OIST

Lecture 4: Quantum Networks and the internet

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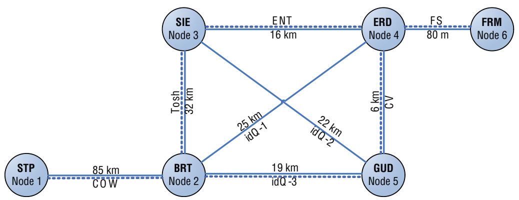
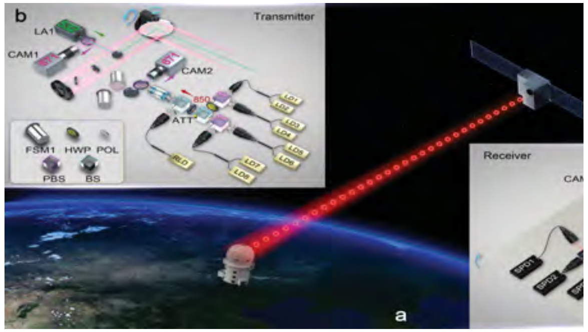
Where are we?

Range/rate limited?

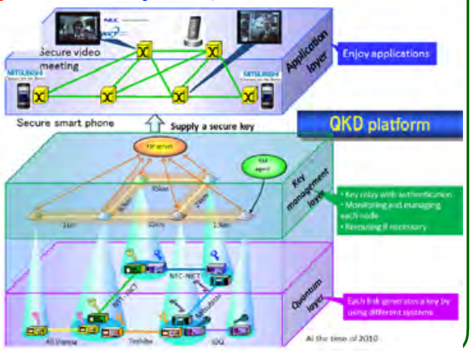
SECOQC - EU network inVienna



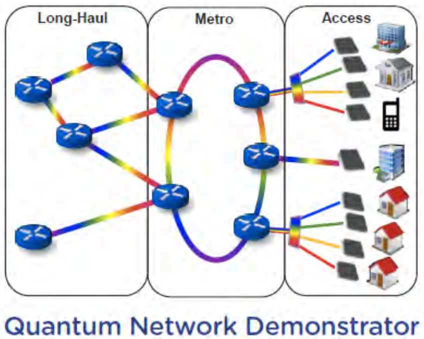
China - Q Networking satellite



Japan - Tokyo QKD network



UK - Quantum Communications Hub



Quantum Key Distribution is being tested!!!

Global Quantum Internet

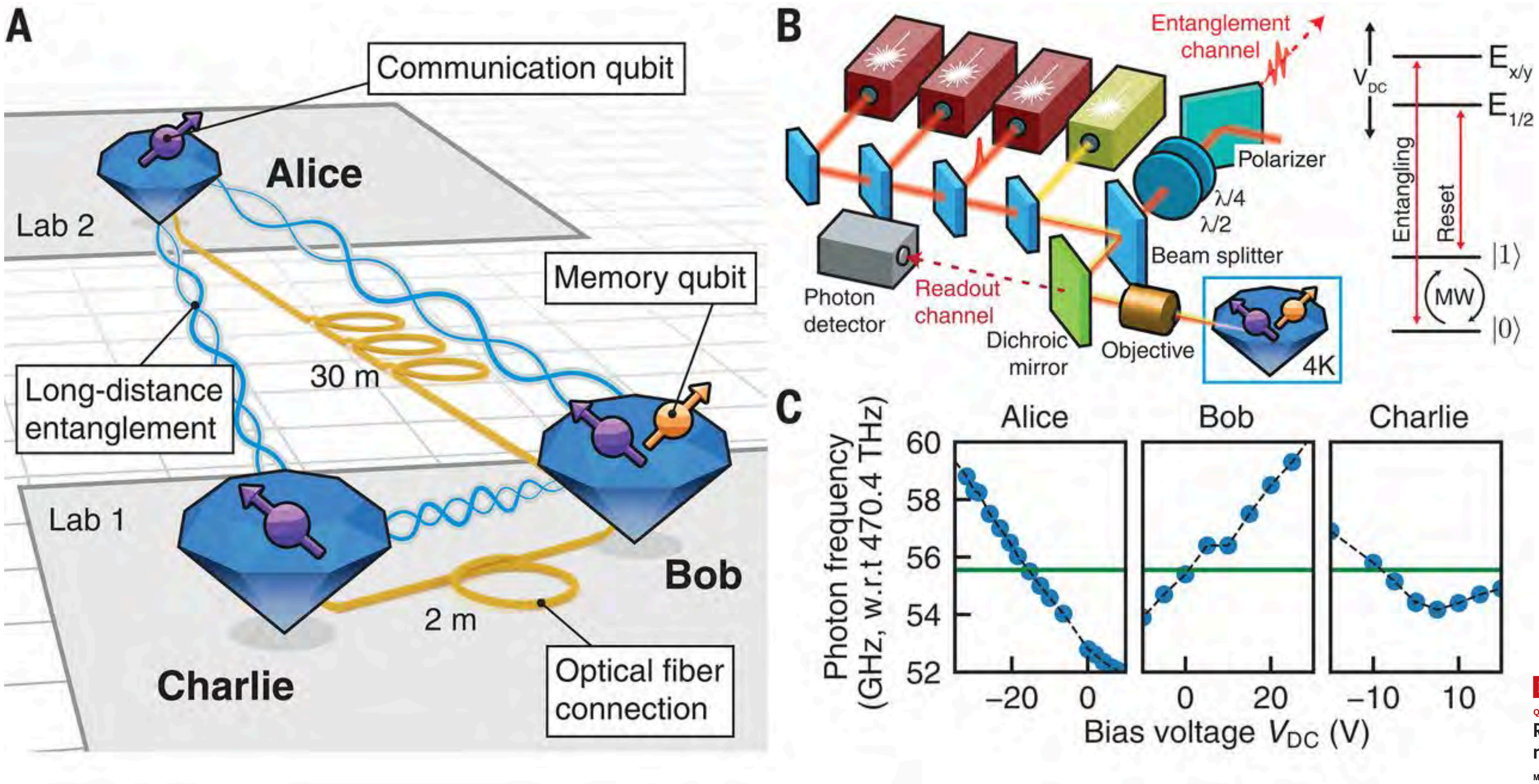
How?

N. Gisin et. al. *Nature Photon. 1,* 165 (2007)
H. J. Kimble, 453,1023 (2008)
W. J. Munro et. al, Nature Photonics 6, 777 (2012).
K. Azuma et. al, Nature Commun. 6, 10171 (2015).

Quantum Communications is much more than QKD

Small scale quantum networks

The beginning our tomorrow internet: a 3 node network



Pompili *et al.*, *Science* **372**, 259–264 (2021)

RESEARCH ARTICLE

QUANTUM NETWORKS

Realization of a multinode quantum network of remote solid-state qubits

M. Pompili[1,2]†, S. L. N. Hermans[1,2]†, S. Baier[1,2]†‡, H. K. C. Beukers[1,2], P. C. Humphreys[1,2]§, R. N. Schouten[1,2], R. F. L. Vermeulen[1,2], M. J. Tiggelman[1,2]¶, L. dos Santos Martins[1,2], B. Dirkse[1,2], S. Wehner[1,2], R. Hanson[1,2]*

Small scale quantum networks

LETTERS
PUBLISHED ONLINE: 19 SEPTEMBER 2016 | DOI: 10.1038/NPHOTON.2016.180
nature photonics

Quantum teleportation across a metropolitan fibre network

Raju Valivarthi[1†], Marcel.li Grimau Puigibert[1†], Qiang Zhou[1†], Gabriel H. Aguilar[1†], Varun B. Verma[2], Francesco Marsili[3], Matthew D. Shaw[3], Sae Woo Nam[2], Daniel Oblak[1] and Wolfgang Tittel[1*]

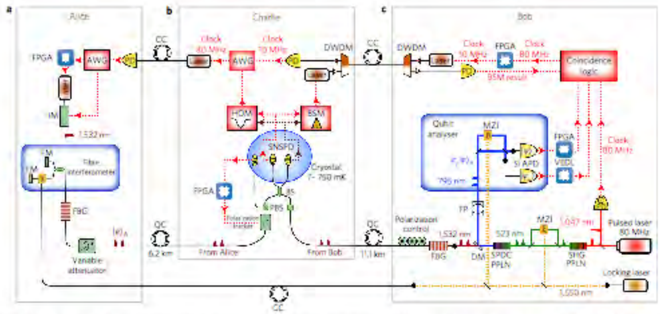


Figure 2 | Schematics of the experimental set-up. a, Alice's set-up. An intensity modulator (IM) tailors 20-ps-long pulses of light at an 80 MHz rate out of

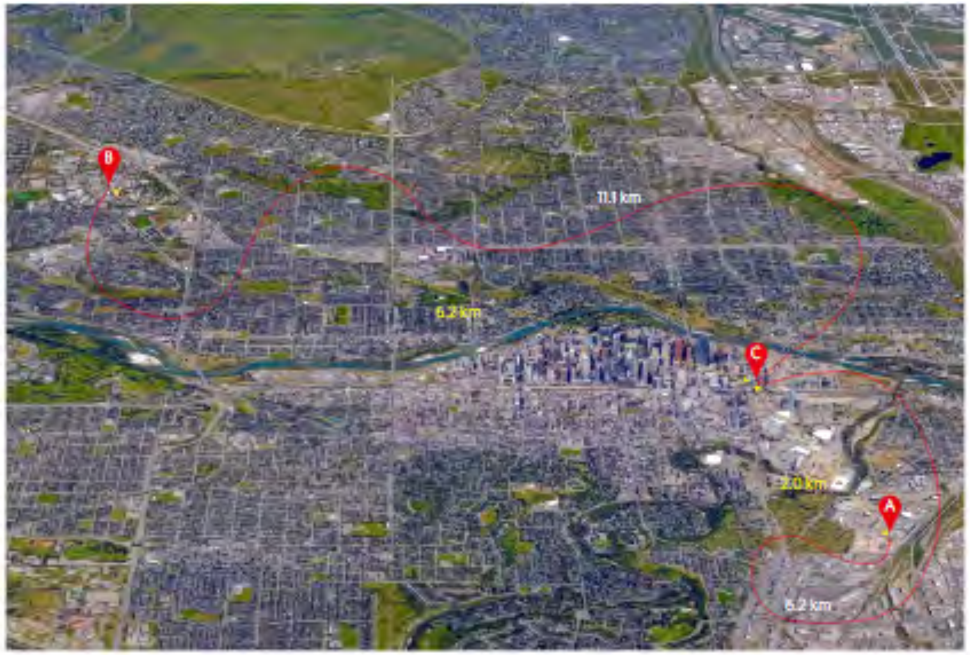
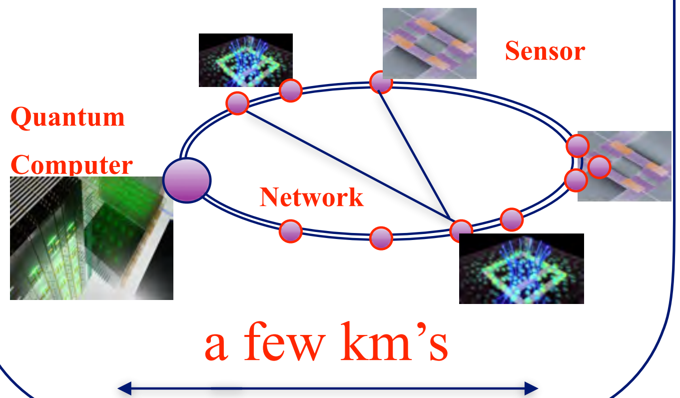


Figure 1 | Aerial view of Calgary. Alice 'A' is located in Manchester, Bob 'B' at the University of Calgary and Charlie 'C' in a building next to City Hall in Calgary downtown. The teleportation distance—in our case the distance between Charlie and Bob—is 6.2 km. All fibres belong to the Calgary telecommunication network but, during the experiment, they only carry signals created by Alice, Bob or Charlie and were otherwise 'dark'. Imagery ©2016 Google. Map data ©2016 Google.

