The bridge to possible

Packet Switching in Quantum Networks: A Path to Quantum Internet

Stephen DiAdamo

Cisco Systems

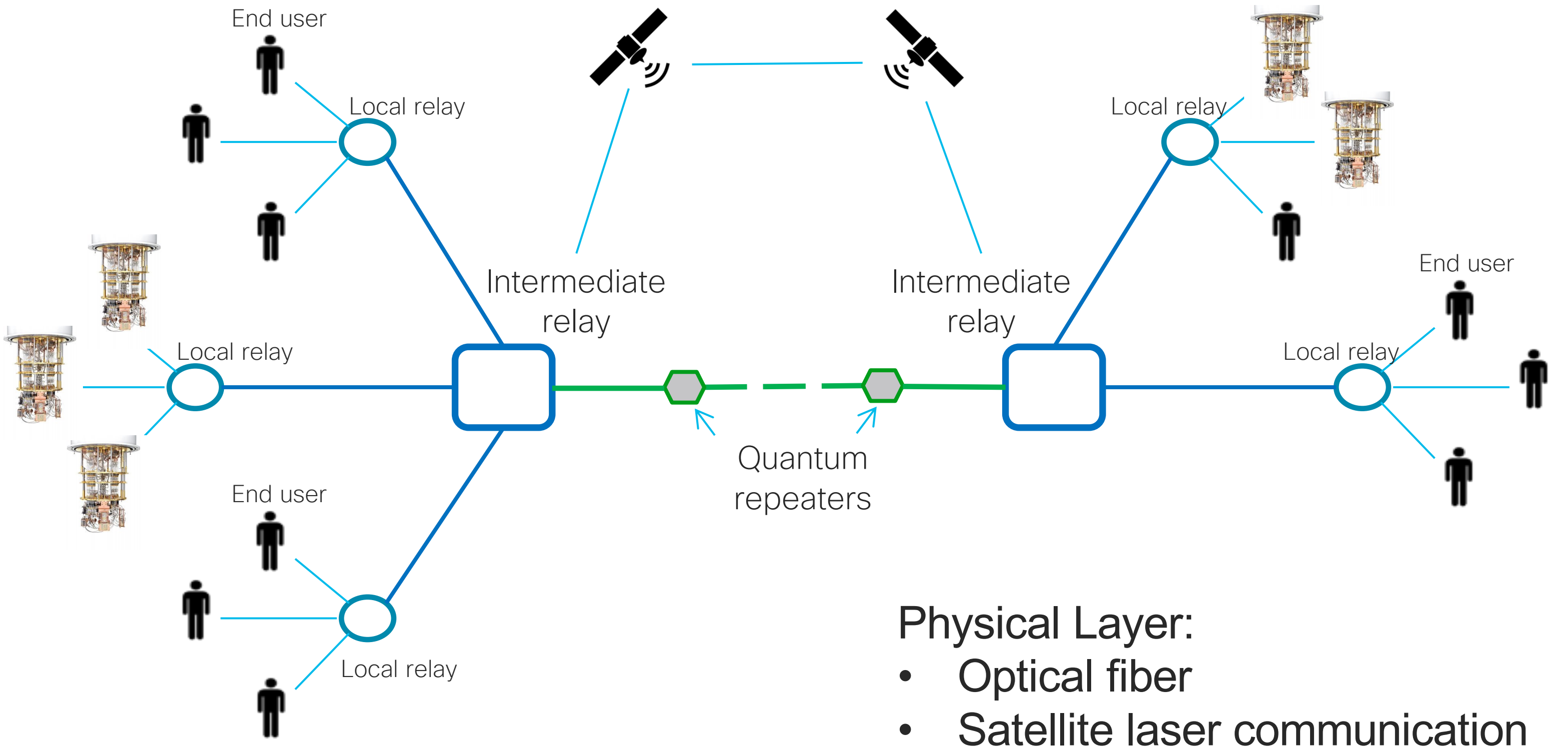
ITU, Future technology trends towards 2030

