

Realizing Quantum Internet

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Bit

0/1

Qubit



$$|\psi\rangle = a |0\rangle + b |1\rangle$$

Qubit - 1



$$|\psi\rangle = a |0\rangle + b |1\rangle$$

$$|\psi\rangle = ac |00\rangle + ad |01\rangle + bc |10\rangle + bd |11\rangle$$

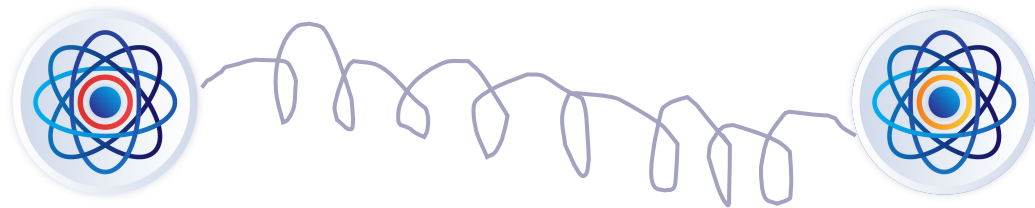
Qubit - 2



$$|\phi\rangle = c |0\rangle + d |1\rangle$$

Qubit - 1

Qubit - 2



$$|\psi\rangle = ac |00\rangle + ad |01\rangle + bc |10\rangle + bd |11\rangle$$

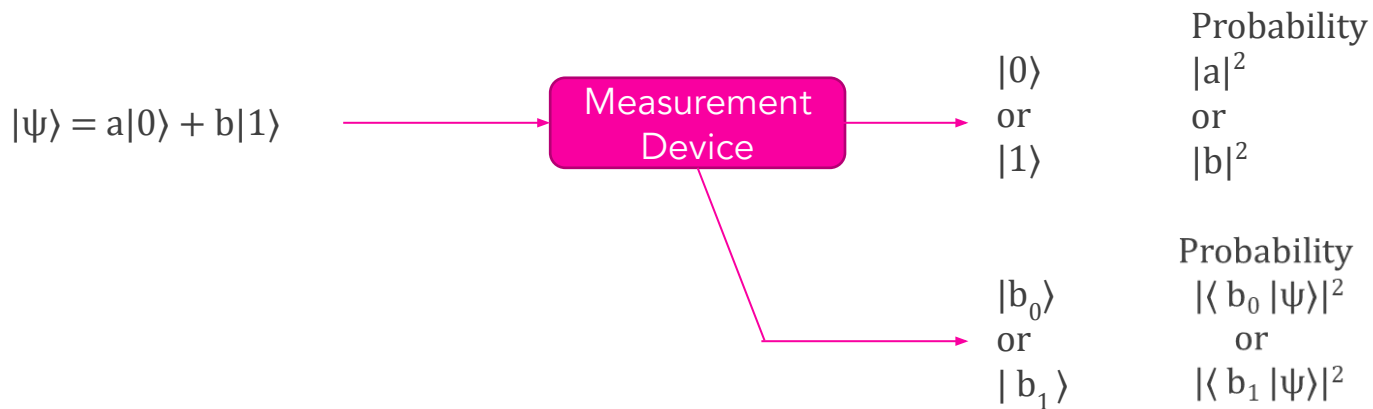
$$|\psi\rangle = ac |00\rangle + bd |11\rangle$$

Entangled Qubits

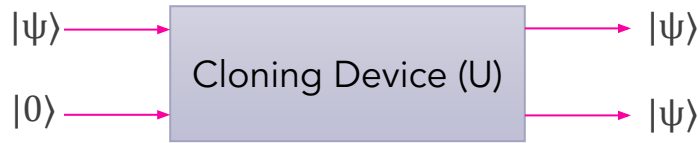
$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

Measurement

- Information Extraction from a Qubit
- Probabilistic nature of quantum



No Cloning Theorem



No Cloning of
Arbitrary State!

$$U|\psi\rangle|0\rangle = |\psi\rangle|\psi\rangle$$

$$U|\phi\rangle|0\rangle = |\phi\rangle|\phi\rangle$$

Taking inner product

$$\langle\phi|\psi\rangle = (\langle\phi|\psi\rangle)^2$$

$$\langle\phi|\psi\rangle = 0 \text{ or } 1$$

$$\text{CNOT}|0\rangle|0\rangle = |0\rangle$$

$$|0\rangle$$

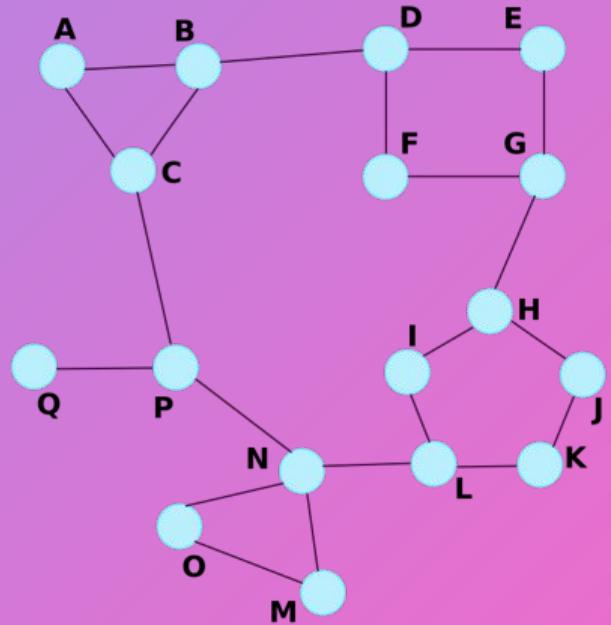
$$\text{CNOT}|1\rangle|0\rangle = |1\rangle$$

$$|1\rangle$$

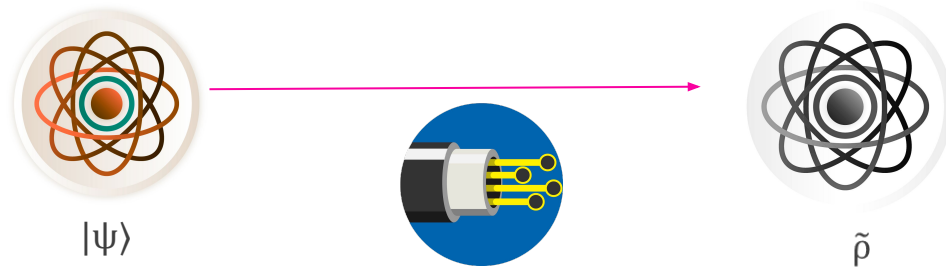
Quantum Network

- Quantum Nodes connected through Physical Channel
- Shared Entanglement (Virtual Link)
- Applications
 - Quantum Key Distribution [BB84]
 - Clock Synchronization [CS]
 - Distributed Quantum Computation [DQC]
 - Blind Quantum Computation [BQC]

