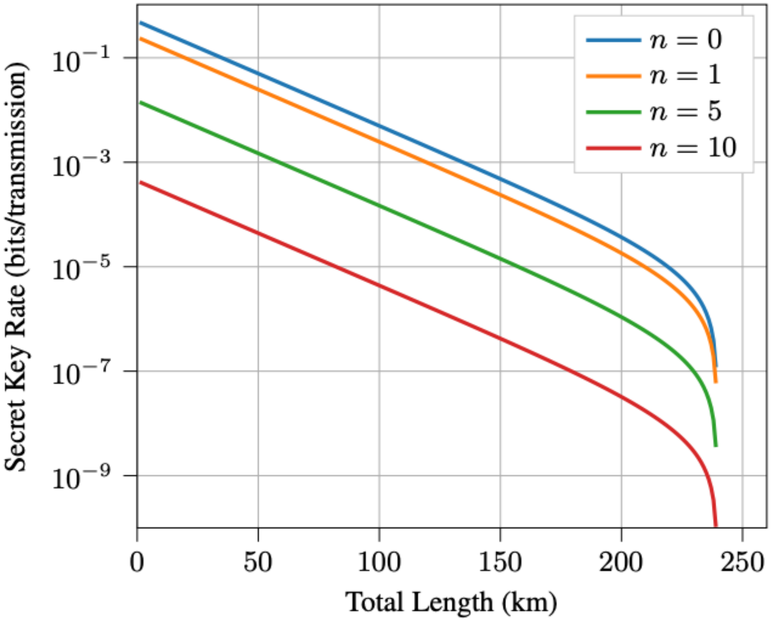


Quantum Key Distribution

$$R = K \cdot Q \cdot [1 - f \cdot H_2(e_z) - H_2(e_x)]$$

Simulation Parameters

- Detector Efficiency: 0.5
- Loss: 0.2 dB/km
- Dark count probability: 10^{-6}
- $f = 1.15$
- $K = P^n \frac{T_Q - nT_P}{T_Q}$, all switches available
- $P = 0.5$, availability rate
- $T_Q = 100 \cdot T_P$, the temporal length of the frame
- T_P, the frame processing time



Suitable Quantum Network Applications

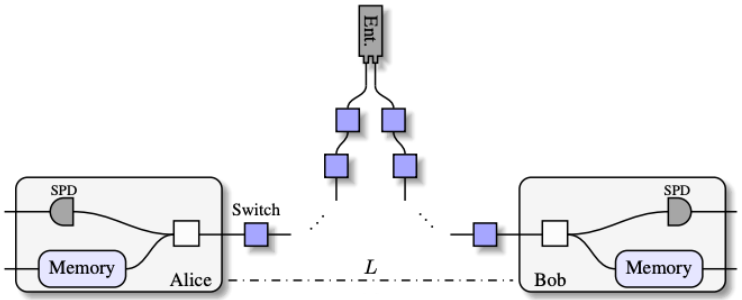
Entanglement Distribution

- We simulate the distribution of the 2-qubit entangled state

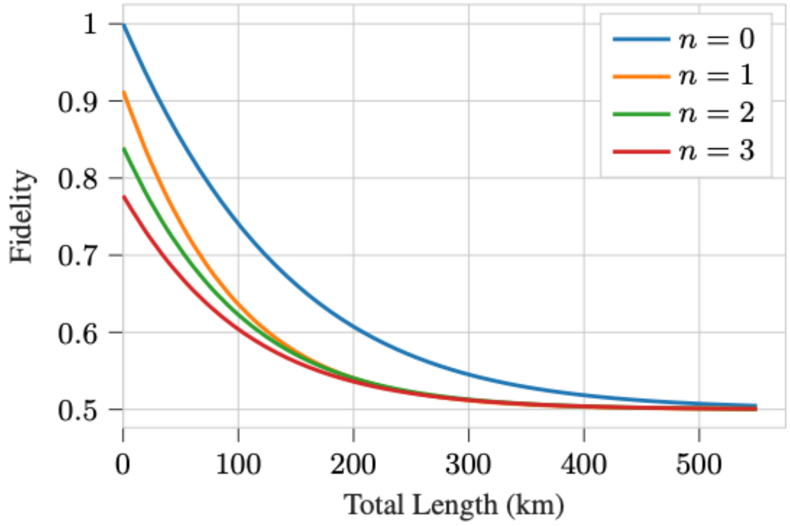
$$|\Psi\rangle = {}^{1}/_{\sqrt{2}}\ (|00\rangle + |11\rangle)$$