July 25, 2023

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. Challenges for near(er)-term quantum networks
5. Applications for near-term quantum networks
6. Outlook and Summary

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 without giving away the algorithm

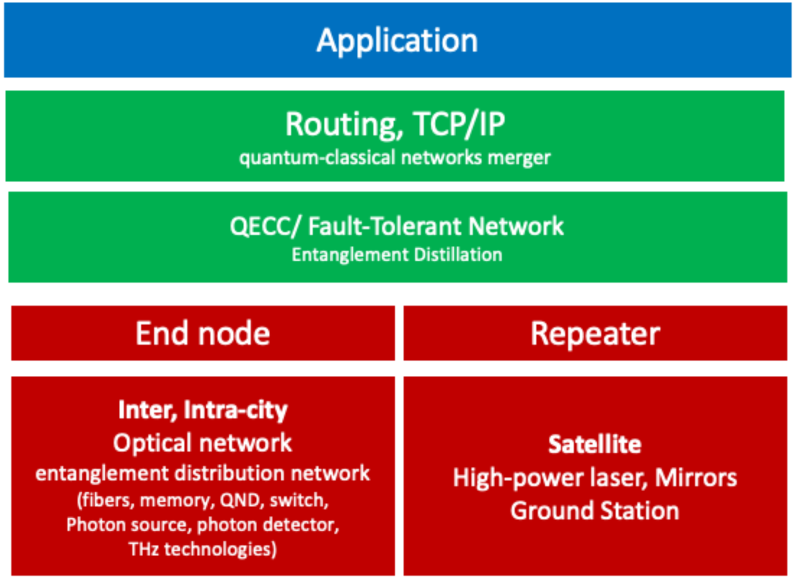
Distributed quantum computing

- Scaling quantum computers up by networking them together

Networked quantum sensors

- Can be used to measure time, physical phenomena with higher sensitivity

Quantum Networking Technology Stack



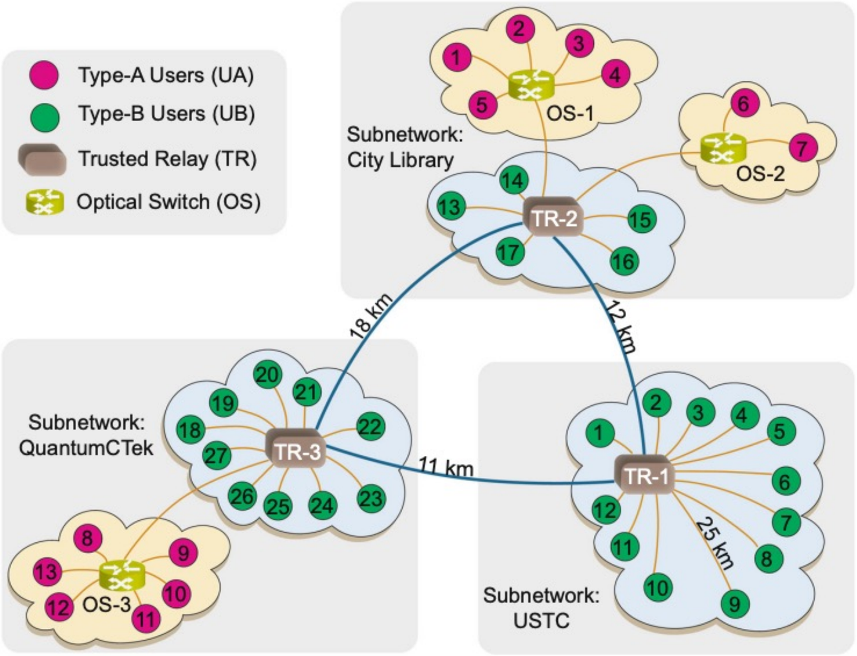
Networking: Protocols and standards, simulation, network control, security