Transmission of Qubits



Direct Transmission



Limited by distance due to fiber attenuation

Teleportation

Site A



$$|\psi\rangle = a|0\rangle + b|1\rangle$$



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

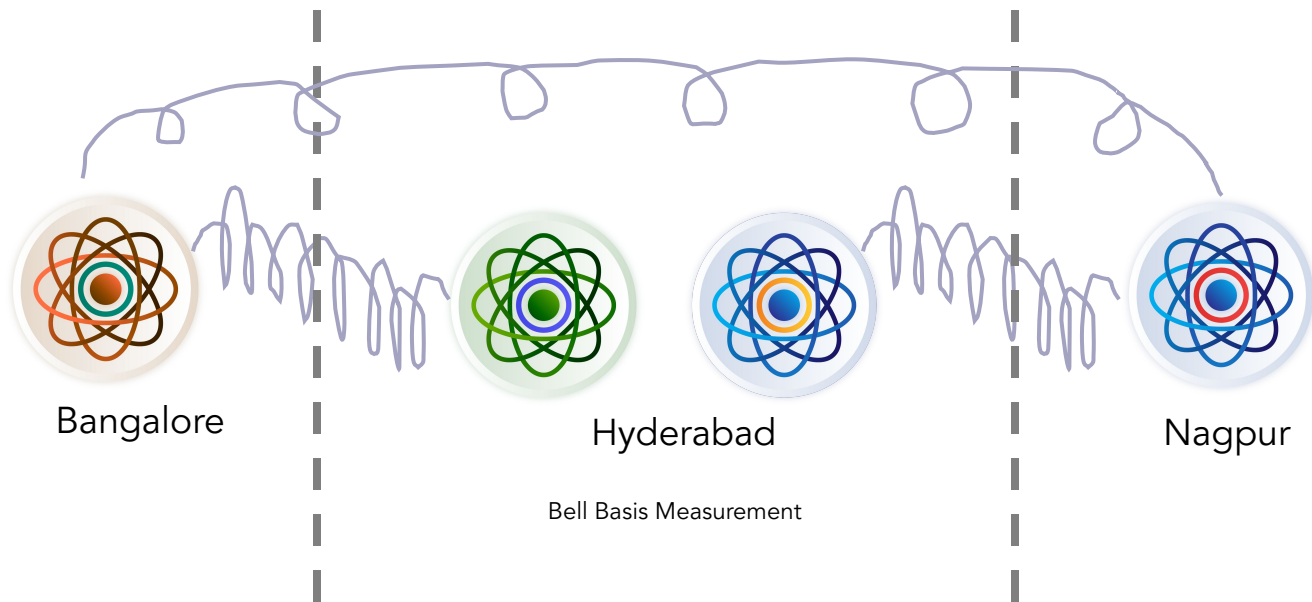
Site B



$$|\psi\rangle = a|0\rangle + b|1\rangle$$

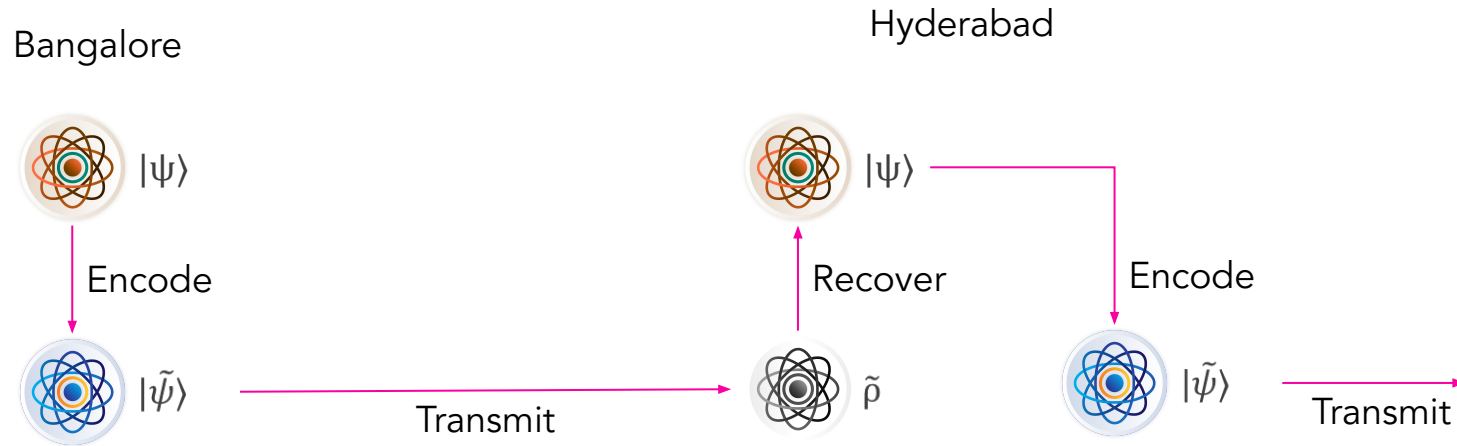
Bell Basis Measurement

Entanglement Swapping



0→000
1→111

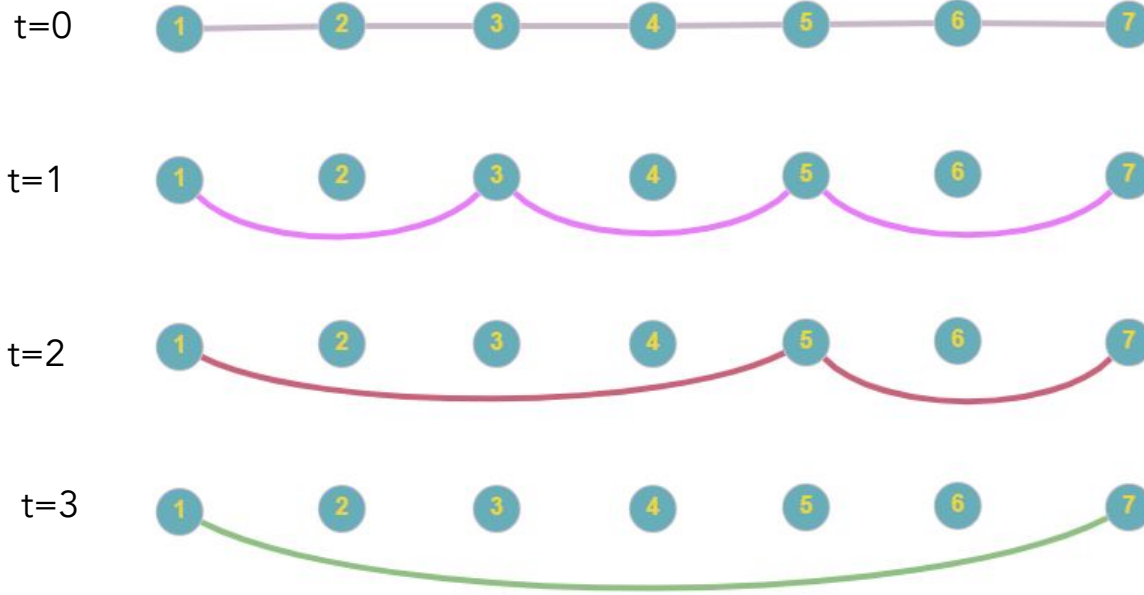
Hop by Hop Transmission with Error Correction