Applications of Quantum Networks

Quantum Edge Computing

- Initial quantum networks will only be able to distribute physically encoded quantum resources over short distances
- Quantum communication will be a bottleneck
- Need to keep our quantum processing and storage as close to possible to the edge nodes in the network where it is generated



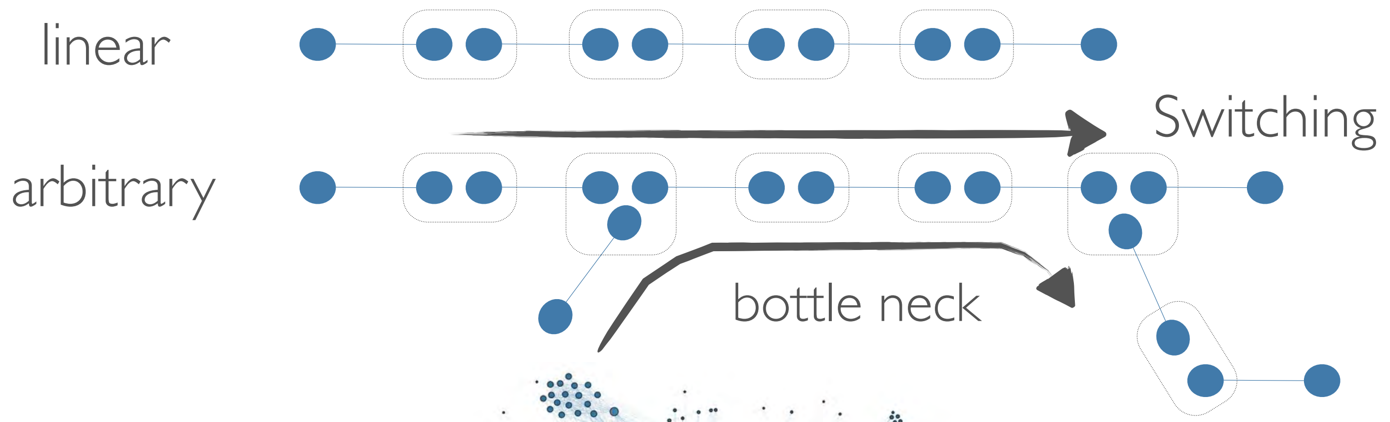
- Quantum Key Distribution (QKD)
- Distributed quantum computing
- Quantum-enhanced sensing
- …

Core Challenges

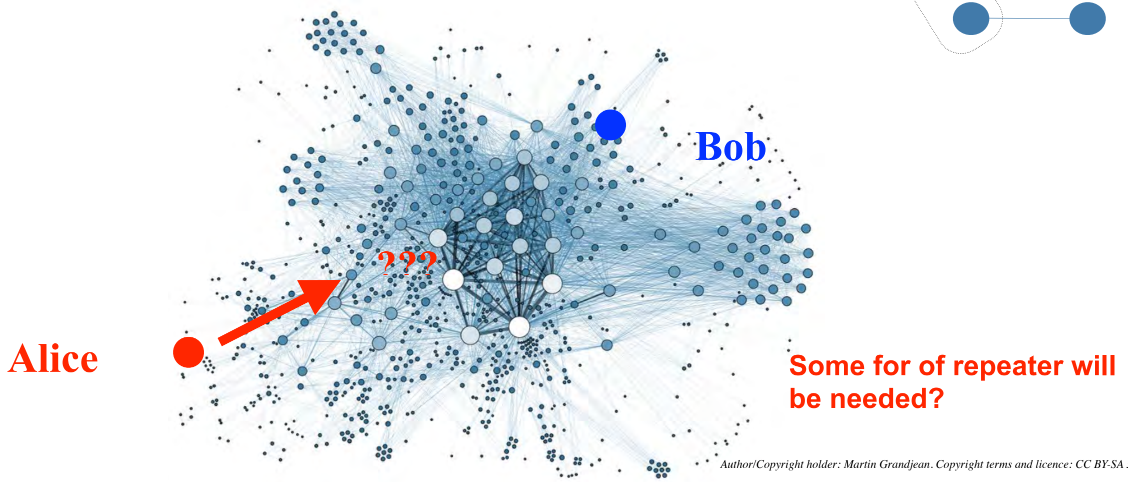
- Entanglement Distribution Over Distance
- Reliable Quantum Memories??
- Synchronization and Timing (Quantum buffers)
- Error Correction at Scale
- Interoperability and Standards

Quantum Networks

We really need to consider how our quantum networks will operate in this environment



Planetary



- For large scale networks (Quantum cloud) **Alice and Bob** may not know the exact path that connects them.

The **OSI Model** (Open Systems Interconnection model)

Quantum Network Layers

Layer 7: Application
(User interface, apps)

Layer 6: Presentation
(Data formatting, encryption, etc.)

Layer 5: Session
(Sessions, dialogs)

responsible for **establishing, managing, and terminating sessions** between two communicating devices or applications

Layer 4: Transport
(Reliable delivery, segmentatio, ports)

ensures **reliable or fast delivery of data** between devices and applications across a network

Layer 3: Network
(Routing, IP addressing)

responsible for **routing packets across multiple networks**

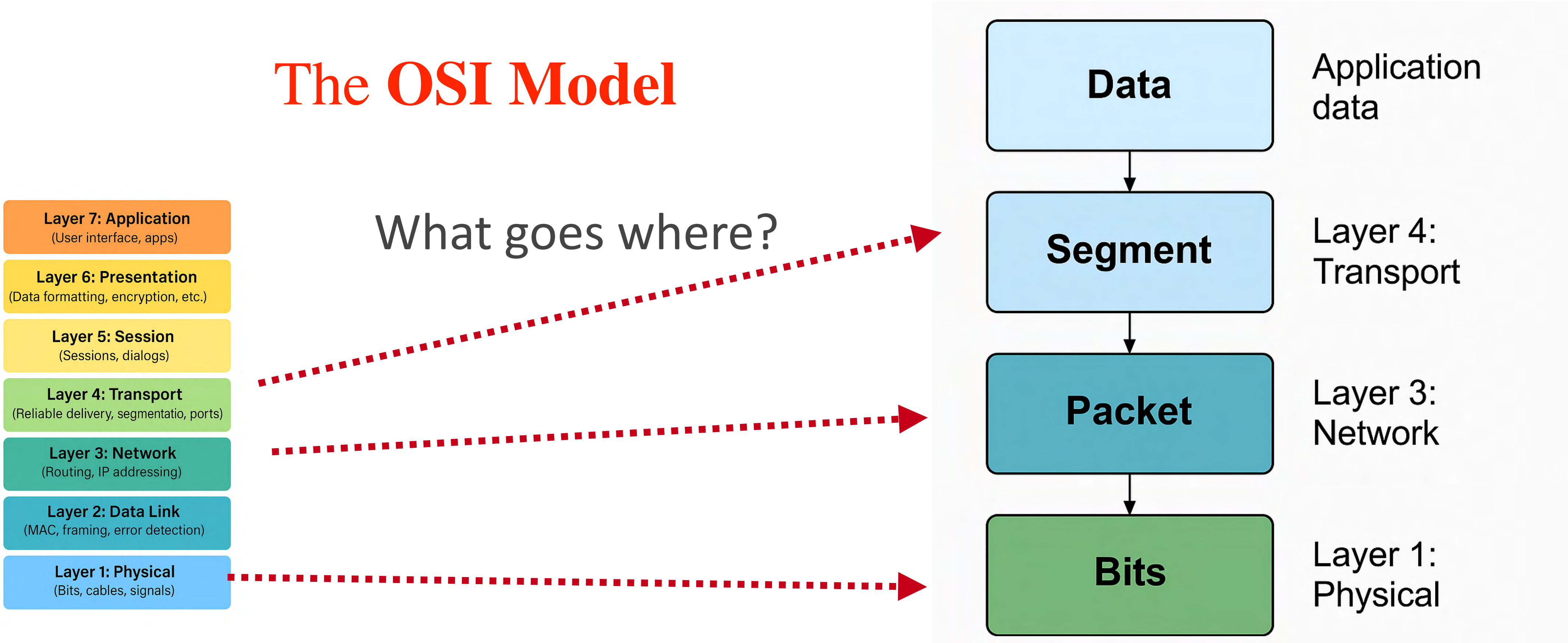
Layer 2: Data Link
(MAC, framing, error detection)

responsible for **node-to-node data transfer** and for ensuring reliable transmission **within a local network segment**

Layer 1: Physical
(Bits, cables, signals)

responsible for **transmitting raw bits over a physical medium**

Quantum Network Layers



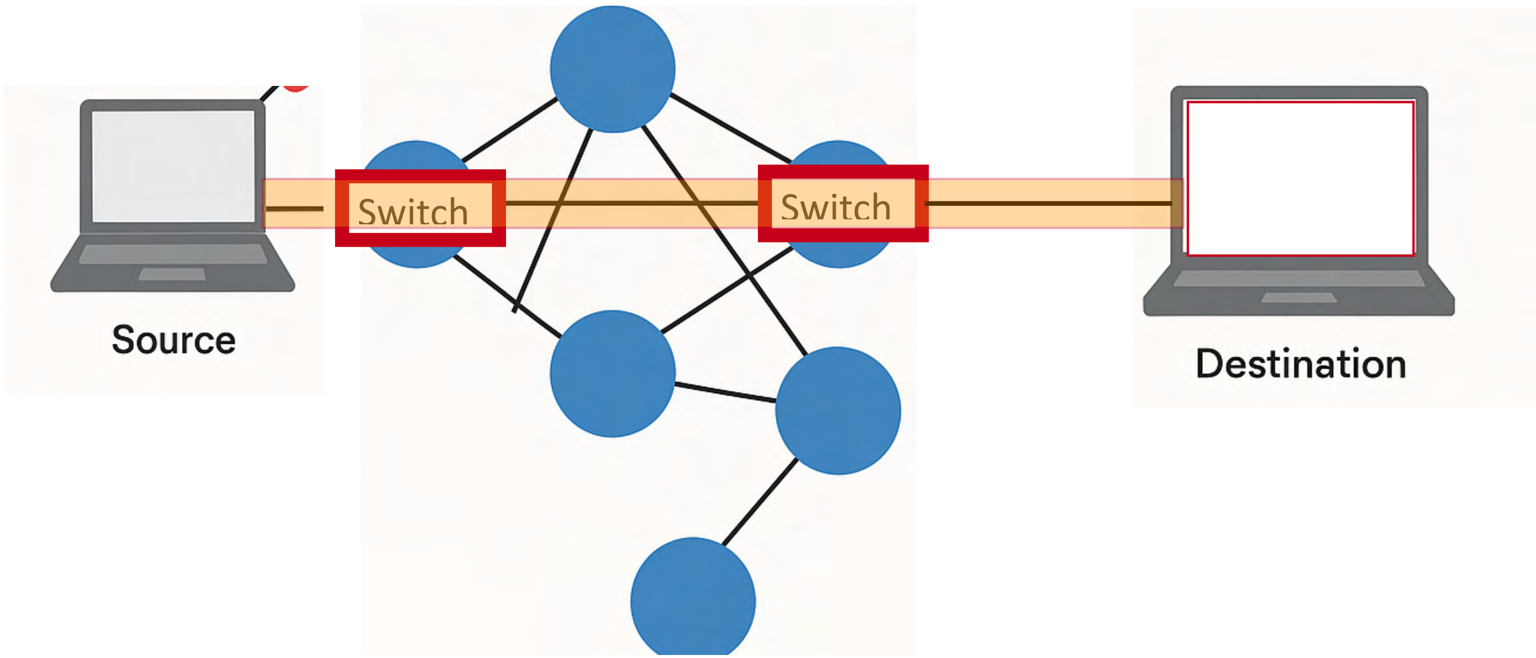
packet: a unit of data used for communication over a network. It contains both the **payload (actual data)** and **control information**

segment: a portion of a computer network where all devices can communicate **directly at the data link layer (Layer 2)** without needing a router

Circuit Switched Networks

How do they work?

- A **circuit-switched network** establishes a **dedicated physical communication path** between users for the **entire duration of a session**.
- This path remains exclusively reserved, regardless of whether data is actively being transmitted — much like a traditional telephone call.