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

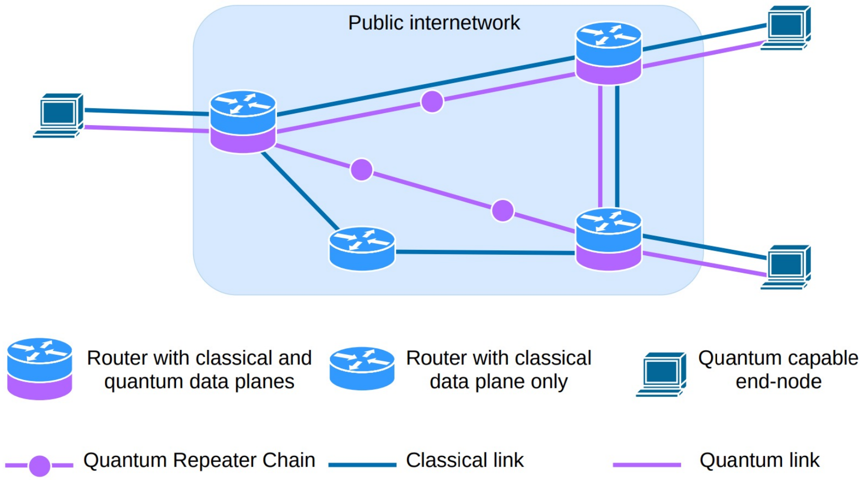


Chen, Teng-Yun, et al. "Implementation of a 46-node quantum metropolitan area network." *npj Quantum Information* 7.1 (2021): 1-6.

Existing Quantum Network Designs

Entanglement-Based Quantum Networks

- Establish an entanglement connections to teleport qubits
- Commonly designed to work side-by-side with a classical network
- Are general-purpose, but require robust entanglement distribution



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 many quantum network applications simultaneously in the near term

Design Vision for Quantum Networks

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

Co-existence networks

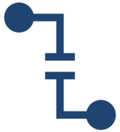
Our Vision of Future Quantum Networks

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

Not user-scalable



Not integrable enough with classical

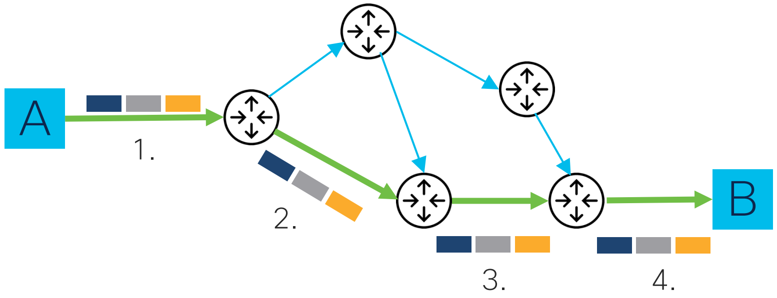
Packet-Switched Quantum Networks

- 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.