Encoding Techniques: Quantum Parity Code, CSS

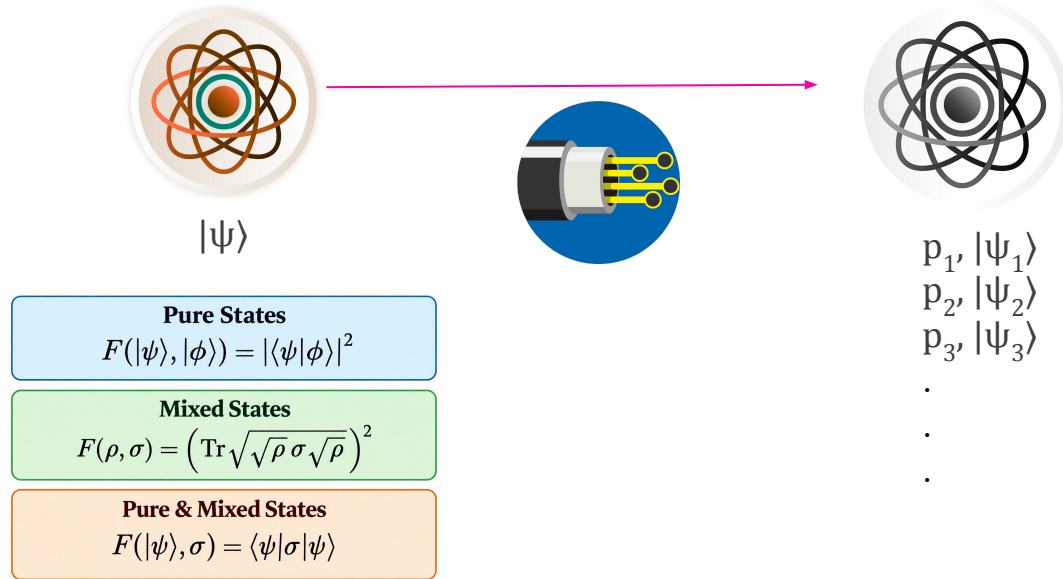
Requires Sophisticated Hardware

End to End Entanglement



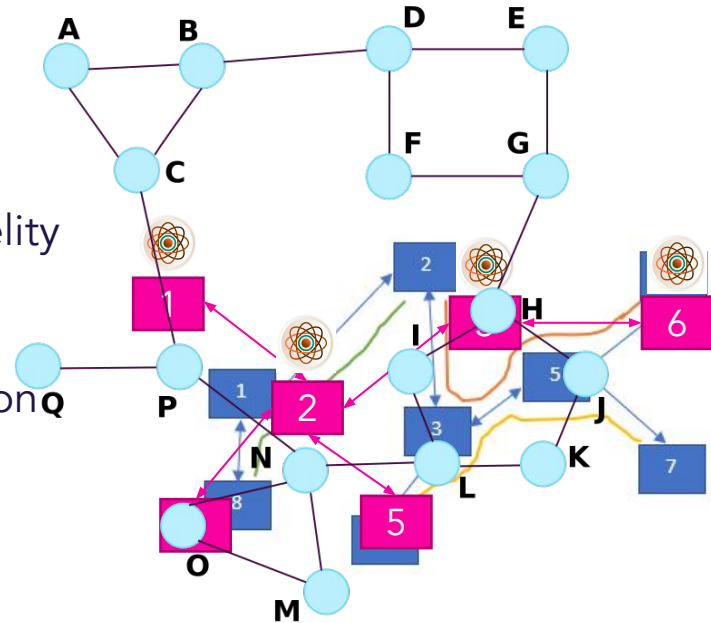
Time Units consumed = $\lceil \log_2 n \rceil$ where n = no of intermediate edges

Fidelity

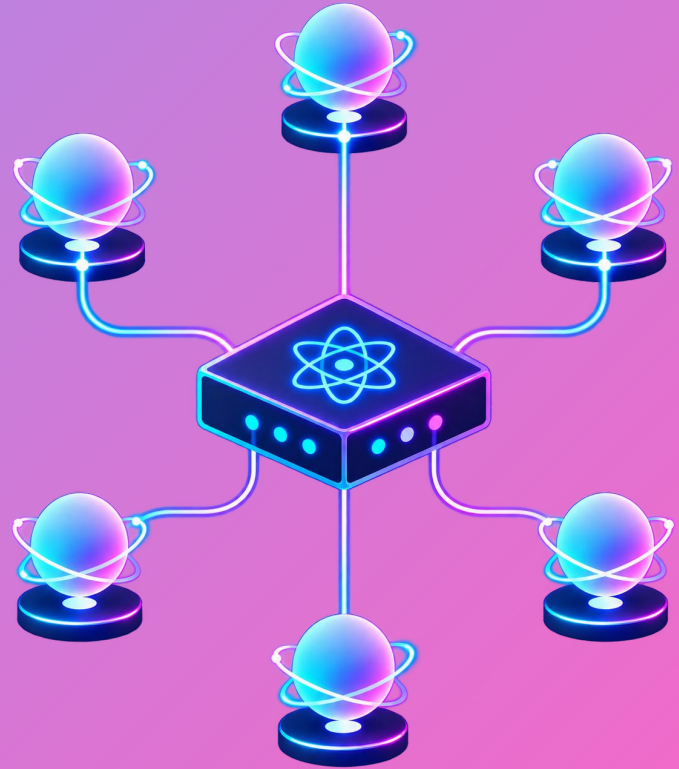


Quantum routing

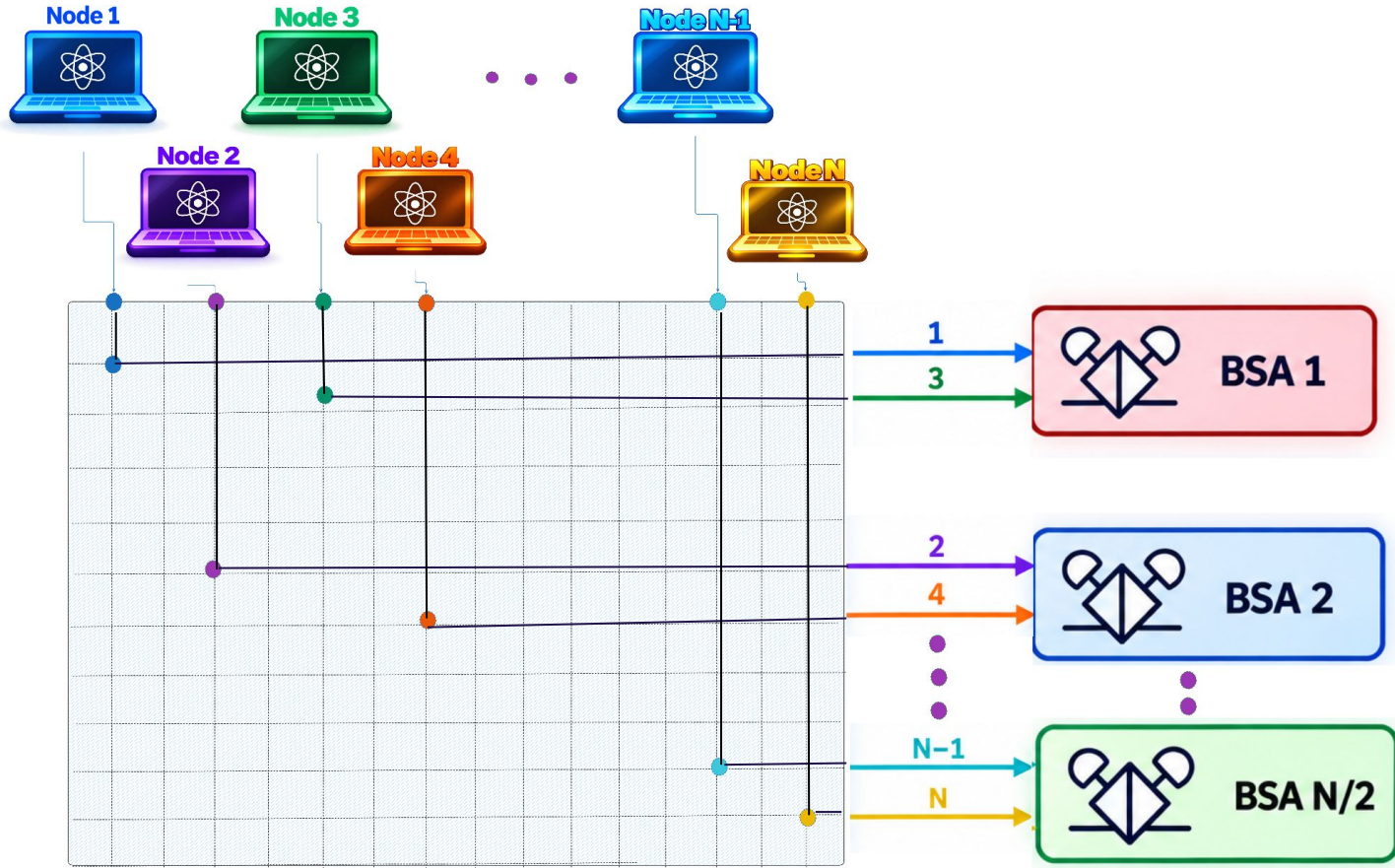
- Introduction
- Challenges
 - No retransmission
 - Hop by Hop teleportation reduces fidelity
 - One unit of Quantum Communication requires Entanglement, Swapping, Purification and Classical communication
- Decoherence
- Multiplexing