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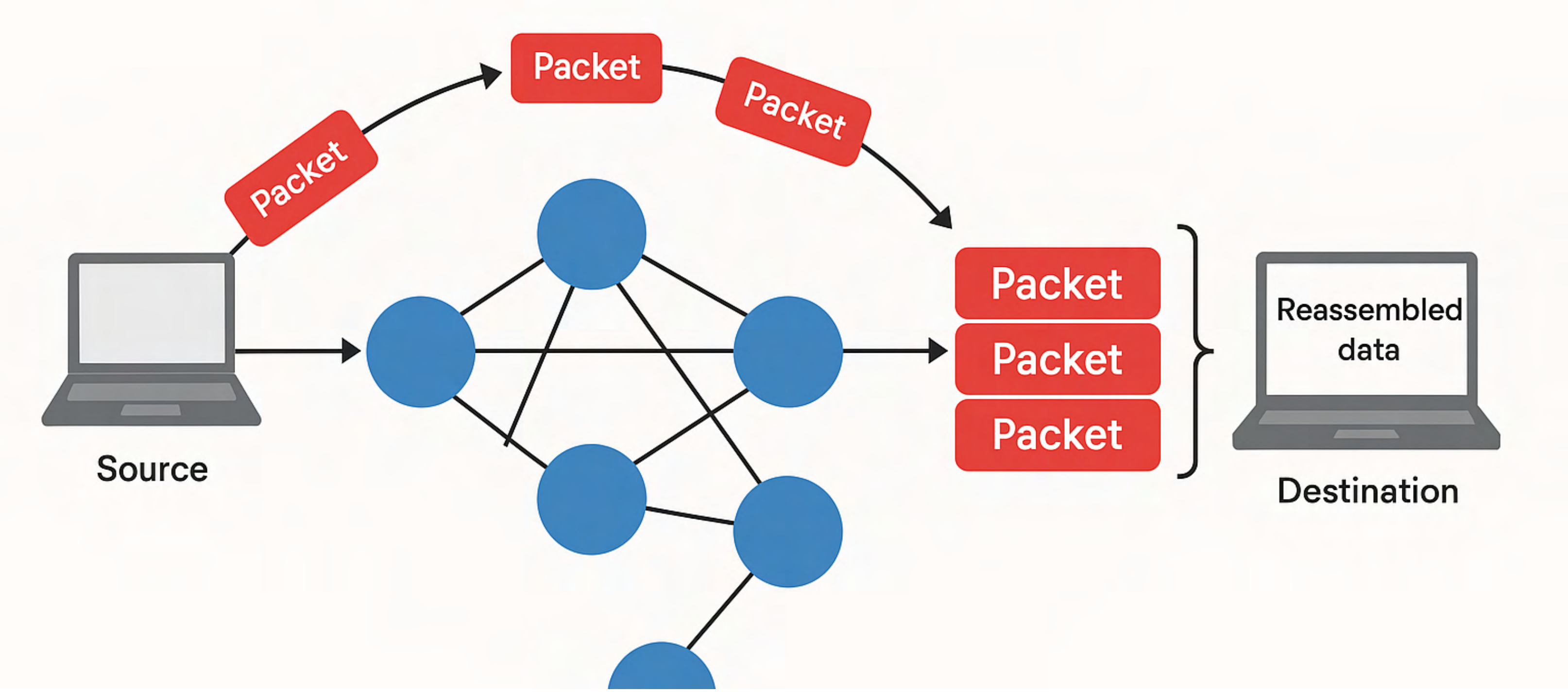
Key Characteristics of Circuit-Switched Networks

- Connection Establishment.
  - Before data transfer begins, a complete path is set up from source to destination.
  - All routers/switches along the way reserve resources for this session.
- Dedicated Path During Communication
  - Once established, this circuit remains **exclusively available** to those users.
  - Bandwidth is reserved, and no other traffic can use this path until it's released.
- Connection Teardown
  - After communication ends, the circuit is **torn down**, freeing up the resources.

Packet Switched Networks

How do they work?

- A **packet-switched network** transmits data by breaking it into **packets**, which are sent independently over shared network paths and reassembled at the destination. Unlike circuit switching, there is **no dedicated connection** — packets may take **different routes** and arrive **out of order**.



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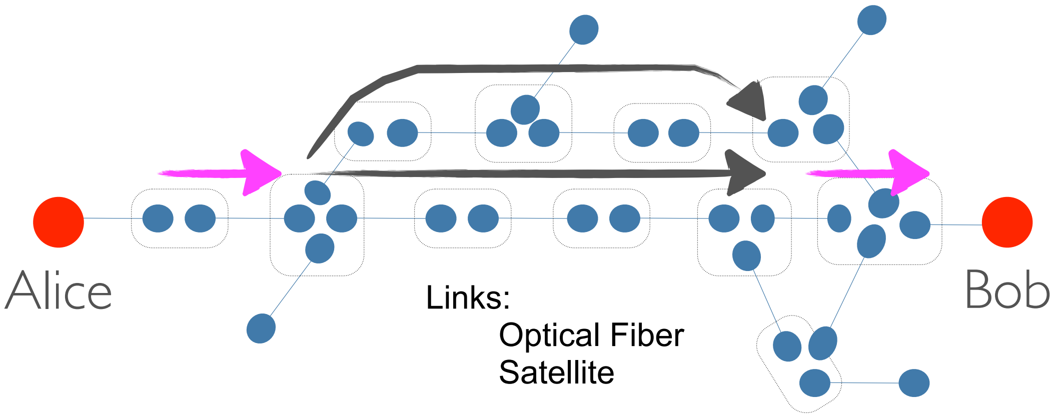
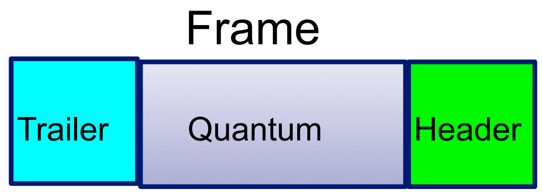
Key Characteristics of Circuit-Switched Networks

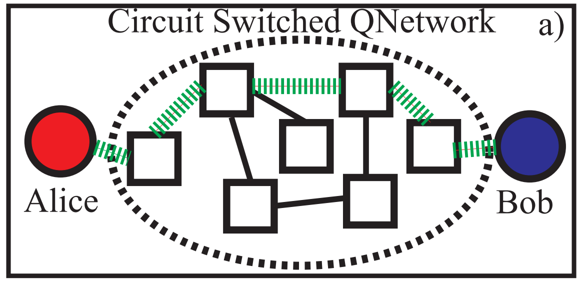
- Data is Split into Packets.
  - Messages are divided into chunks each with its own **header**.
- Dynamic Routing
  - Each packet may travel a **different path** through the network.
- Reassembly at Destination
  - Packets are **reassembled** into the original message at the receiving end.
- Efficient Resource Use
  - No bandwidth is reserved; network resources are shared dynamically.

Entanglement Switched Networks

- From naive considerations: it seems we are looking at a circuit switched network approach. May have to establish the path before we start

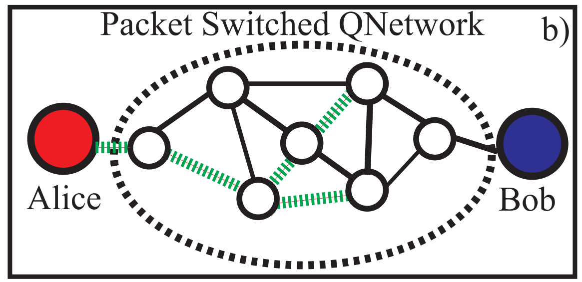






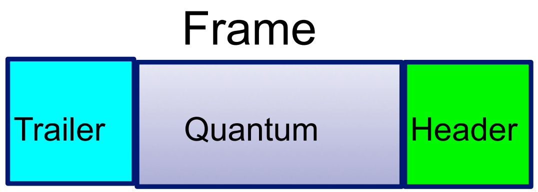
- Route is reserved.
- Frame arrive in order

- Do we really want the old fashion telephone exchange models?
  - First generation repeater probably leave us no choice
  - Second and third can use packet switched approaches - so much more multi user friendly

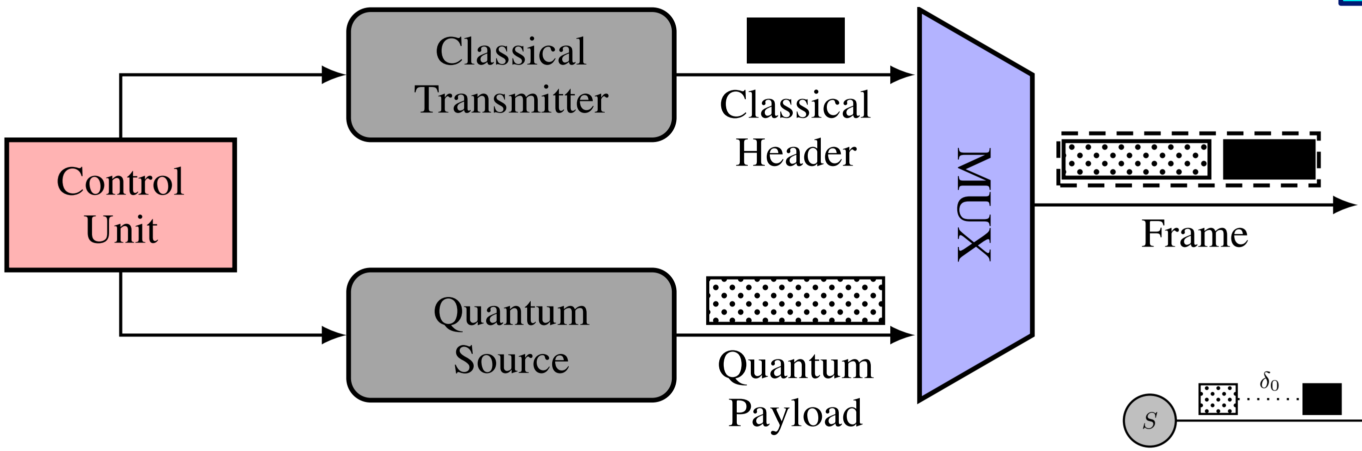


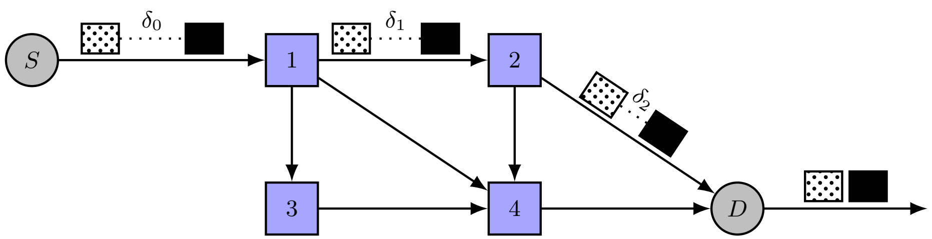
- Route is dynamic.
- Frame arrive out of order

Packet Switched Networks



- Need to generate the classical quantum frame





- Work done at CISCO

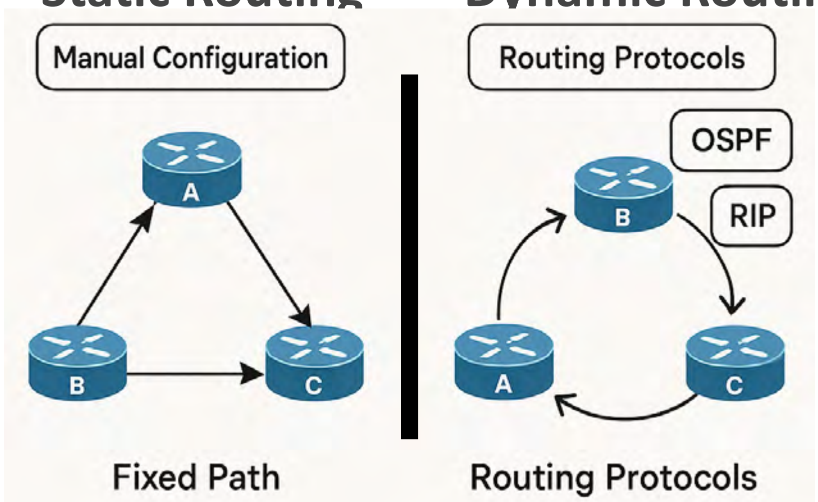
Packet switching in quantum networks: A path to the quantum Internet

Stephen DiAdamo, Bing Qi, Glen Miller, Ramana Kompella, and Alireza Shabani
Phys. Rev. Research **4**, 043064 – Published 28 October 2022

Routing

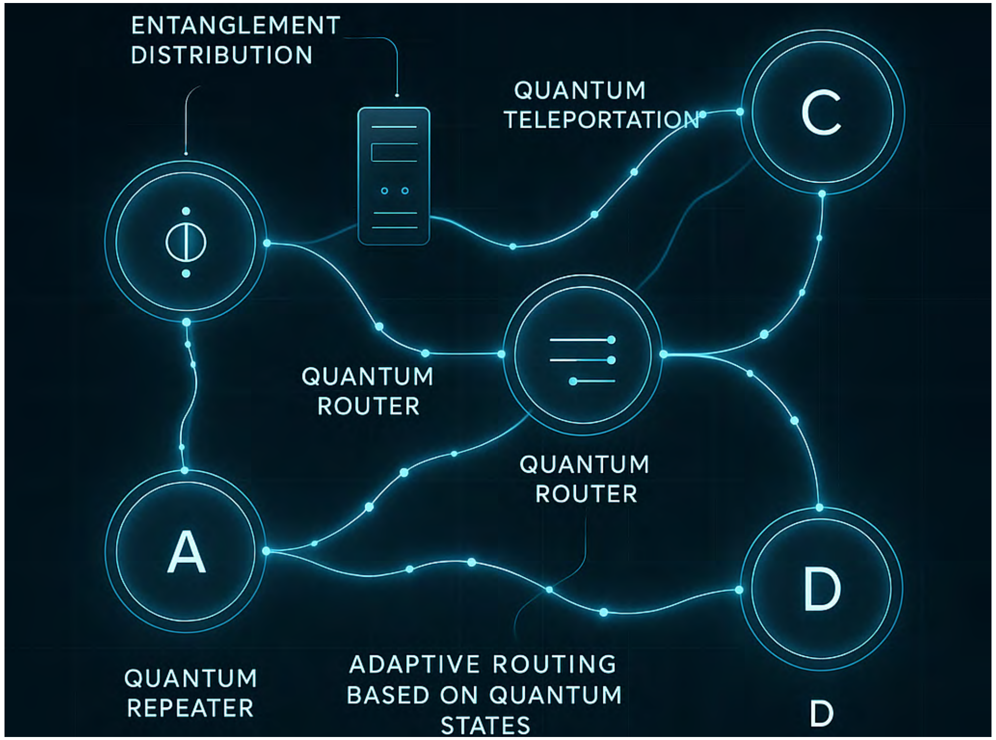
- To forward incoming data packets, a router learns all available network routes and stores them the routing table
- There are 2 types of routes: **static route and dynamic route.**
    - A **static route** is a route that is either directly configured on the router or manually added to the routing table
    - A **dynamic route** is where the router learns dynamic routes by running a routing protocol. This leads to centralized routing and distributed routing protocols