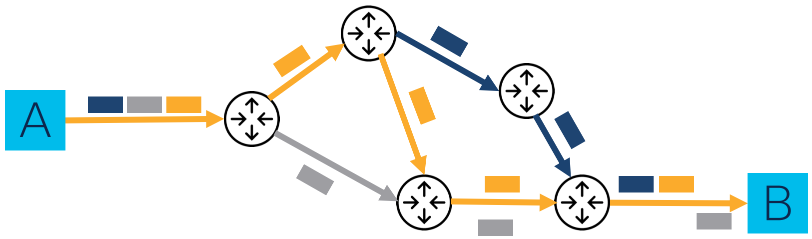
Switching in Communication Networks

Circuit Switching



- Route is reserved
- Frames arrive in order

Packet Switching

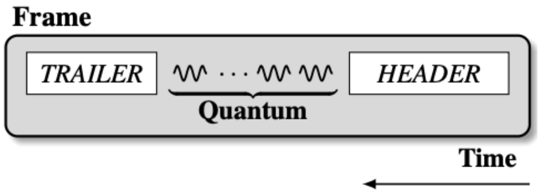


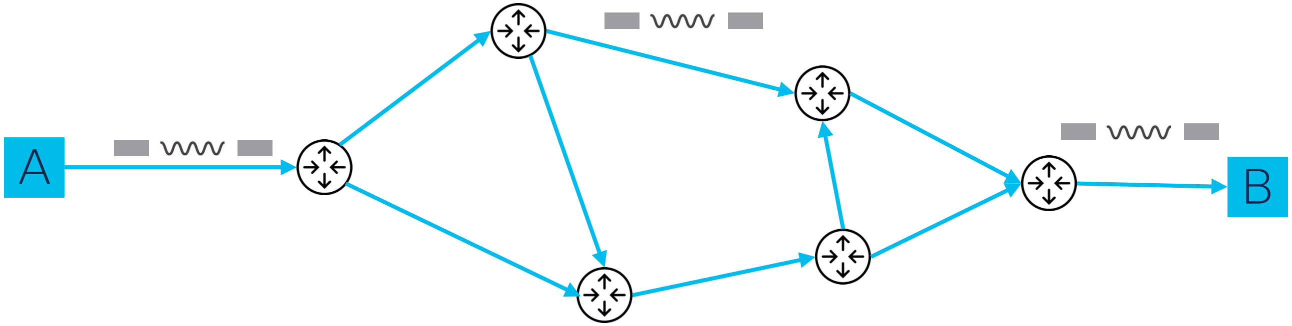
- Route is dynamic
- Frames can arrive out of order

Future Quantum Networks

Packet-Switched Quantum Network

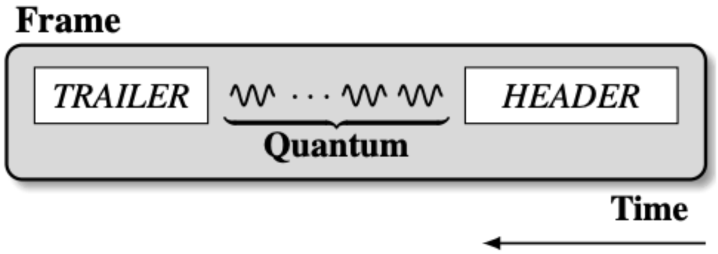
- We propose a quantum network design based on packet switching
- The frames are hybrid classical-quantum data frames