Quantum Infrastructure: Switch to End Node



Quantum Switch: Crossbar Architecture



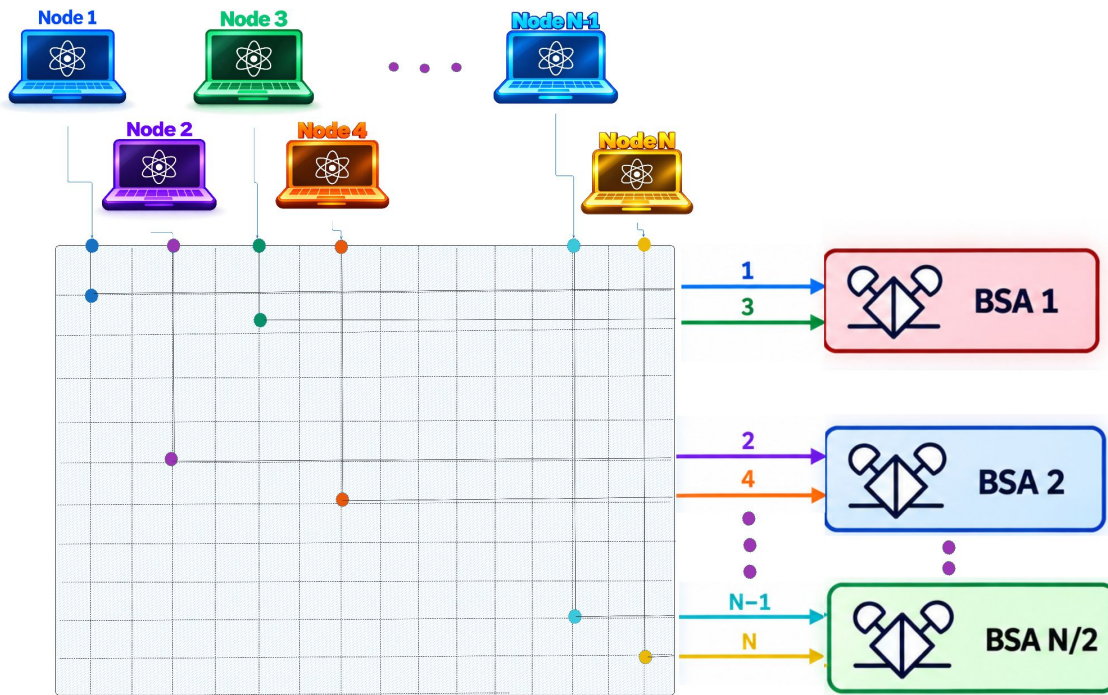
Simplicity & Scalability



**Zero Memory
Overhead**
Switches photons
immediately

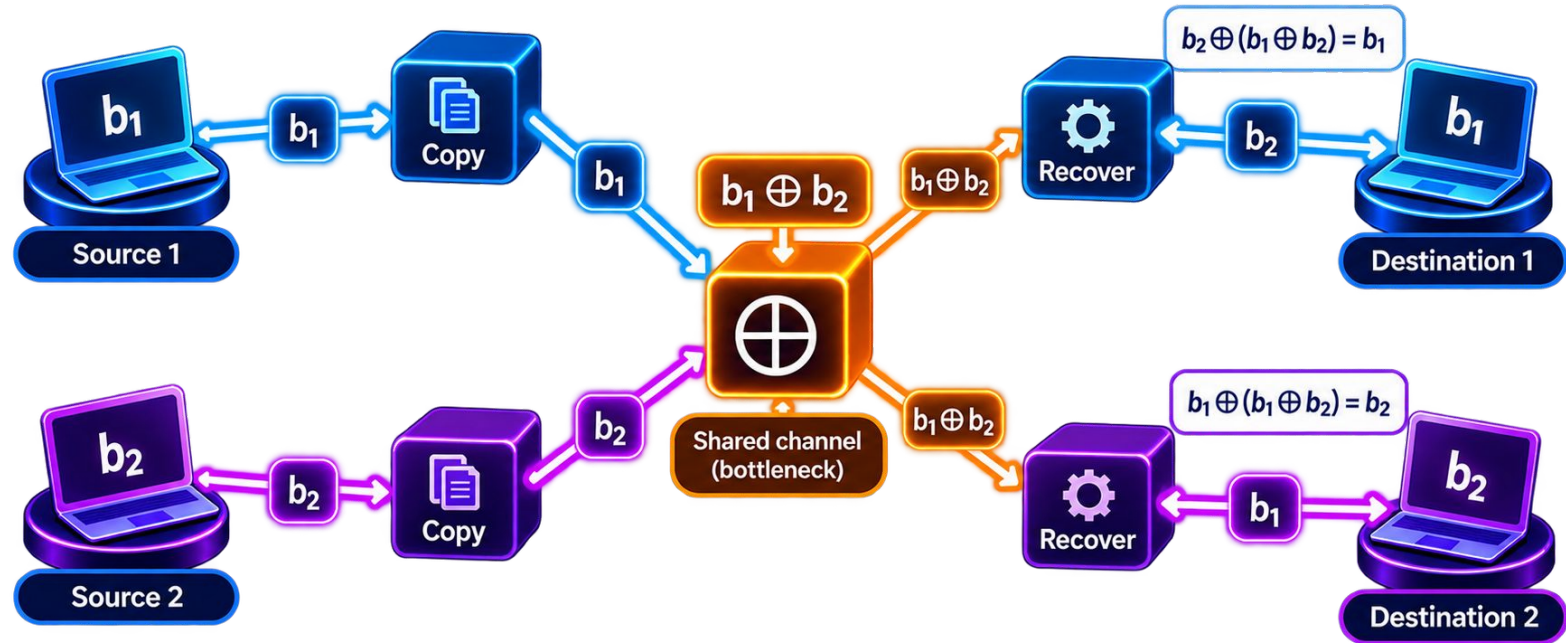


**Strict
Non-Blocking**
All N nodes can pair