Static Routing **Dynamic Routing**



Quantum Routing

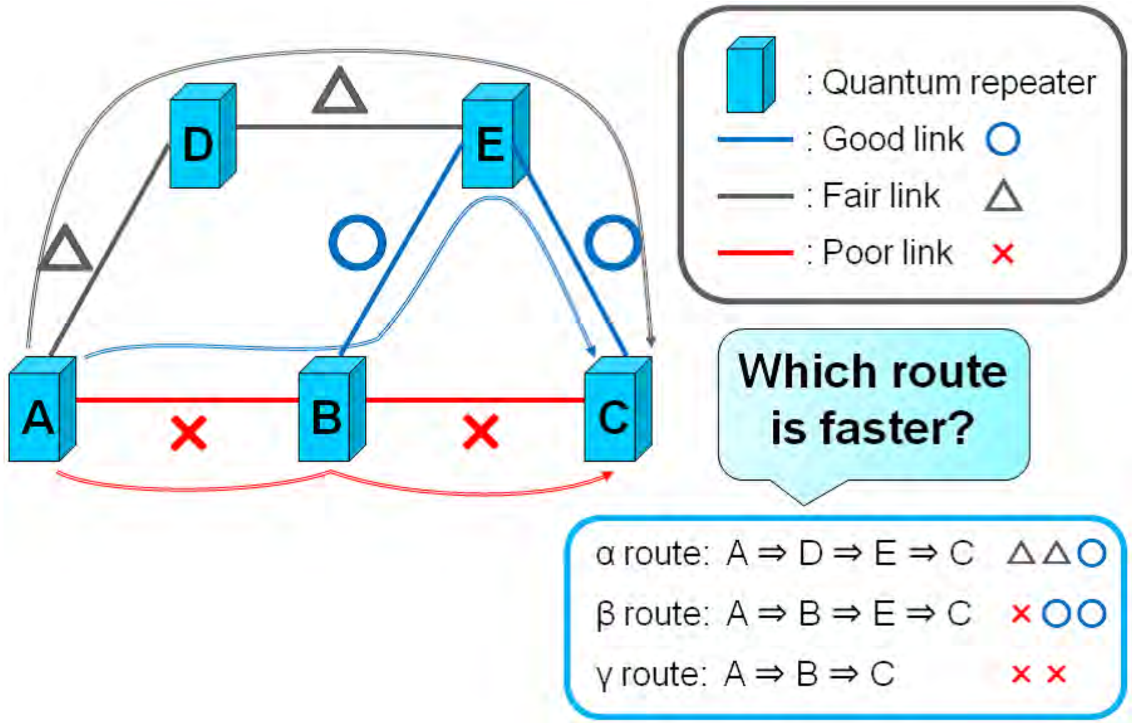
Quantum routing refers to the process of directing quantum information—typically encoded in qubits or entangled quantum states—through a **quantum network**. It's the quantum analog of classical network routing, but with unique challenges and principles due to the nature of quantum mechanics.



- In the quantum regime we can now send our quantum data packets via a superposition of paths at the same time.
    - This leads to the concept of a **quantum route** and **quantum network aggregation**!

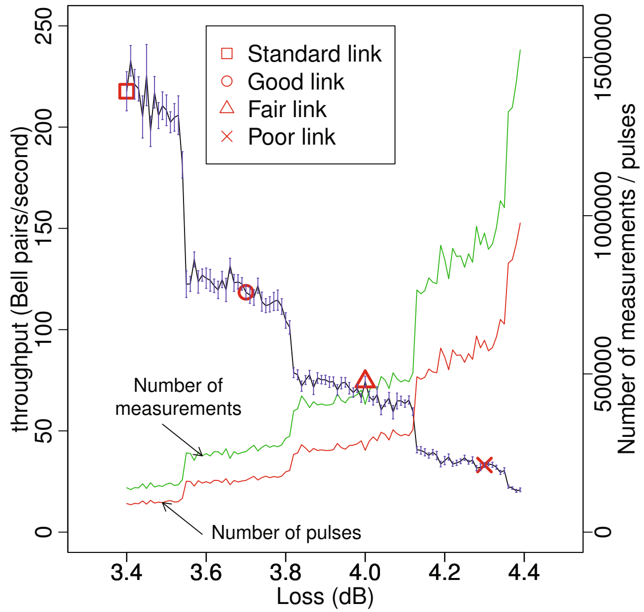
Path selection for for quantum repeater networks

- What happens if we have links for different quality?



Networking Science 3, 82-95 (2013)

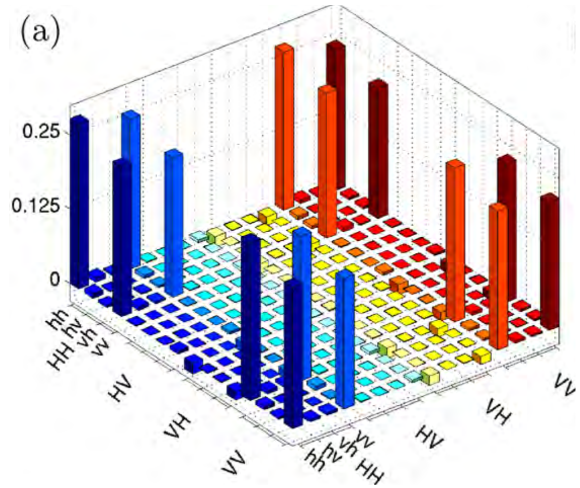
A single hop



Quantum Multiplexing

- **As photon get lost in optical fiber channels should we not try to conserve them?**
- **Why not use higher dimensional encoding or multiple degrees of freedom**

$$|\psi_t\rangle = \Phi^{+}_{\mathrm{poln}} \otimes \Phi^{+}_{\mathrm{spa}}$$

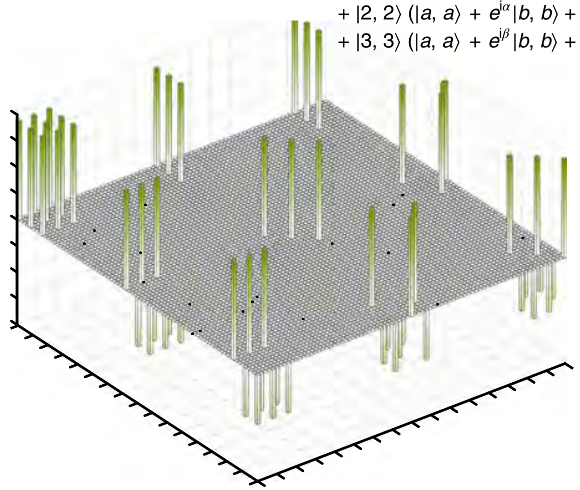


Polarization and spatial

Julio T. Barreiro et.al, Rev. Lett. 95, 260501 (2005)

Cluster state

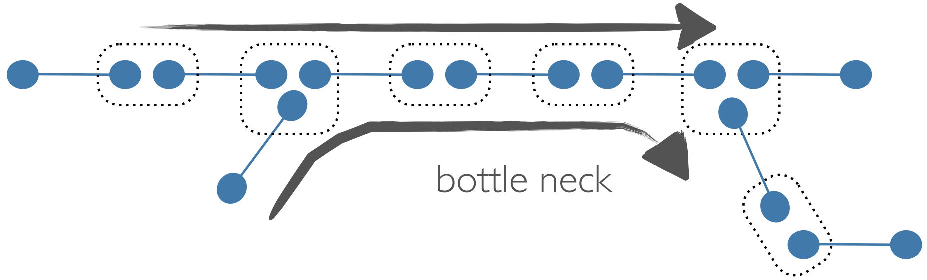
$$(|\psi_C\rangle = |1,1\rangle\,(|a,a\rangle + |b,b\rangle + |c,c\rangle) + |2,2\rangle\,(|a,a\rangle + e^{i\alpha}|b,b\rangle + e^{i\beta}|c,c\rangle) + |3,3\rangle\,(|a,a\rangle + e^{i\beta}|b,b\rangle + e^{i\alpha}|c,c\rangle)$$



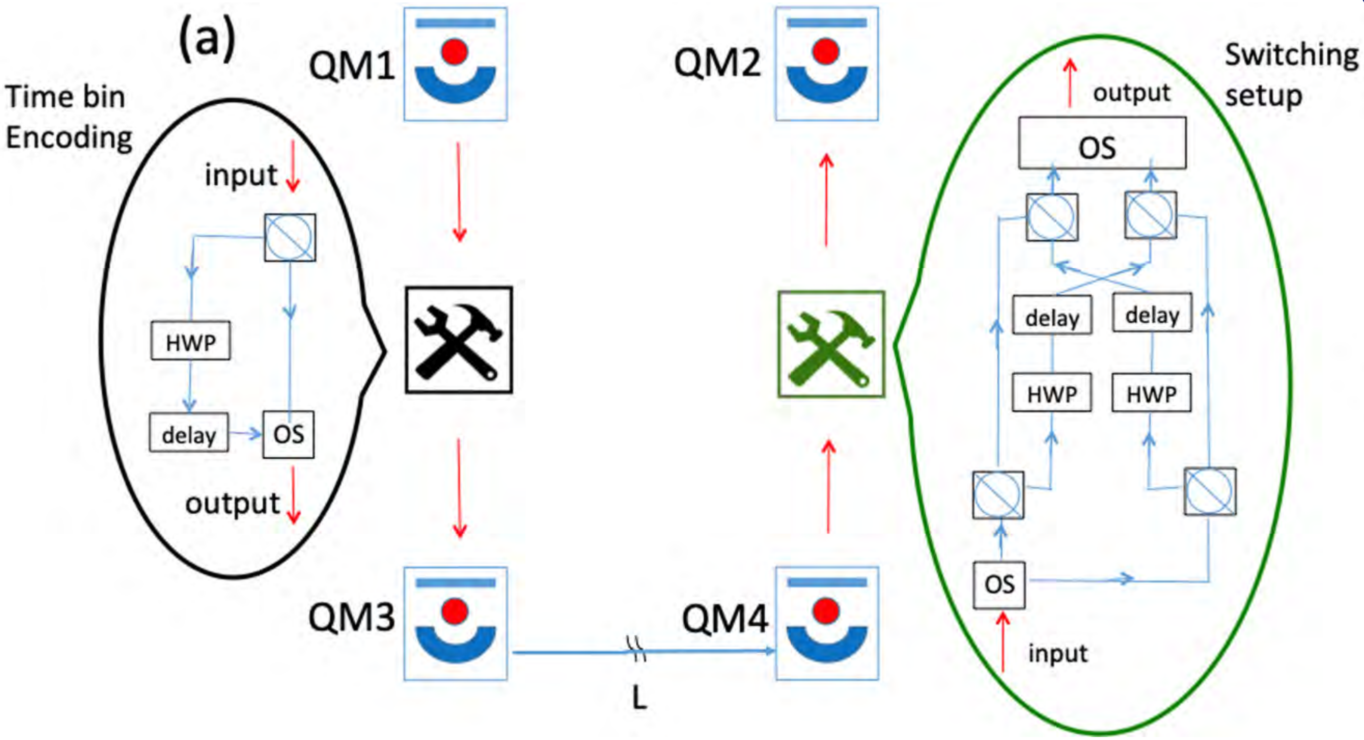
Time and frequency bin

Christian Reimer et.al, Nature Physics 15, 148-153 (2019)