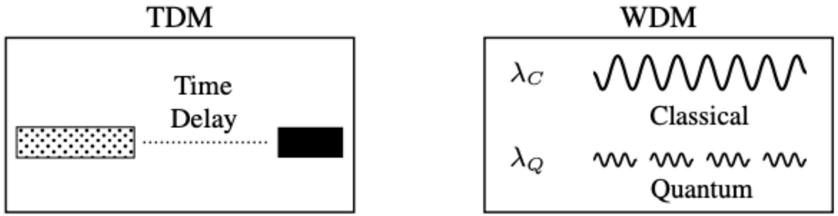
Packet-Switched Quantum Networks

Classical-Quantum Data Frame



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

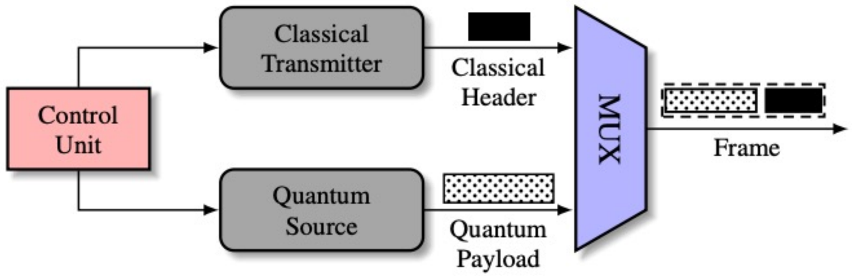
Modulation



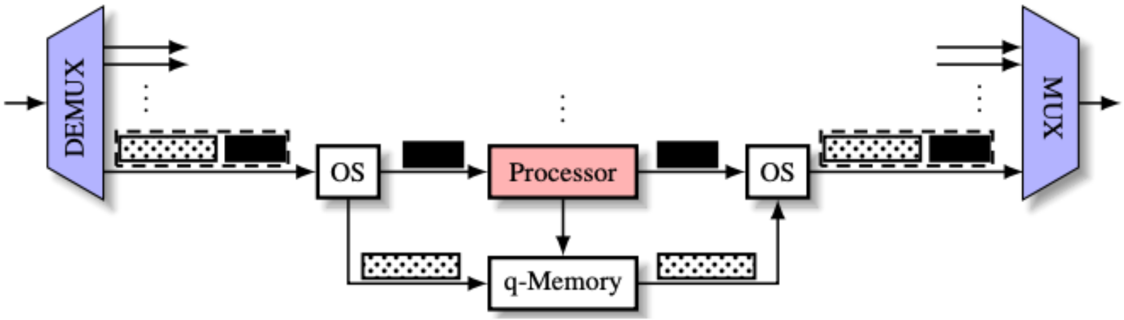
- Multiplexed with time, wavelength, etc.

Packet-Switched Quantum Networks

Frame Generation



Quantum Switches



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 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