concurrently



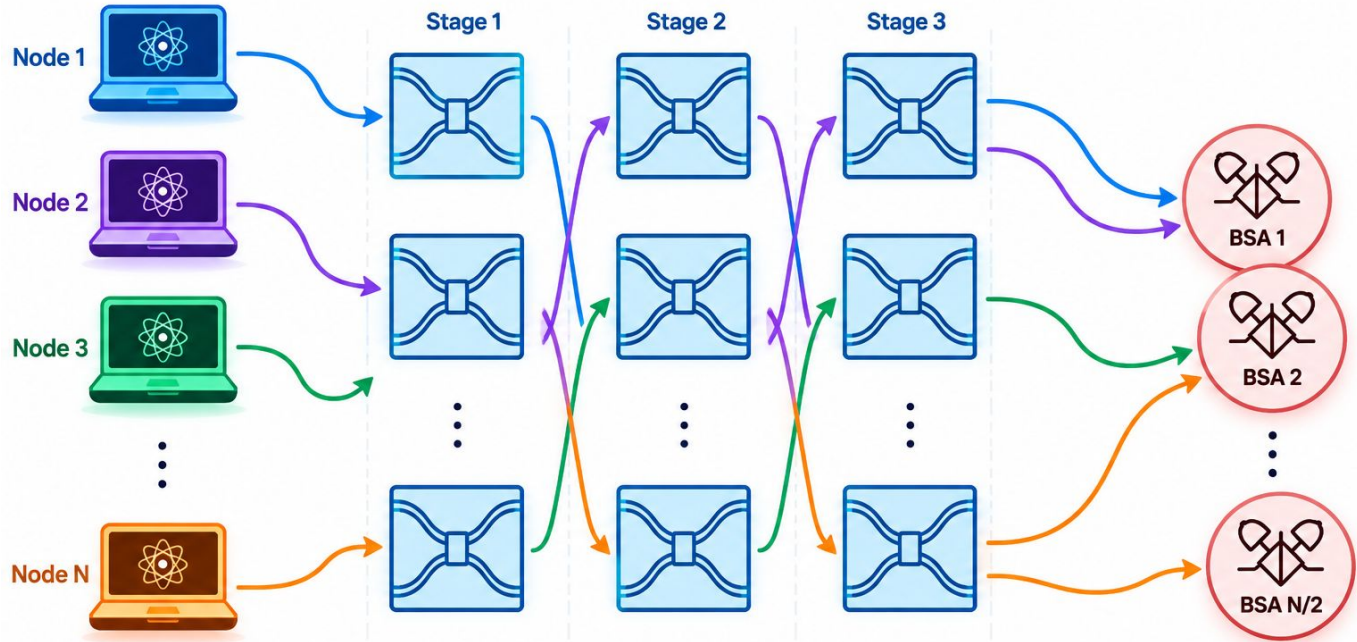
Network Coding: Butterfly Topology

Classical

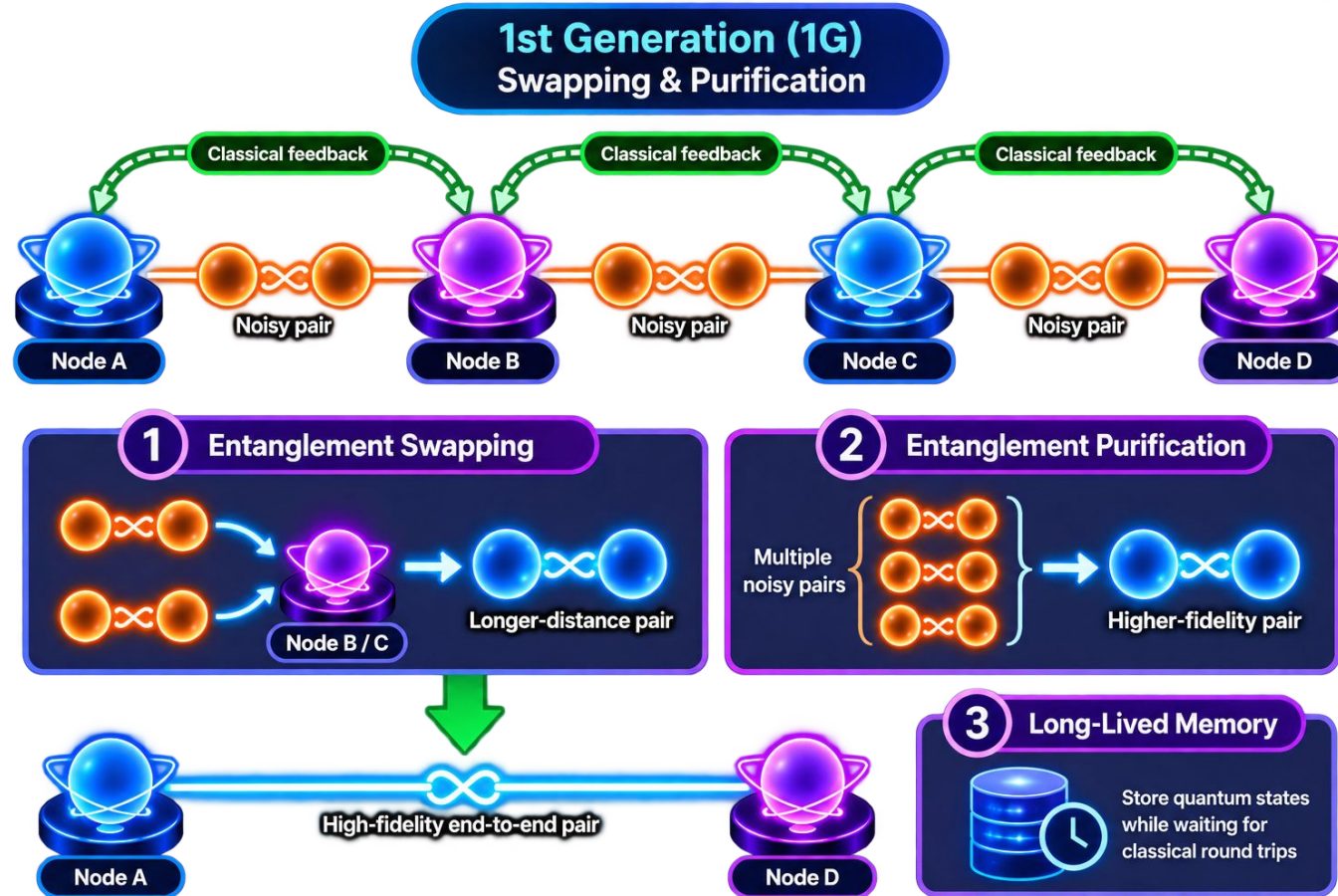


Network Coding: Butterfly Topology

Using a multi-stage interconnect
comprised of smaller switches
(also called a *butterfly network*)