- We use quantum network simulator NetSquid to simulate a burst-switched-based entanglement distribution protocol
- We assume the nodes have noisy quantum memories and can store qubits
- We assume the quantum channel has length-dependent depolarizing noise
- We measure the output fidelity

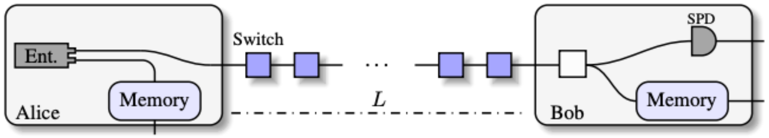
Entanglement Distribution

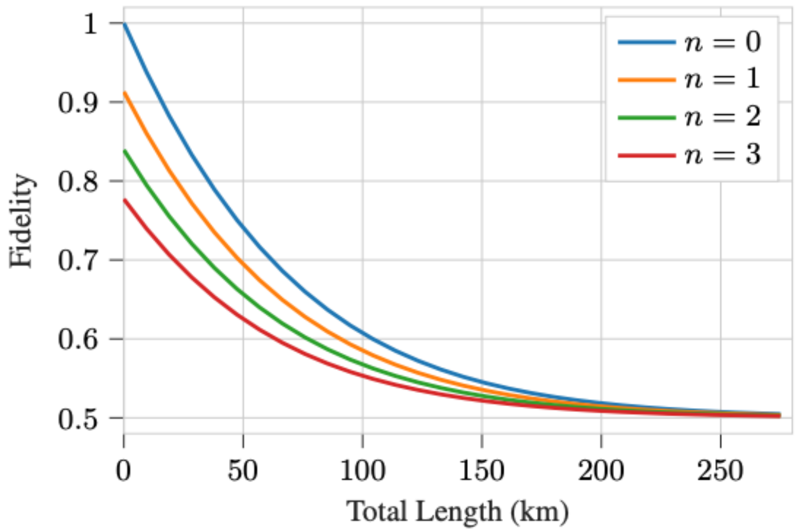


$$F(\rho) := \left(\mathrm{Tr}\sqrt{\sqrt{\rho}\,|\Psi\rangle\langle\Psi|\,\sqrt{\rho}}\right)^2$$