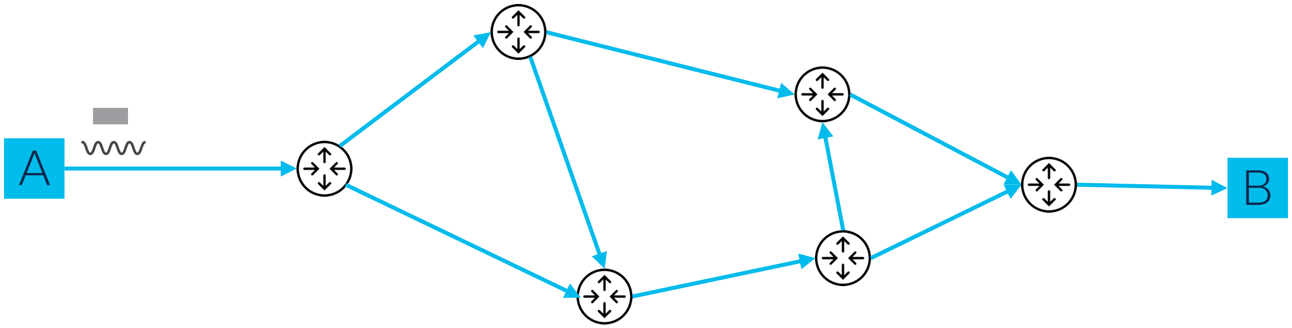
Quantum Network Challenges

- 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

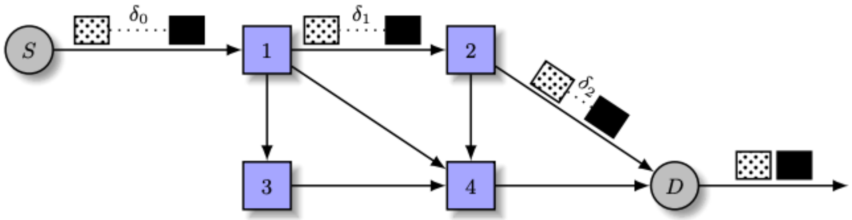
Burst-Switched Quantum Networks

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



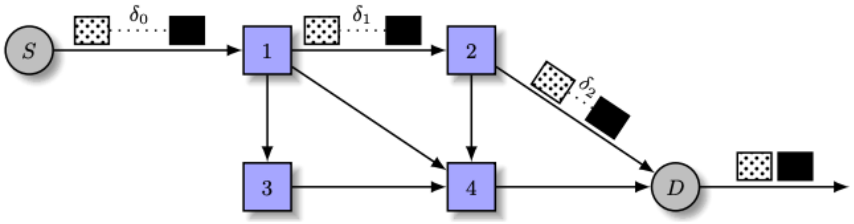
Burst Switching

- 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



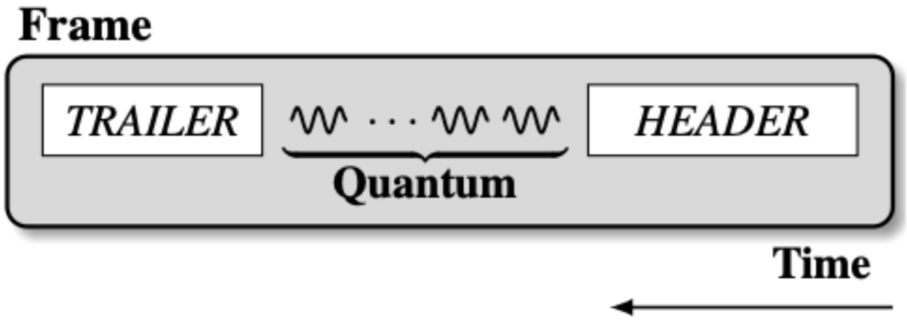
Applications for Intermediate-Stage Quantum Networks

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

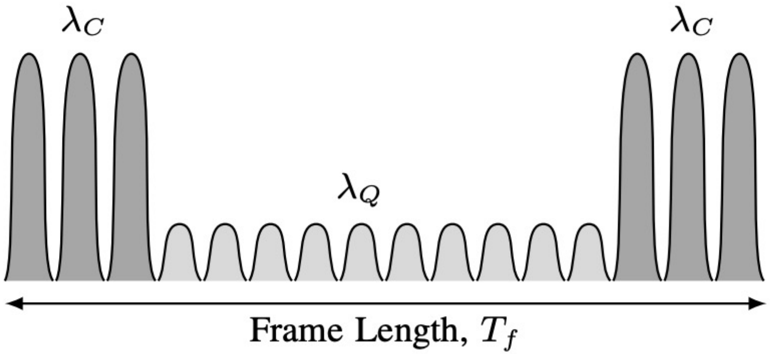
Quantum key distribution and entanglement distribution meet the criteria

We simulated these two scenarios for a rough benchmark

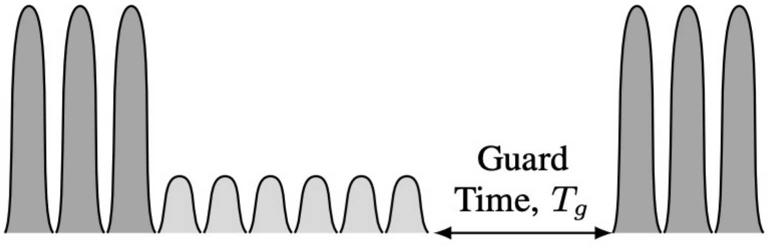
Implementation



- Quantum payload can be any quantum state
  - QKD qubits encoding classical information
  - Parts of entangled



(a)



(b)