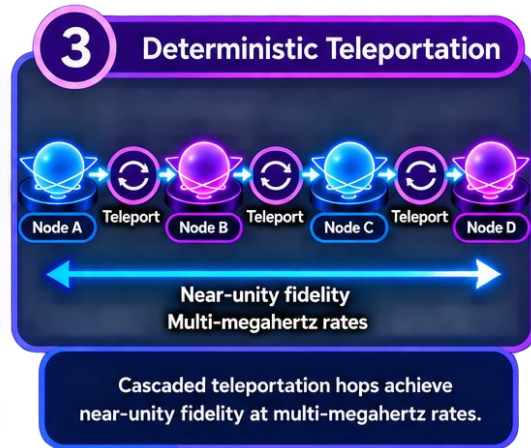
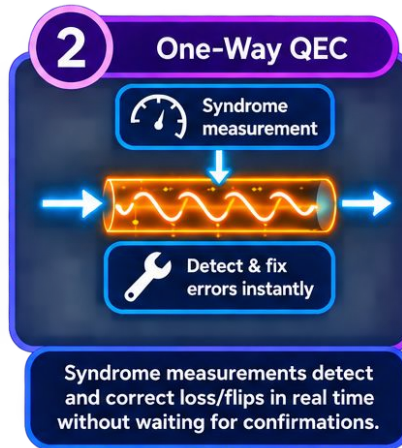
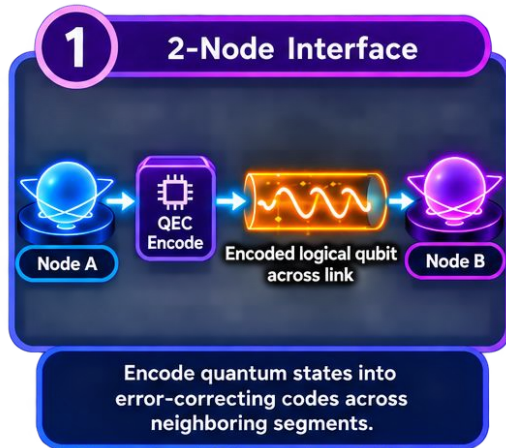
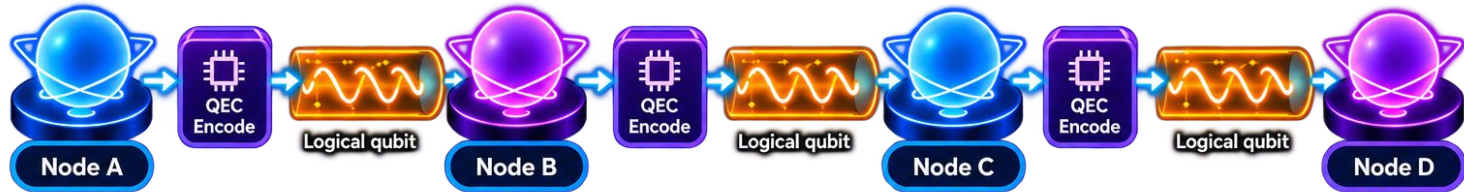