Quantum Multiplexing

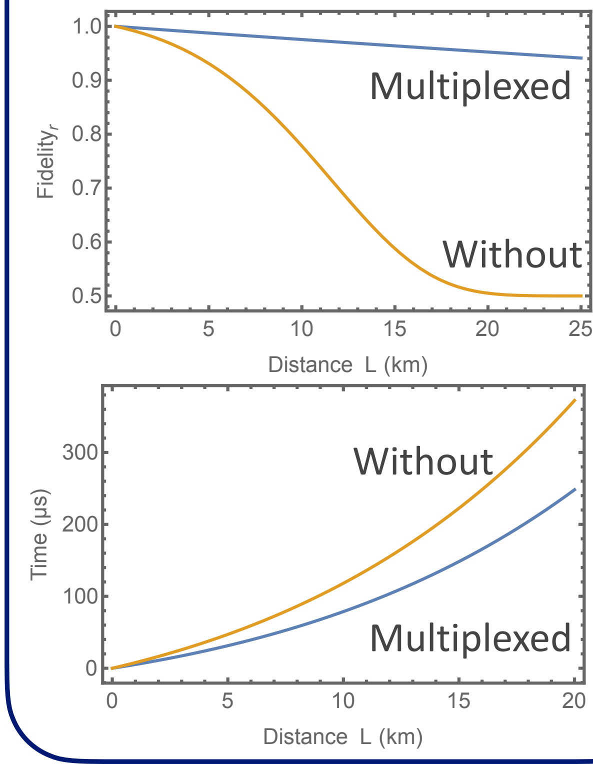


- Creating multiple Bell pairs



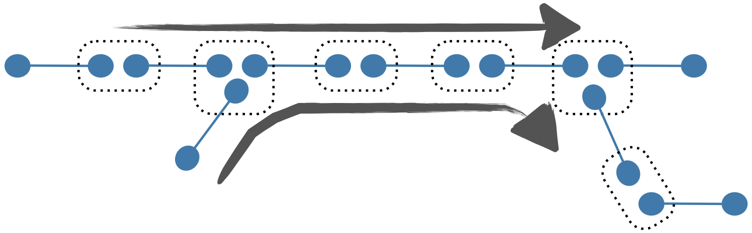
Two independent entangled links with 1 photon

Average Performance

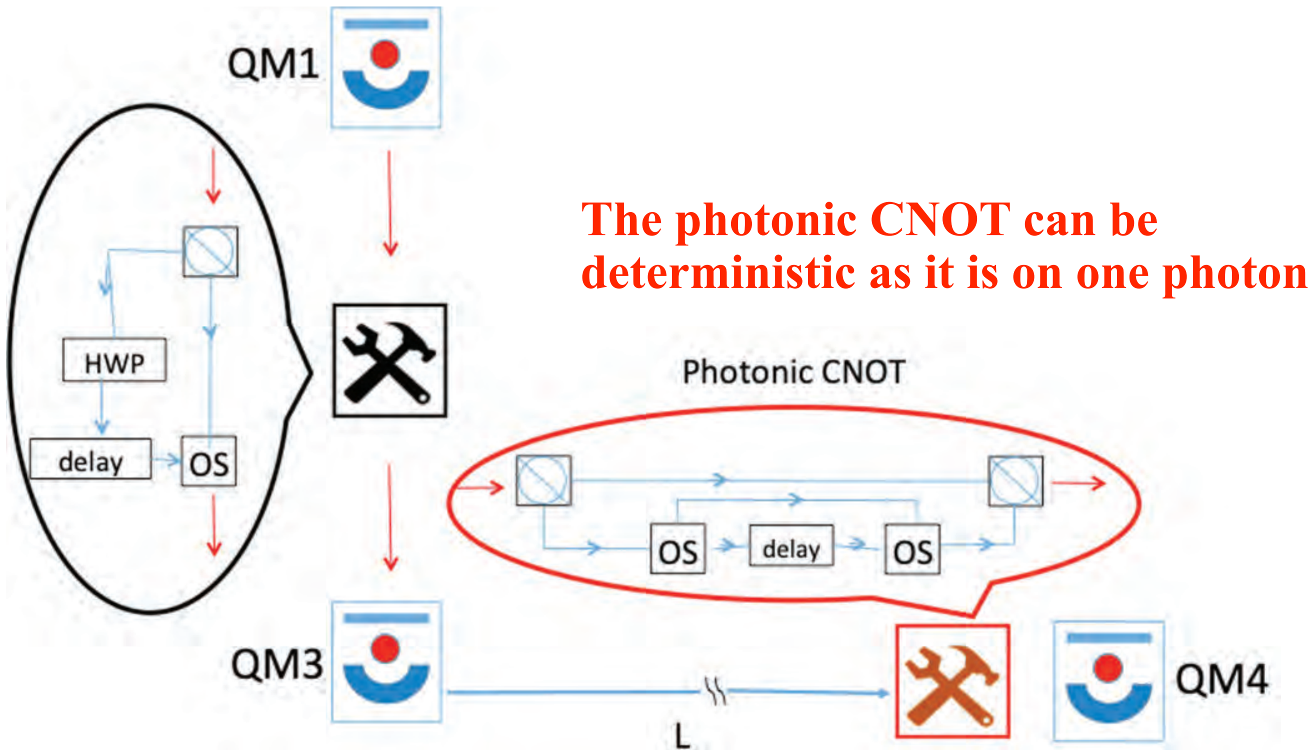


Nicolò Lo Piparo et.al, PRA **99**, 022337 (2019)

Quantum Multiplexing and Purification

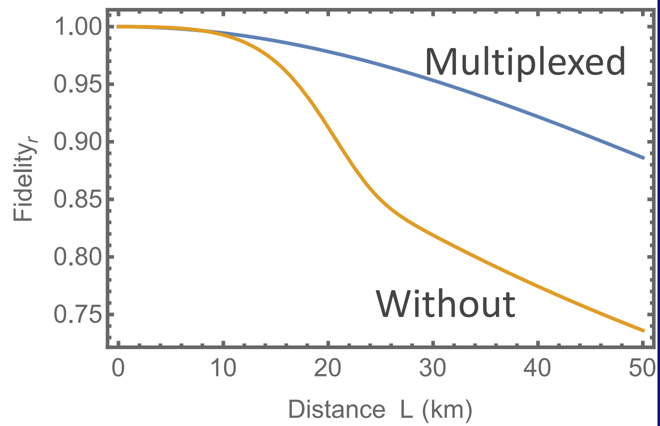


- As we can generate two Bell pairs with one photon - can we also increase their quality at the same time?



A purified link using only one photon

Average Performance



We can save both quantum memories and photons

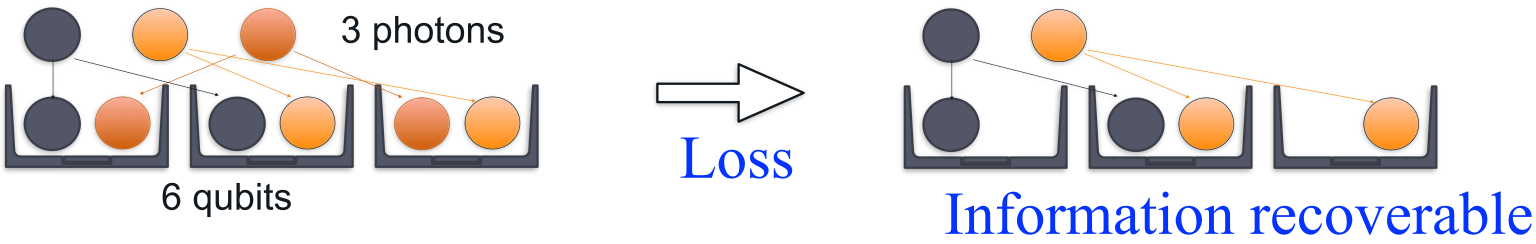
- even get a higher fidelity link

Nicolò Lo Piparo et.al, PRA **99**, 022337 (2019)

Hyper entanglement and Quantum Multiplexing

- **A very old concept**
- Photons have many degrees of freedom, polarization, time bin, frequency bin, …

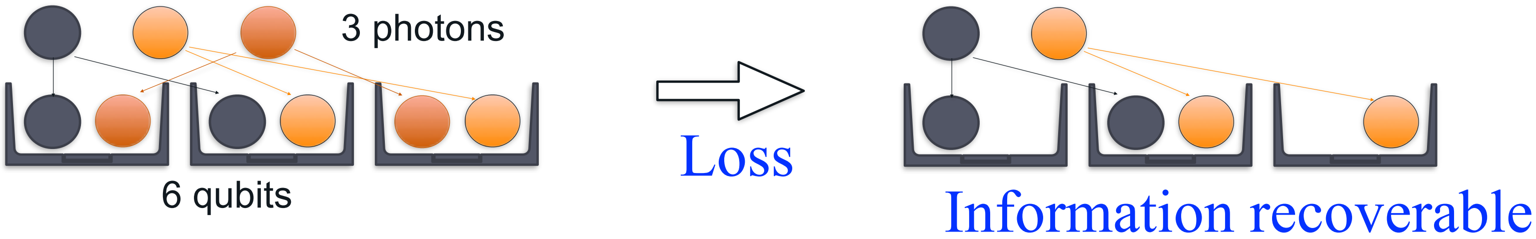
  - There is a trade off - it really can be useful



- How does this work?

Hyper entanglement and Quantum Multiplexing

- There is a trade off - it really can be useful



- First consider the 6 qubits case with no multiplexing.
- We can write the state as

$$\alpha|00+11\rangle|00+11\rangle|00+11\rangle+\beta|01+10\rangle|01+10\rangle|01+10\rangle$$

- In density matrix form

$$|\alpha|^2|00+11\rangle|00+11\rangle|00+11\rangle\langle 00+11|\langle 00+11|\langle 00+11|$$
$$+\alpha\beta^*|00+11\rangle|00+11\rangle|00+11\rangle\langle 01+10|\langle 01+10|\langle 01+10|$$
$$+\alpha^*\beta|01+10\rangle|01+10\rangle|01+10\rangle\langle 00+11|\langle 00+11|\langle 00+11|$$
$$+|\beta|^2|01+10\rangle|01+10\rangle|01+10\rangle\langle 01+10|\langle 01+10|\langle 01+10|$$

Hyper entanglement and Quantum Multiplexing

- When we lose the qubit 4 and 6 we have

$$
\begin{aligned}
&|\alpha|^2 |00+11\rangle\langle 00+11| \otimes I_3 \otimes I_5 \\
&+\alpha\beta^* |00+11\rangle\langle 01+10| \otimes \{ |0\rangle_3\langle 1| + |1\rangle_3\langle 0| \} \otimes \{ |0\rangle_5\langle 1| + |1\rangle_5\langle 0| \} \\
&+\alpha^*\beta |01+10\rangle\langle 00+11| \otimes \{ |0\rangle_3\langle 1| + |1\rangle_3\langle 0| \} \otimes \{ |0\rangle_5\langle 1| + |1\rangle_5\langle 0| \} \\
&+|\beta|^2 |01+10\rangle\langle 01+10| \otimes I_3 \otimes I_5
\end{aligned}
$$

- Measure qubit 3 and 5 in the X basis to give

$$
\begin{aligned}
&|\alpha|^2 |00+11\rangle\langle 00+11| + \alpha\beta^* |00+11\rangle\langle 01+10| \\
&+\alpha^*\beta |01+10\rangle\langle 00+11| + |\beta|^2 |01+10\rangle\langle 01+10|
\end{aligned}
\qquad X_3 = X_5 = +1
$$

- In state form we have

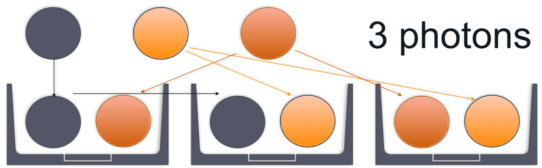
$$\alpha |00+11\rangle + \beta |01+10\rangle$$

You can go through the other 3 cases as well

Hyper entanglement and Quantum Multiplexing

- Now when we have 3 photons and loss one, it is equivalent to losing two qubits
- So the previous procedure works as well

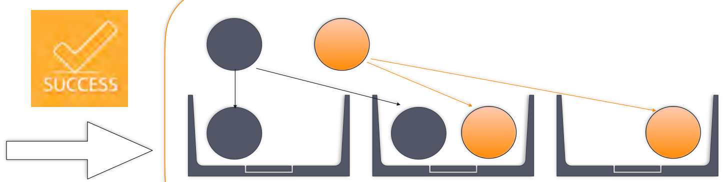
A photon can carry multiple qubits



3 photons

6 qubits

$$|H_{s1}H_{s2}H_{s3}\rangle + |Hs_1H_{L2}V_{s3}\rangle + |HL_1V_{s2}H_{s3}\rangle + |HL_1V_{L2}V_{s3}\rangle + |V_{s1}Hs_2H_{L3}\rangle + |V_{s1}H_{L2}V_{L3}\rangle + |V_{L1}V_{s2}H_{L3}\rangle + |V_{L1}V_{L2}V_{L3}\rangle$$



$$P_S^{hyper} = \sum_{i=0}^{Ph_{tot}} \left[\binom{Ph_{tot}}{i} - \left(U_i + E_i\right) \right] P_t^{Ph_{tot}-i} \left(1 - P_t\right)^i$$