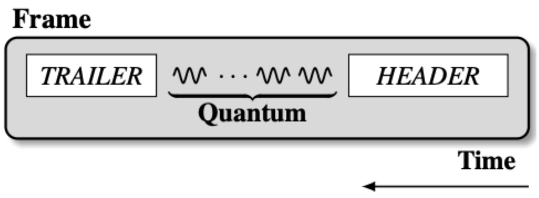
Suitable Quantum Network Applications

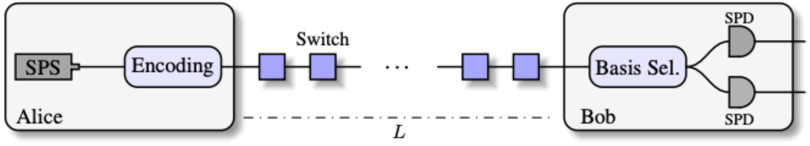
Quantum Key Distribution

- 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



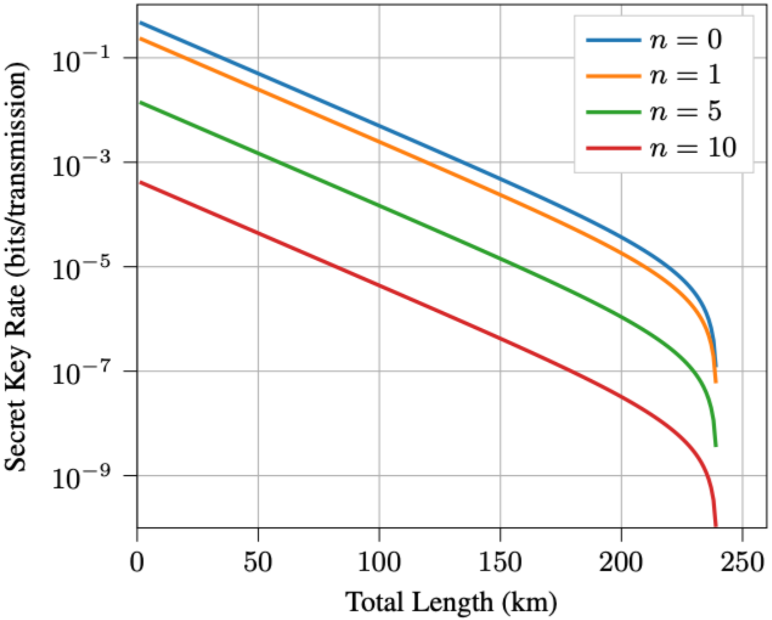


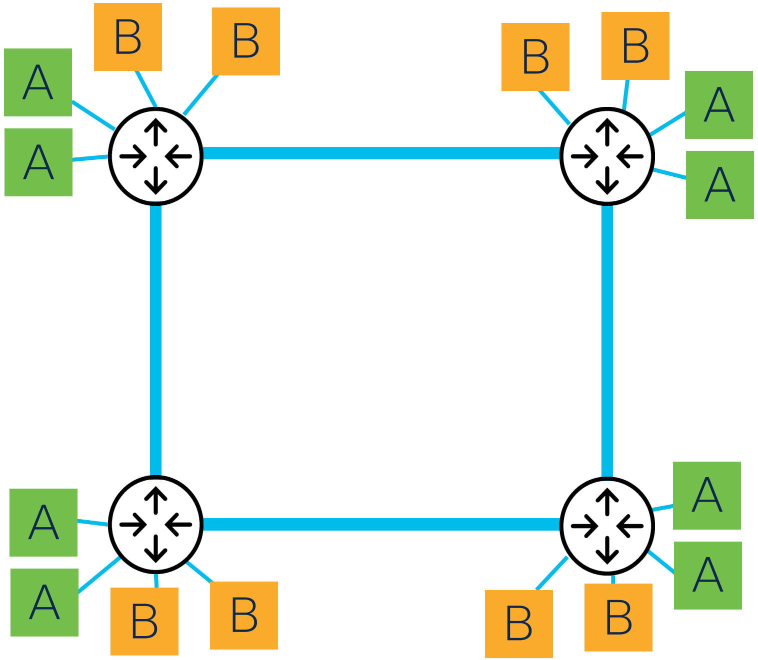
Quantum Key Distribution

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

Simulation Parameters

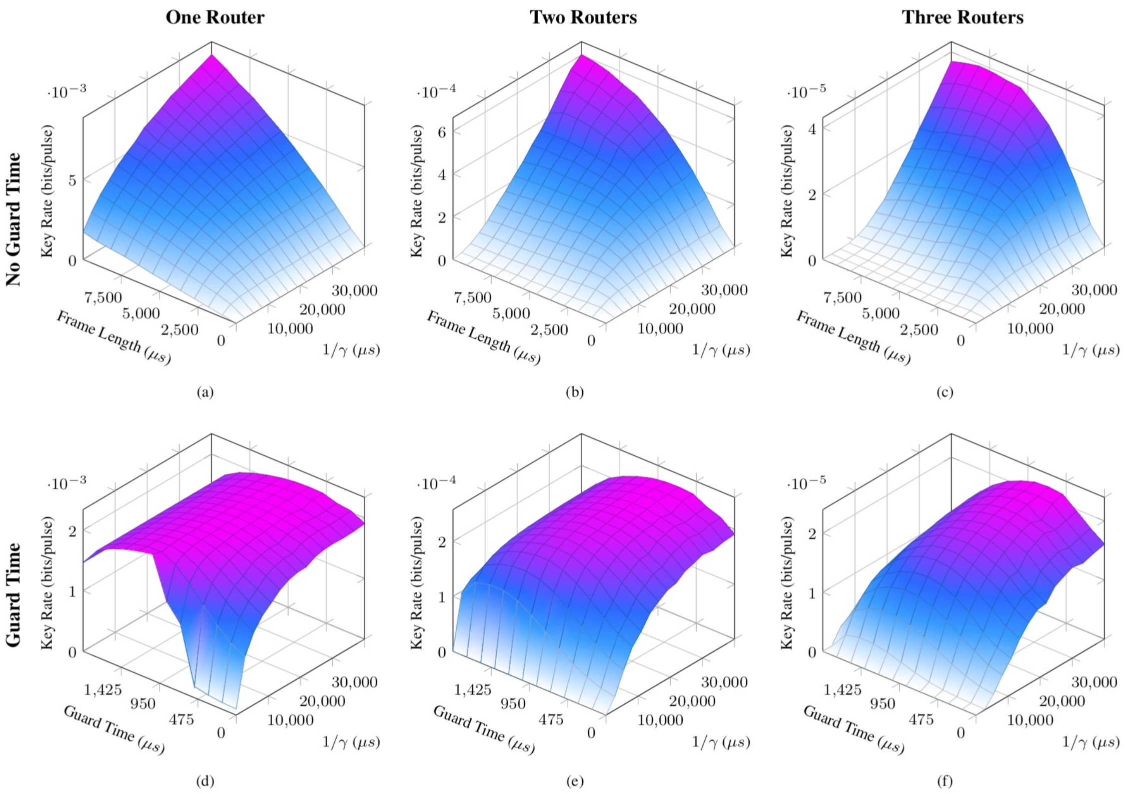
- Detector Efficiency: 0.5
- Loss: 0.2 dB/km
- Dark count probability: 10^{-6}
- $f = 1.15$
- $K = P^n \frac{T_Q - nT_P}{T_Q}$, all switches available
- $P = 0.5$, availability rate
- $T_Q = 100 \cdot T_P$, the temporal length of the frame
- T_P, the frame processing time





Mandil, DiAdamo, Qi, and Shabani. arXiv preprint arXiv:2302.14005 (2023).

Packet-Switched QKD Networks



Packet-Switched QKD Networks

- Practical key rates may be achieved without any optical storage
- Limited storage time in a fiber delay line can enhance performance
- QKD in a packet-switched network is feasible with today's technology!

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

Stephen DiAdamo

Contact:
sdiadamo@cisco.com

arXiv: 2205.07507

Thank you for your attention

- Bing Qi,
- Reem Mandil
- Glen Miller,
- Ramana Kompella, and
- Alireza Shabani

The bridge to possible