Quantum Repeaters: 1G

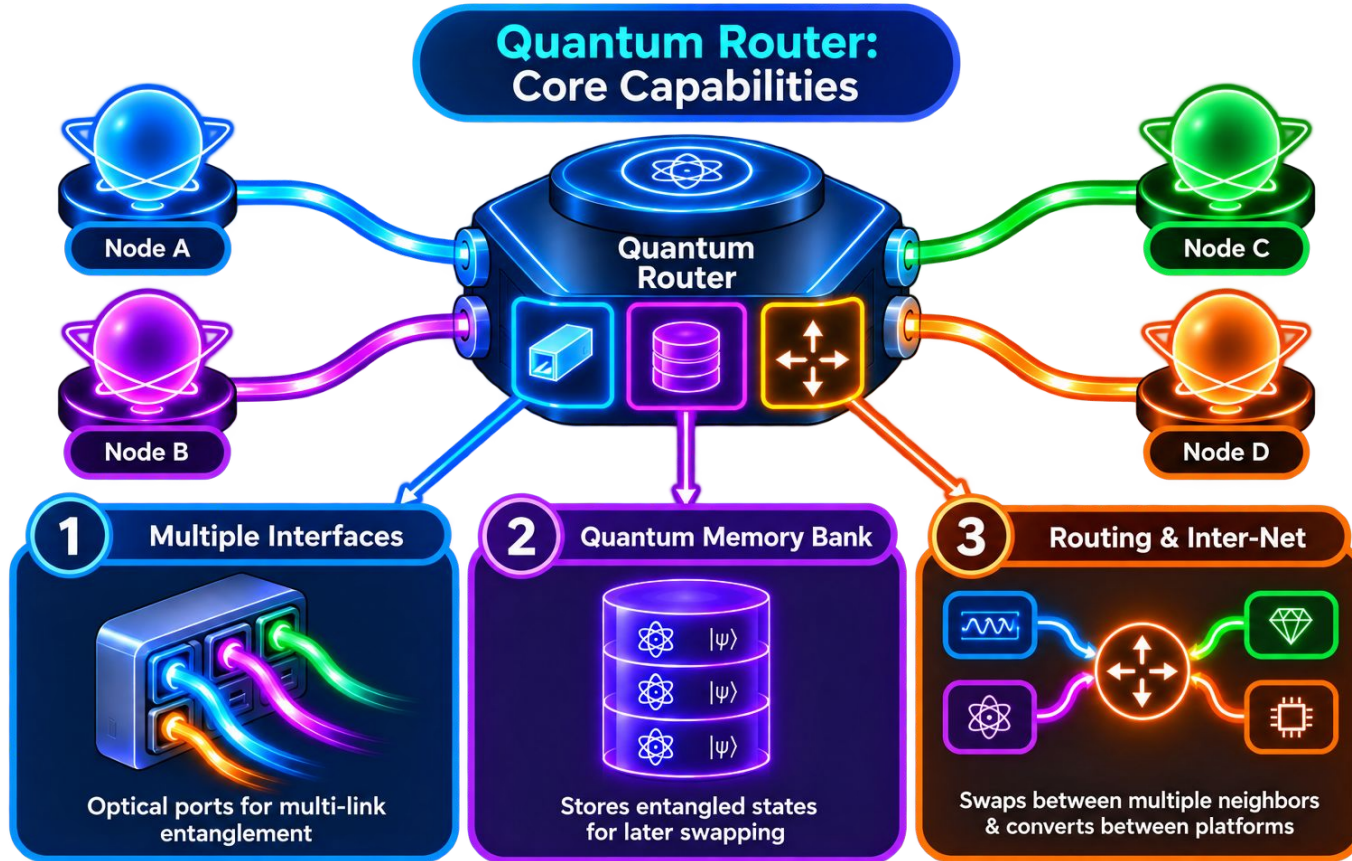


Quantum Repeaters: 2G

2nd Generation (2G) Error Correction & Teleportation

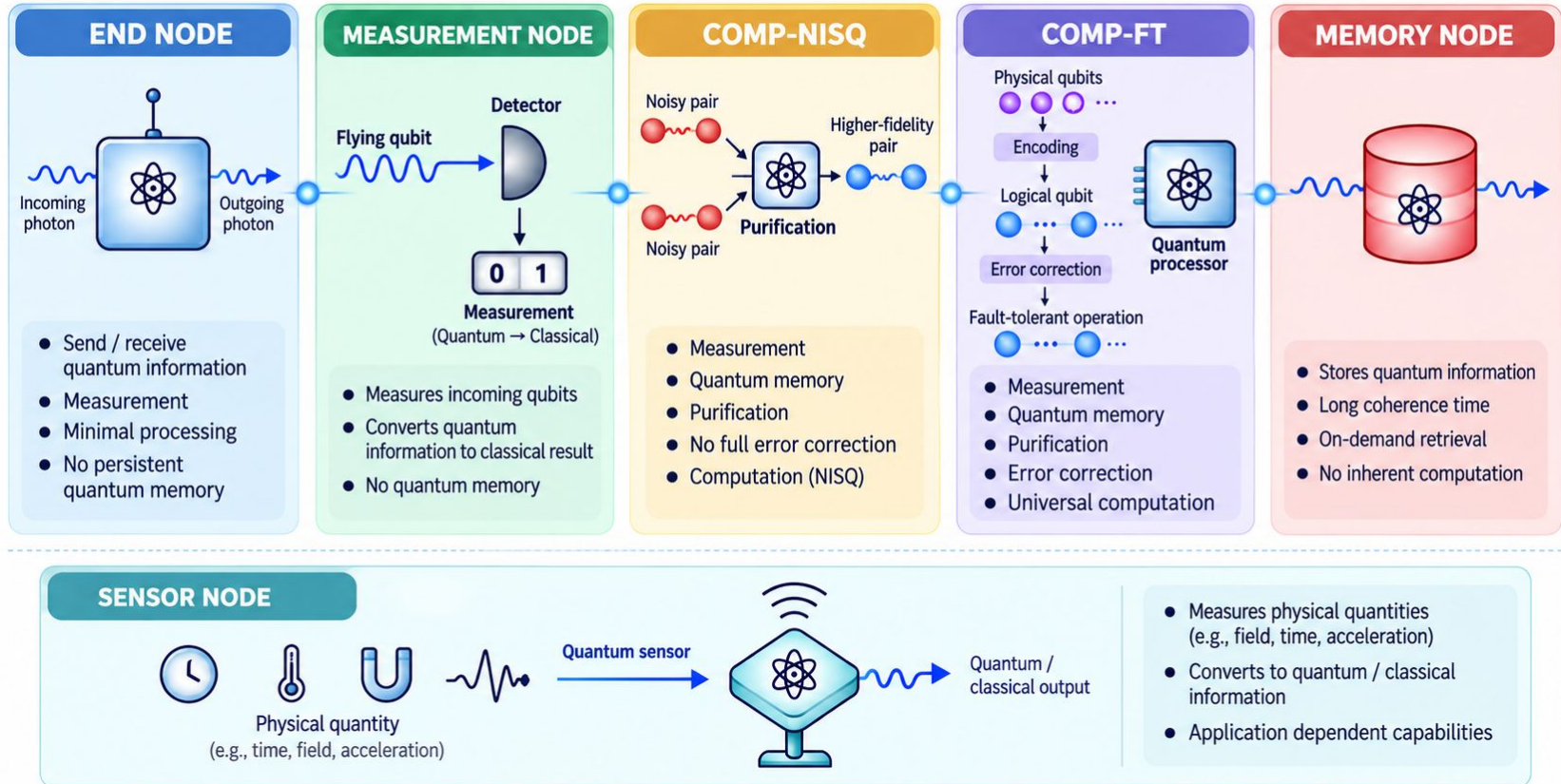


Quantum Router



Quantum Network: Node Types

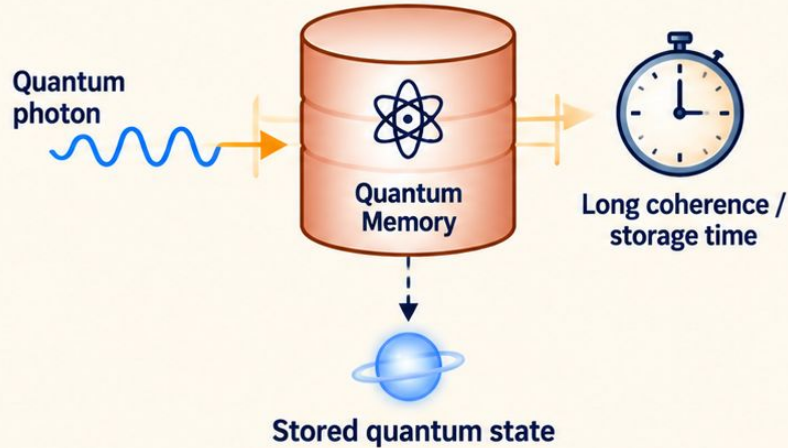
Quantum Network Nodes



Specialized Quantum Nodes

Memory Node

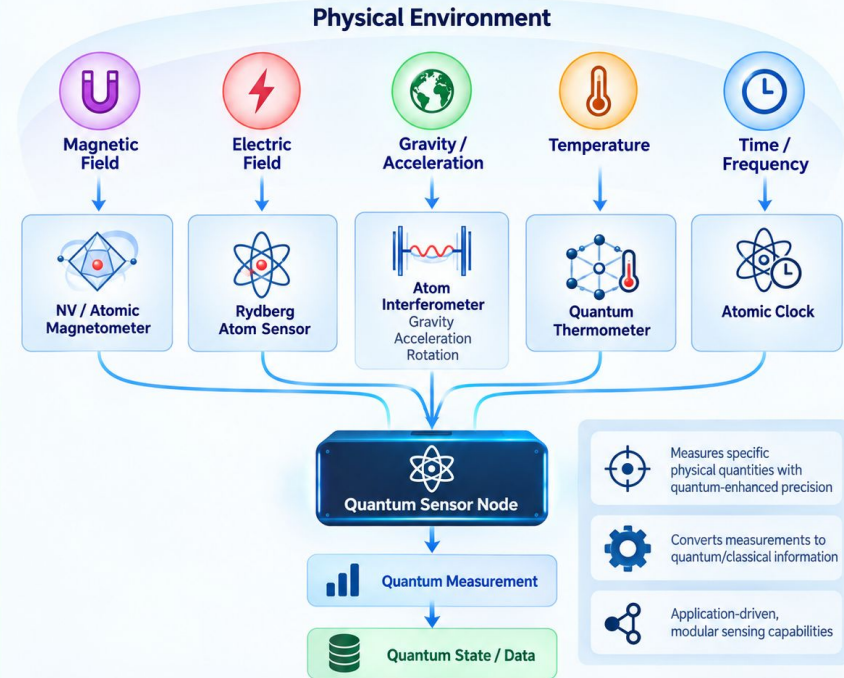
For quantum state storage



- Stores quantum information
- Long coherence time (relative to network protocol)
- On-demand retrieval
- No inherent computation