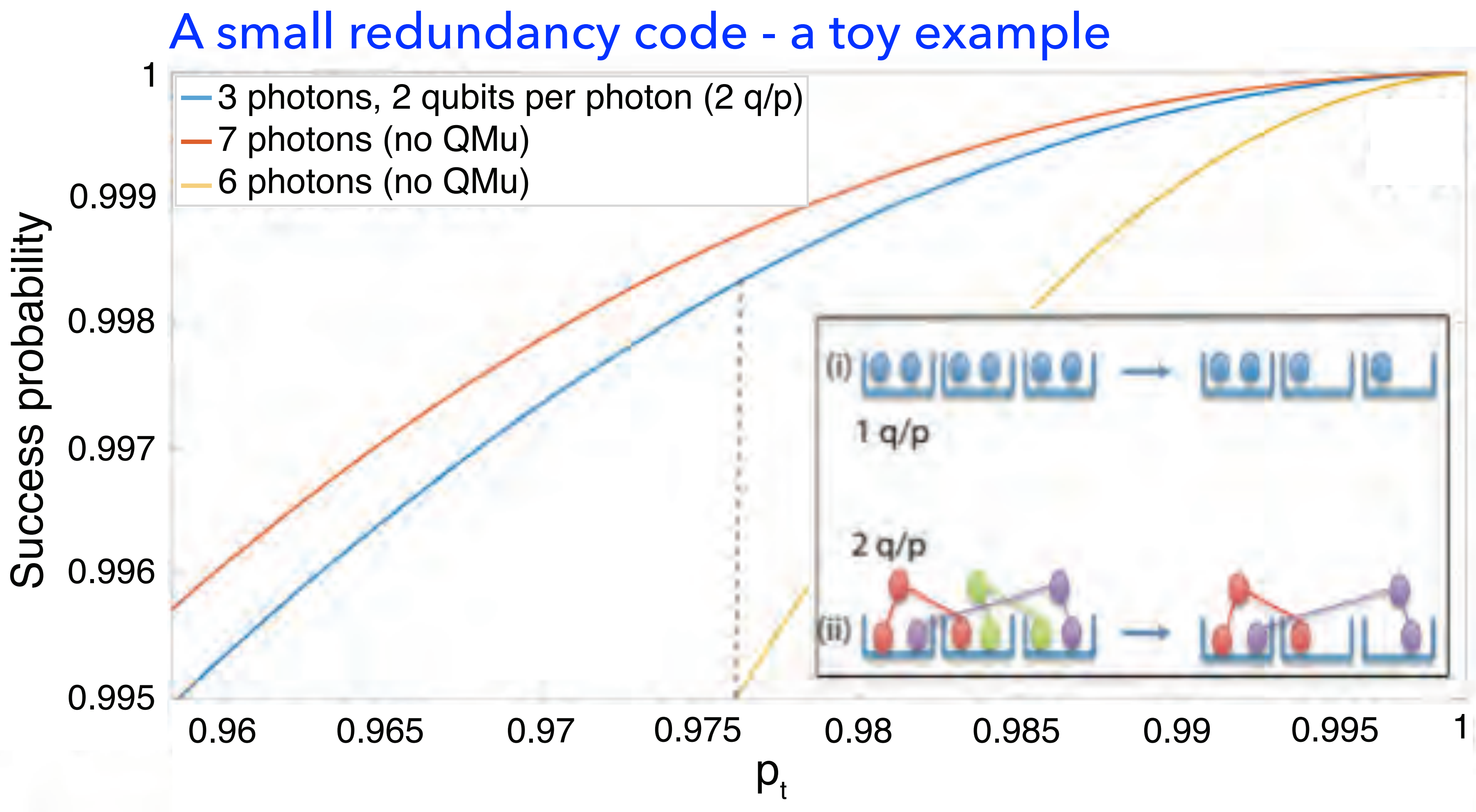
Failure cases
(we need to compute them numerically)

P_t photon transmission probability

Ph_{tot} total number of photons

N. Lo Piparo, et.al. Phys. Rev. A 99, 022337 (2019) ; Phys. Rev. Lett 124, 210503 (2020)

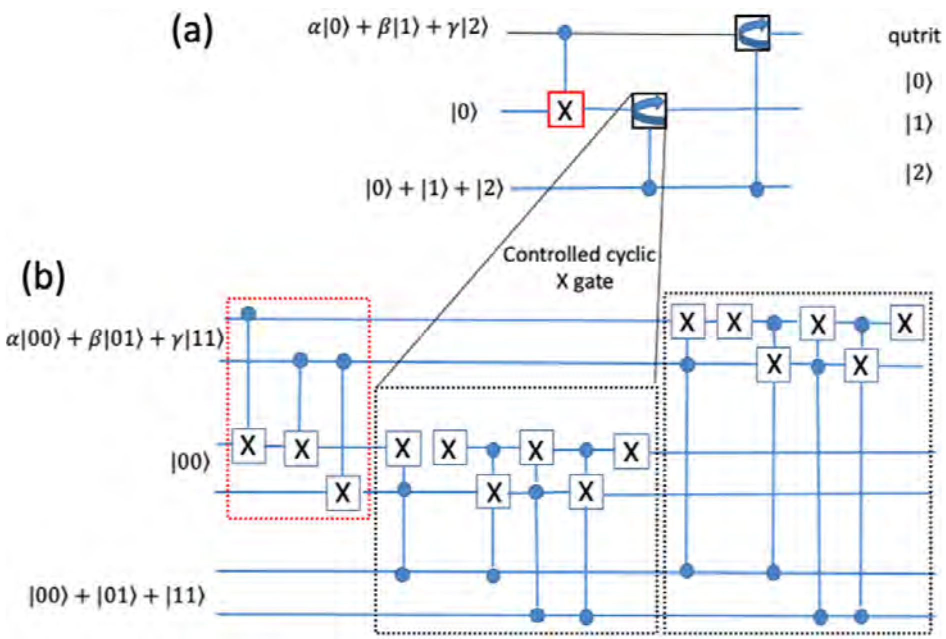
Hyper entanglement and Quantum Multiplexing

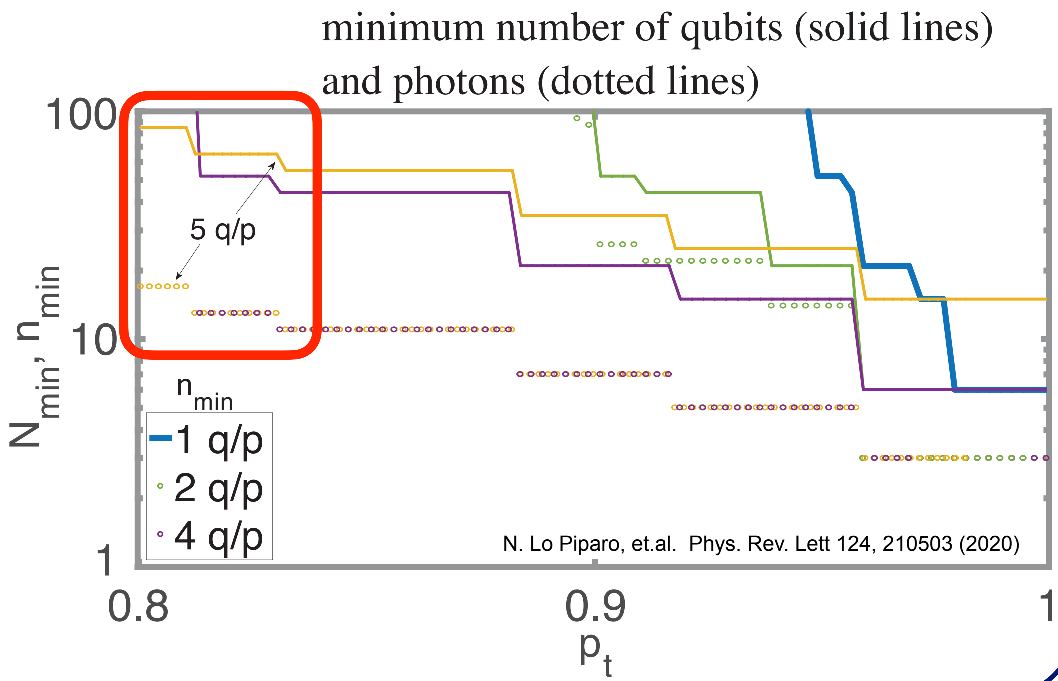


N. Lo Piparo, et.al. Phys. Rev. A 99, 022337 (2019) ; Phys. Rev. Lett 124, 210503 (2020)

Quantum Multiplexing and error correction

- The quantum reed solomon (QRS) code $[[d,2k\text{-}d,d\text{-}k+1]]_d$ is a nice example where we can save both qudits & photons
  - The simplest case is qutrits $|D\rangle = \alpha|0\rangle_L + \beta|1\rangle_L + \gamma|2\rangle_L$



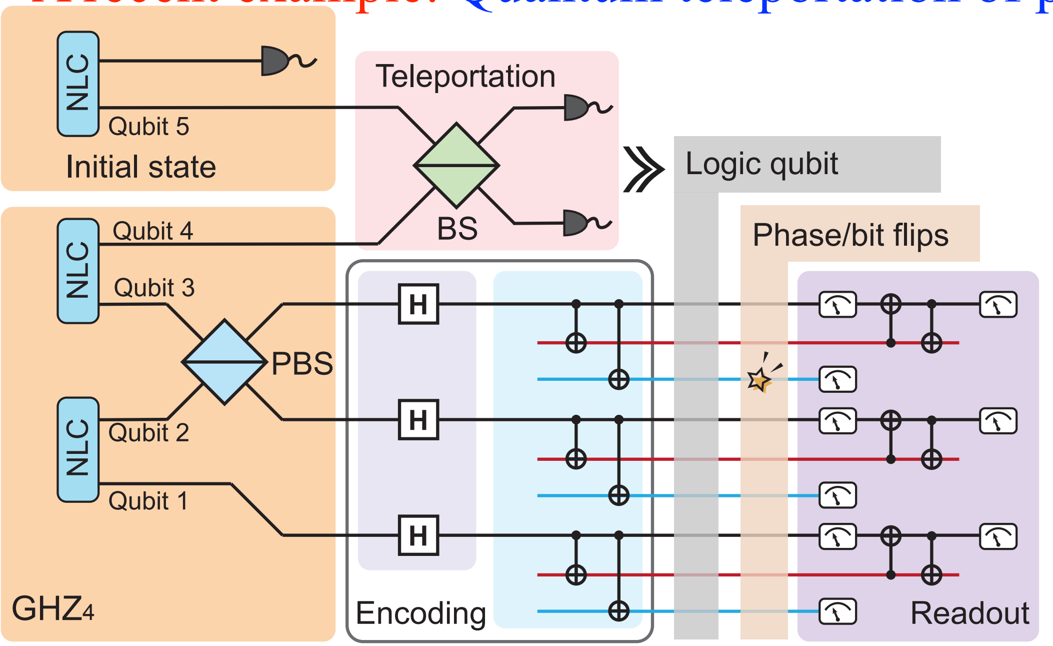


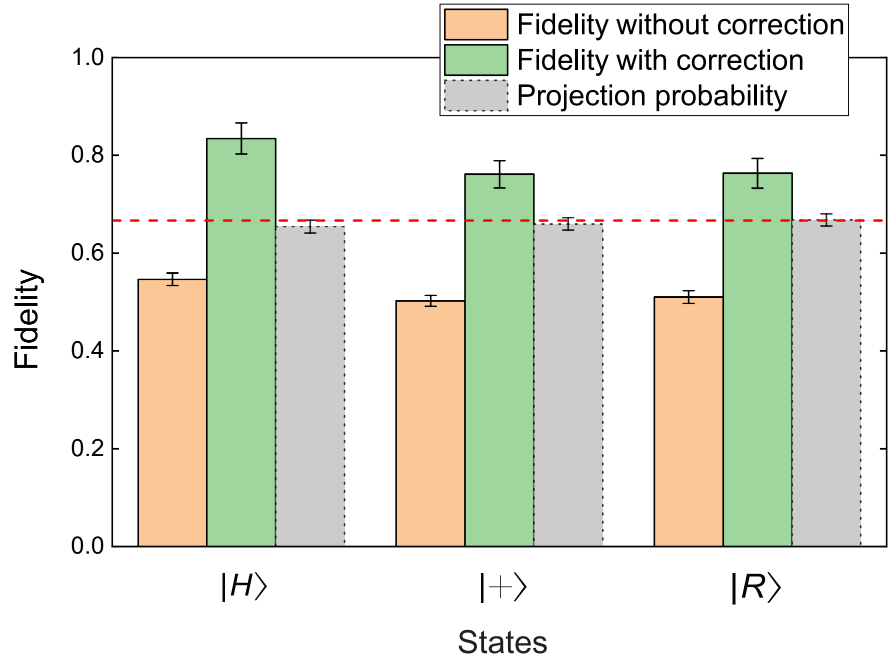
Multiplexing only requires extra optical switches

N. Lo Piparo, et.al. Phys. Rev. A 99, 022337 (2019) ; Phys. Rev. Lett 124, 210503 (2020)

Quantum multiplexing in action

- Photonic many degrees of freedom are very useful when we have limited resources
- In photonic quantum computation we do.
- A recent example: Quantum teleportation of physical qubits into logical code-spaces





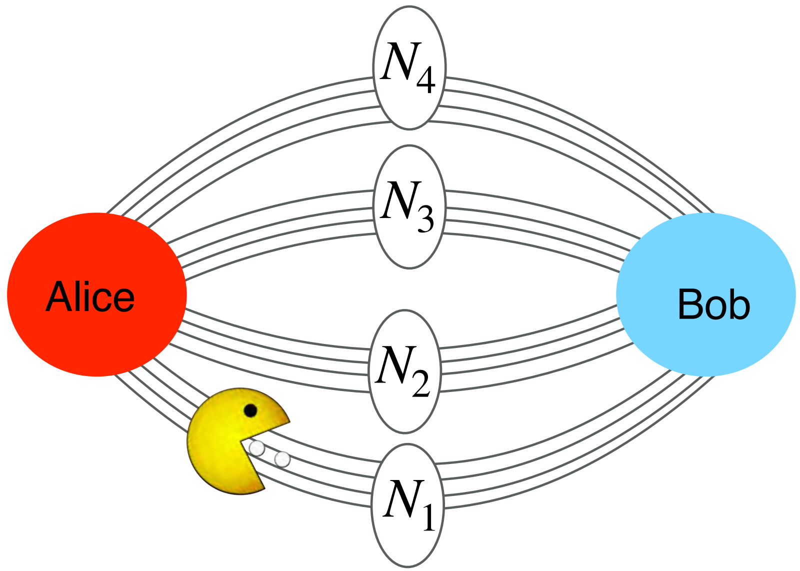
6 photon - but 12 qubits

Yi-Han Luo et.al, Proc Natl Acad Sci USA 118 (36), e2026250118 (2021).