Entanglement Distribution





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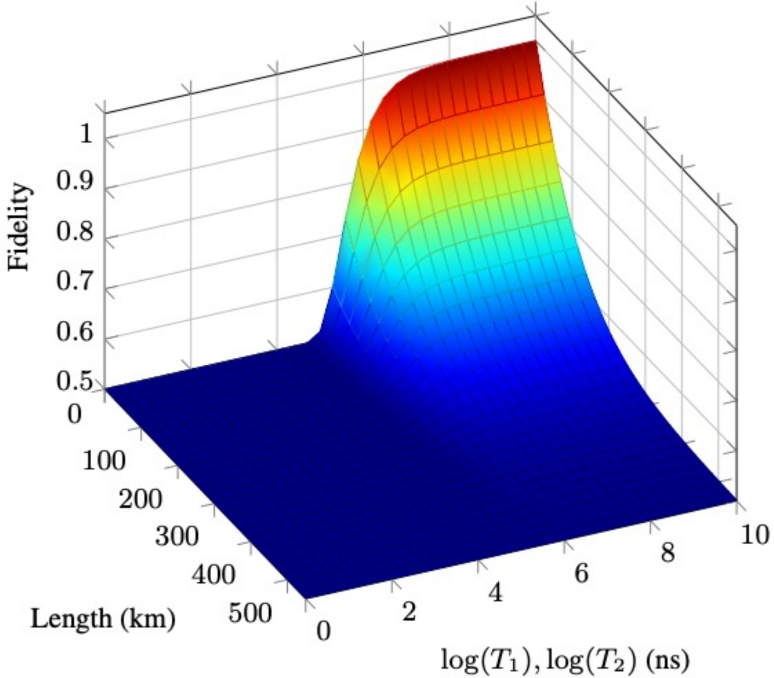
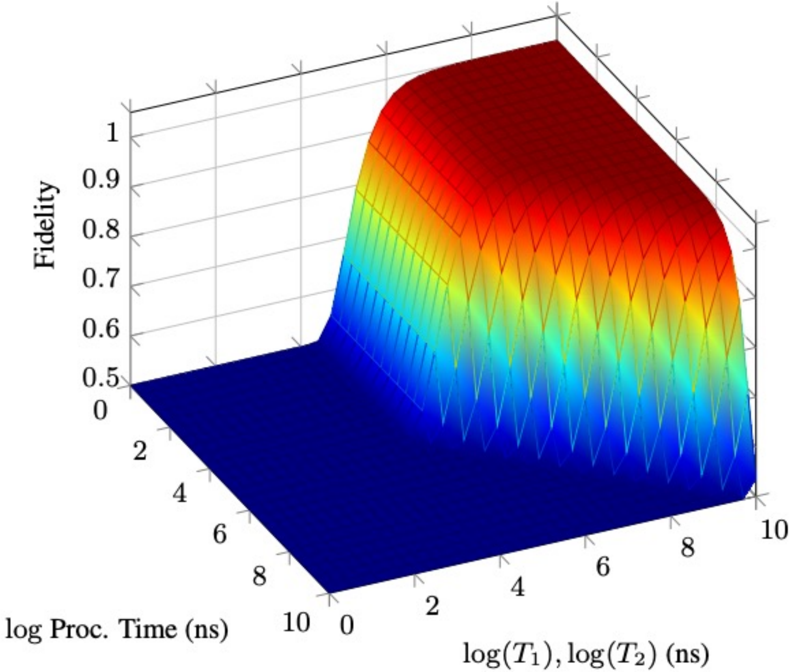
Entanglement Distribution





Open Problems

- **Cross-talk:** How to design a network and protocols for co-existent data transmissions to minimize cross-talk effects between classical and quantum signals over the same fiber? When is it beneficial to share the same fiber?
- **Analysis:** What are the scenarios in which packet-switched quantum network outperforms the other designs? By what metrics?
- **Frame generation:** How do we choose the optimal guard time for burst switching? Can we reduce header processing time? What is the frame metadata?
- **Many more…**

Outlook

- If we expect quantum networks to be widely used, then we better start thinking about user-scalability

- Hybrid approaches using a mixture of network designs and concepts (as is done in classical wide-area networks) can be a viable direction for supporting more users and applications

- Other perspective: *Designing tomorrow's quantum internet*
  - Munro, William J., Nicolo'Lo Piparo, Josephine Dias, Michael Hanks, and Kae Nemoto. "Designing tomorrow's quantum internet." *AVS Quantum Science* 4, no. 2 (2022): 020503.

Conclusion

- Packet switching in quantum networks can be a viable means for scaling quantum networks up in users
- Burst-switching in quantum networks can be used to avoid storage
- Packet-switched quantum networks may lead to better quantum network utilization, but will require various hardware innovations
- Intermediate-future quantum networks can merge packet-switched and entanglement-based networks to scale in distance and in number of users

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Thank you for your attention

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