Why not for quantum communication

Quantum Aggregation

- Generally one thinks of our quantum packet taking one route (similar to what happens in the classical world)



- What happens when we have constrained resources?
- **In the quantum world we could route this single packet over 2 or more independent paths.**

N. Lo Piparo, et.al. Phys. Rev. A **102**, 052613 (2020)

Quantum Aggregation:

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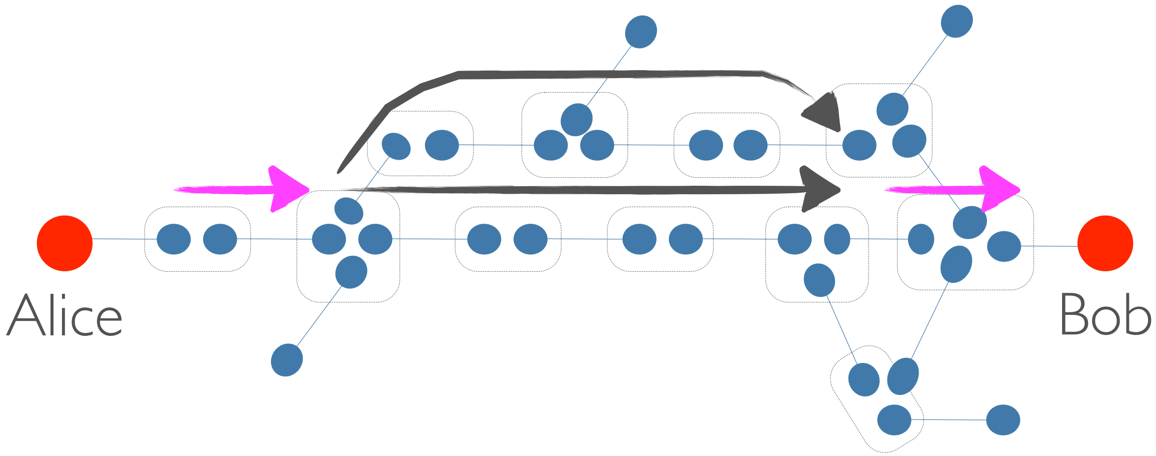
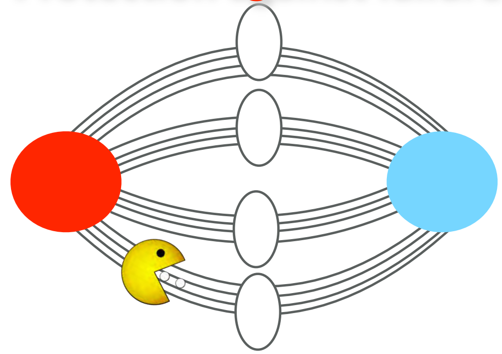
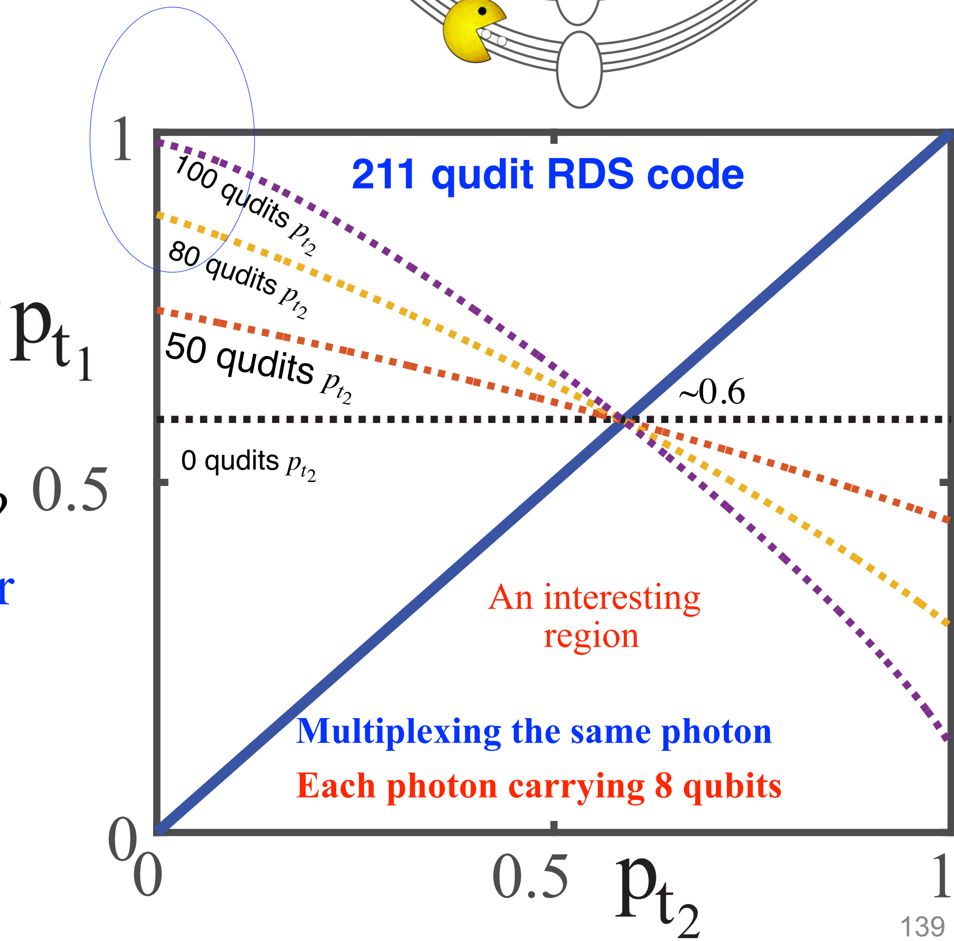
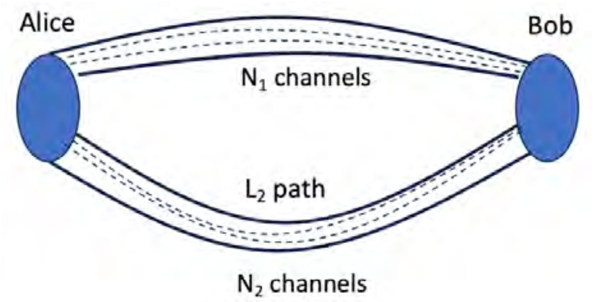


- What happens when we have constrained resources?
- Alice and Bob may not be able to communicate over an individual route
- **In the quantum world we could route this single packet over 2 or more independent paths.**

Protection against failure



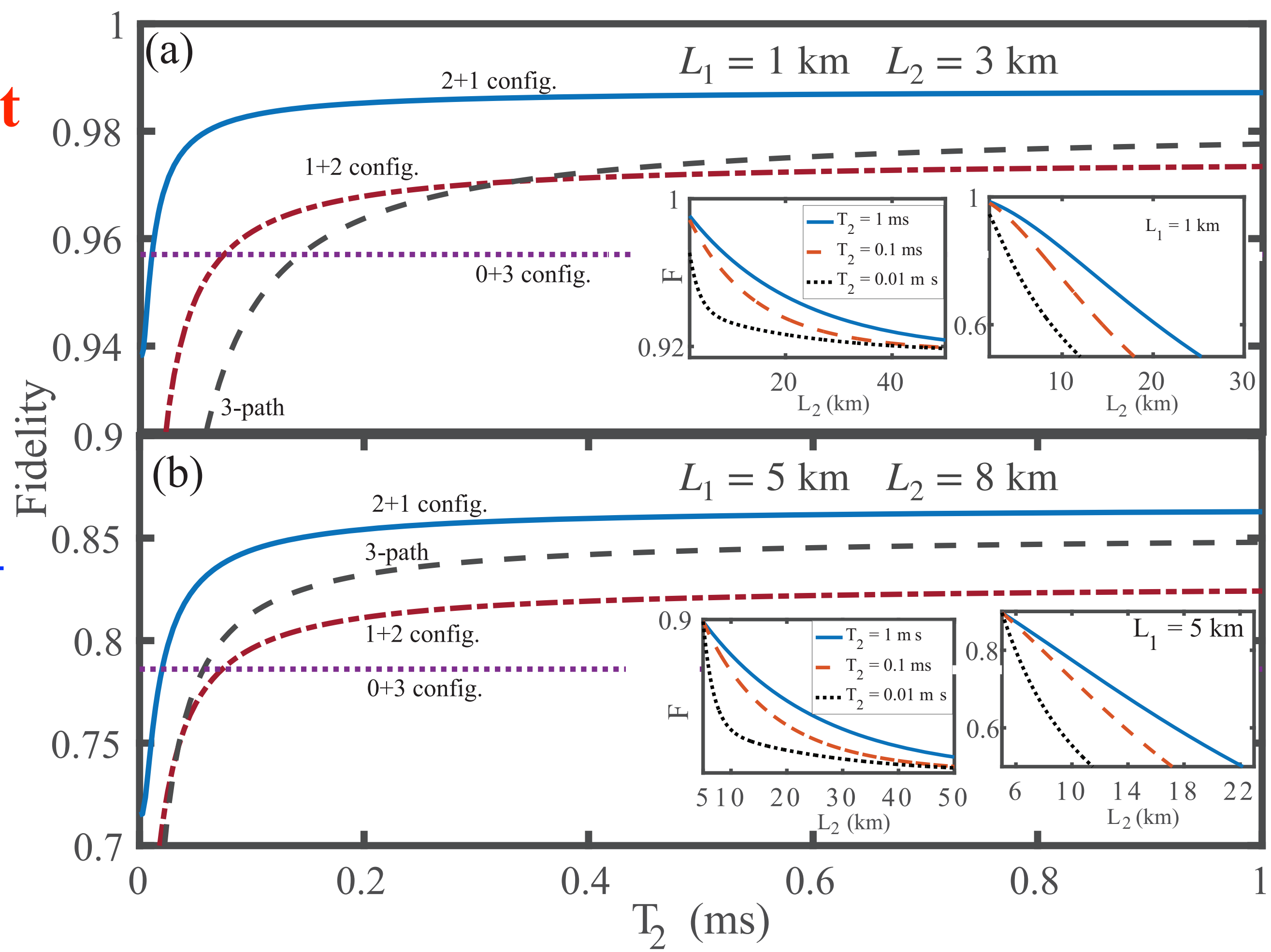




Quantum Aggregation

Channel length differences

- **Let us look at the simplest case [[3,1,2]]$_3$ code**
- If our channel lengths are different we have to delay the arrival of the earlier photons or store them.
- In this 3 channel case we have 4 configurations
  - 2 short + 1 long
  - 1 short + 2 long
  - 3 Long
  - 1 short, 1 medium, 1 long



The quantum network realm

The quantum internet will provide an infrastructure to be able to distribute and process quantum information on the planetary scale.

- Such an internet will in the long term be formed from quantum error corrected links able to distribute information over large distances all while maintaining their coherence

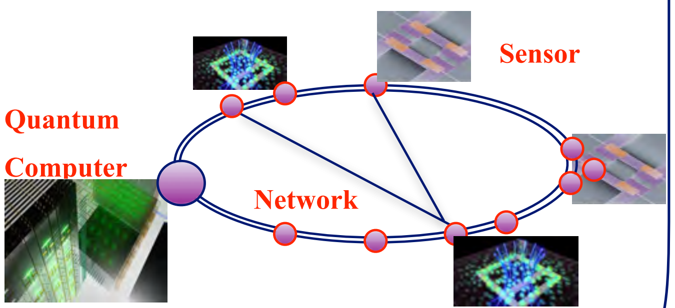
- **The key question** however is how we evolve from today small-scale test networks to that future quantum internet. How do we bridge this divide?

Quantum edge & fog computing may be a solution?

A potential route forward

Quantum Edge Computing

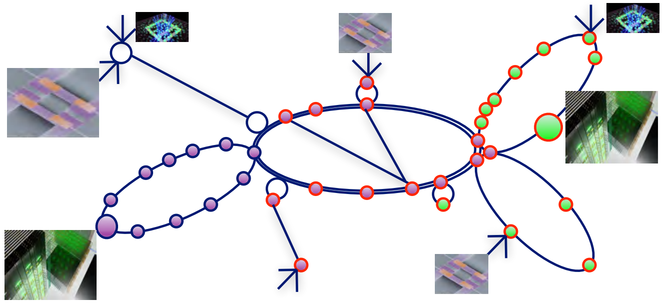
- Initial quantum networks will only be able to distribute physically encoded quantum resources over short distances
- Quantum communication will be a bottleneck
- Need to keep our quantum processing and storage as close to possible to the edge nodes in the network where it is generated



a few km's

Quantum Fog Computing

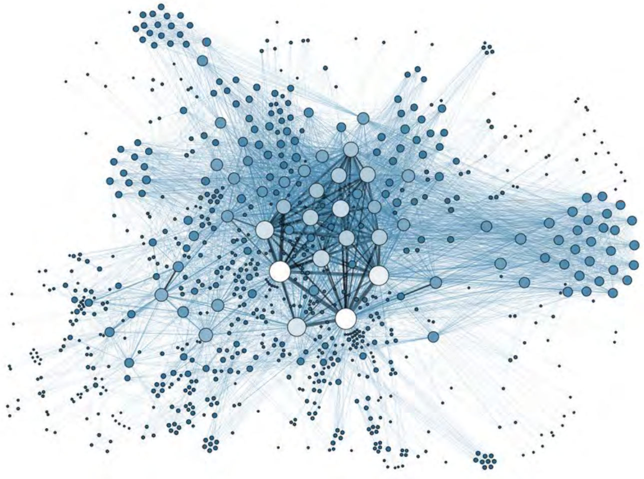
- Quantum data transmission will require quantum repeaters (probably first generation and potentially second).
- Will need to begin logically encoding quantum data.
- Quantum routing protocols will need used.



a few hundred km's

Quantum Internet and Cloud

- A quantum network of quantum networks supported by an efficient classical internet.
- Fully fault tolerant
- Most likely based on third generation QR's



Global

Time and Degree of Networking

Edge Computing

What is edge computing? Why is it important when we have todays internet?

- It is a topology based location-sensitive form of distributed that computing to brings the processing and storage of data to its source at the periphery (edge) of the network close to the user.

- **The internet of things (IoT) is an example of edge computing**

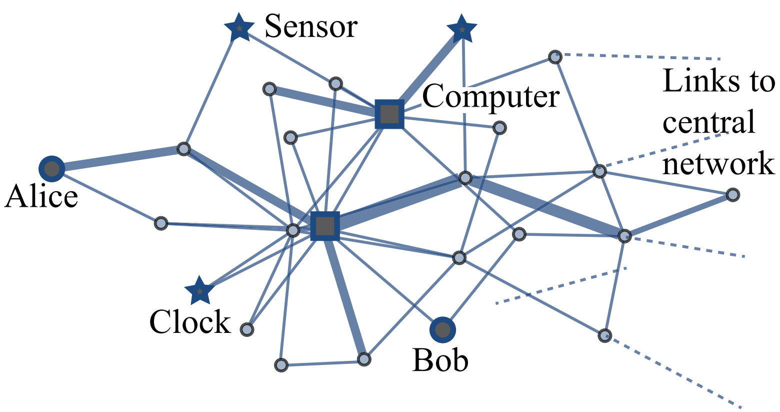
- **Edge computing is not about a specific technology rather instead it is an architecture.**

- Why use it? It addresses three important network issues: bandwidth, latency and congestion.

We may have similar network issues in the quantum world !!!

Quantum Edge Computing

- Initial quantum networks based off first generation QR will only be able to distribute physically encoded quantum resources over modest distances with limited fidelities and rates.
- Quantum communication will be a bottleneck, meaning we need to keep our quantum processing and storage as close to possible to the edge nodes in the network where it is generated (within few miles!).

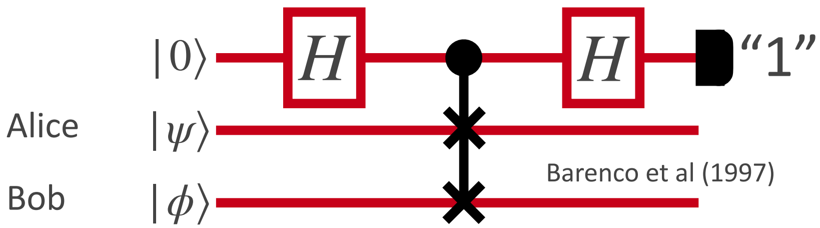


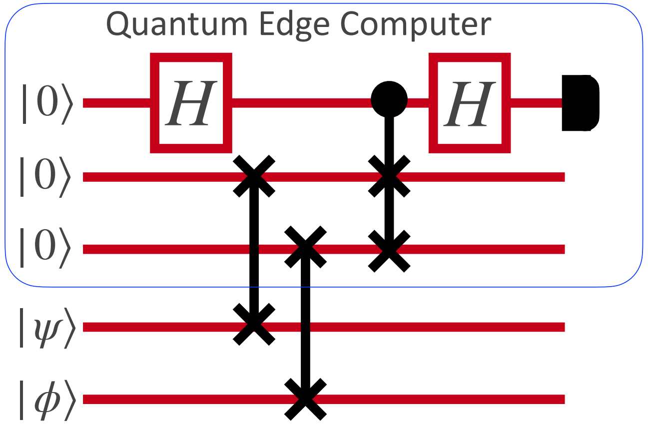
- Our network will be mainly classical with a little shared entanglement available.
- One can envision a cluster of quantum devices within short distances of one another, that is at the edge of the network.
- **As greater communication resources become available we can migrate to quantum fog computing**

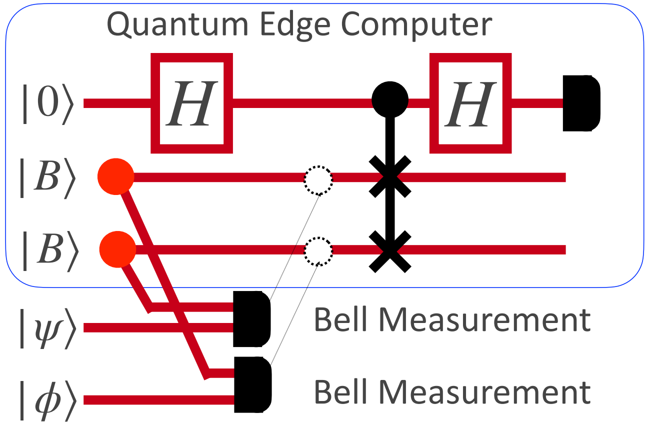
Quantum Edge Computing

- **An example: The SWAP test in the edge environment**
- Estimate the overlap between the two states in a remote edge setting

$$\text{Prob}(1) = \frac{1}{2} - \frac{1}{2}|\langle\phi|\psi\rangle|^2$$

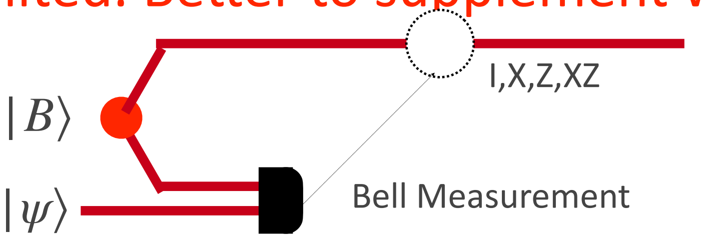






Remote gates or Teleportation?

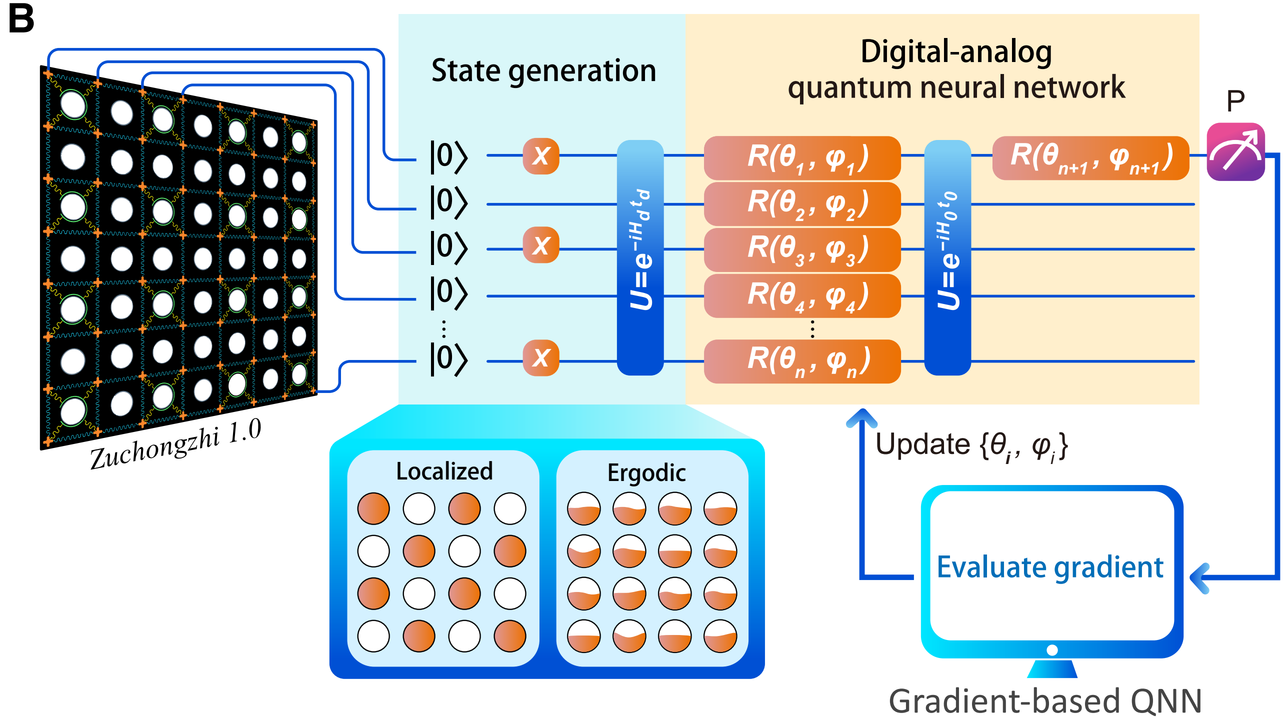
- In the quantum edge regime - our quantum communication resources are quite limited. Better to supplement with classical communication



Teleportation requires a **shared Bell pair**, a local Bell measurement and classical feedforward

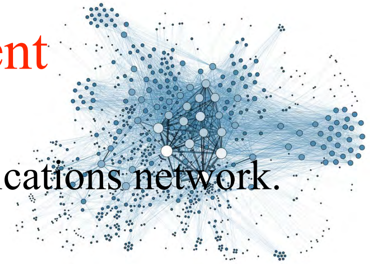
Quantum Neuronal Sensing (Fog Computing?)

- **A potential quantum edge / fog task involving classical computation**
  - Distinguish different states of quantum matter
  - Uses a hybrid digital-analog quantum neural networks where we measure only one qubit

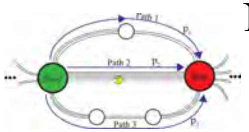


Unlikely to have the quantum sensor, processor etc in one location

Design Considerations



- A complex quantum network must be supported by an extremely fast & efficient telecommunications network
  - otherwise the performance of the quantum network is likely to be limited by the telecommunications network.
- Two parties will not generally know the path joining them and that path may change over time.
  - One should be looking at packet switched networks when multiple users are on the network.
- The first-generation repeater schemes are inherently slow and require significant classical signaling between nodes due to the probabilistic nature of their operations
  - One must carefully allocate resources and introduce cutoff timings to optimize their performance.
- The higher generation QR approaches allow both the direct transmission of quantum messages and entanglement generation over very large networks.
  - The usual telecommunication tools can be used for routing etc.
  - Network aggregation techniques can be used to overcome resource limitations within nodes.



The take home message

Quantum communication is the key enabler to fully realize the potential the second quantum revolution gives

Thank You!!

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