Quantum Sensor Node

Interfaces the quantum network with the physical world

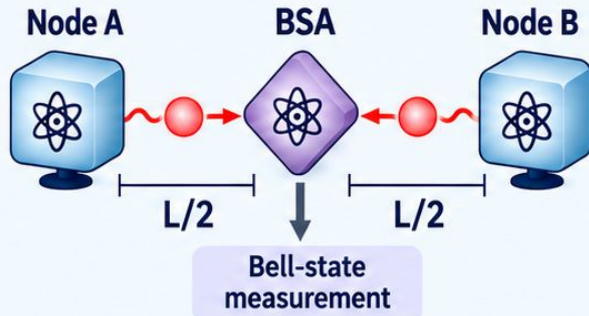


SENSE | CONNECT | ENABLE A QUANTUM-POWERED TOMORROW

Quantum Link Architectures

A. Midpoint BSA (MIM)

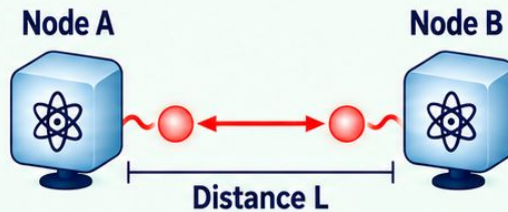
Two nodes and one BSA at the middle



- Photons/qubits from two nodes travel to a central BSA
- BSA performs Bell-state measurement
- Used for entanglement generation between distant nodes

B. Direct Connection

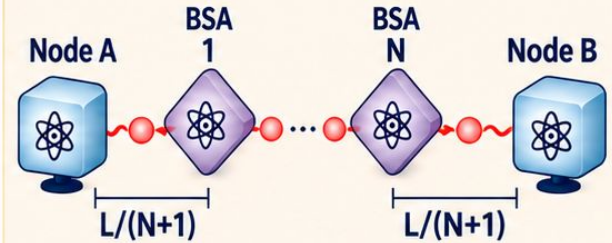
Two nodes with a direct quantum link



- Direct quantum link between two nodes
- Qubits/photons transmitted over distance L
- Simplest architecture
- Challenging for long distances due to loss and decoherence

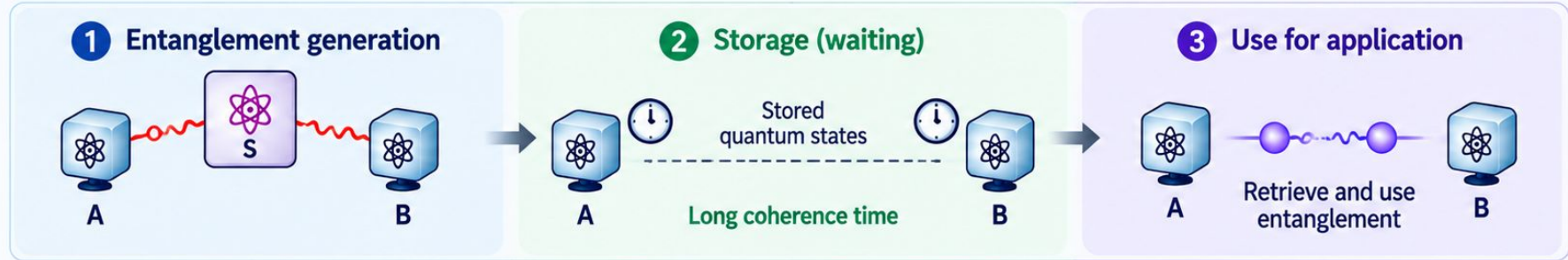
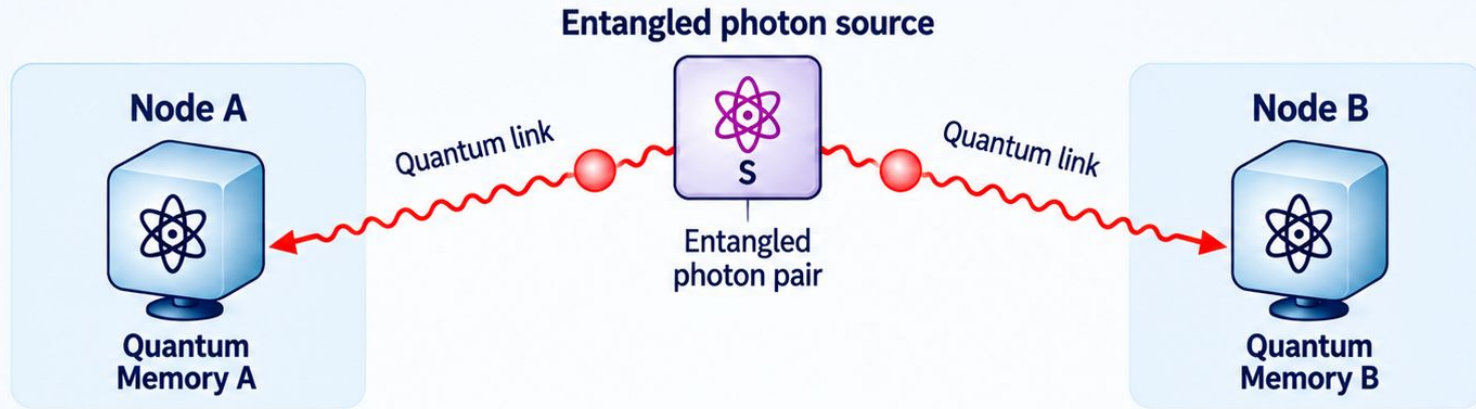
C. Multi-hop (Entanglement Swapping)

Multiple intermediate BSAs



- Multiple intermediate BSAs between two nodes
- Entanglement swapping at each BSA extends the link
- Enables long-distance quantum communication
- Requires synchronization and high-fidelity operations

Memory-Source-Memory Architecture



The memories decouple entanglement generation from when the application actually uses the entanglement.

Quantum Link Challenges



Cost

Expensive hardware and infrastructure



Fidelity

Fidelity ↓
Noise and imperfect operations degrade the quantum state.



Line of sight

Important particularly for free-space optical and satellite links.



Node A



Atmospheric loss



Beam spreading



Environmental noise



Maintenance



Node B



Noise

Background photons, detector noise, channel noise.



Maintenance

Alignment, optics, detectors, cooling, etc.



Scaling

A system that works for two nodes may become difficult to operate with hundreds or thousands.

Long-distance quantum link

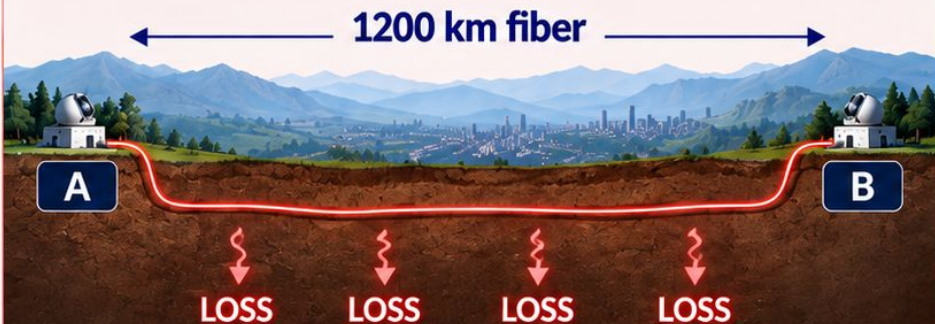
Satellite Based Entanglement Distribution



Why Use a Satellite for Long-Distance Entanglement?

Direct Fiber Link

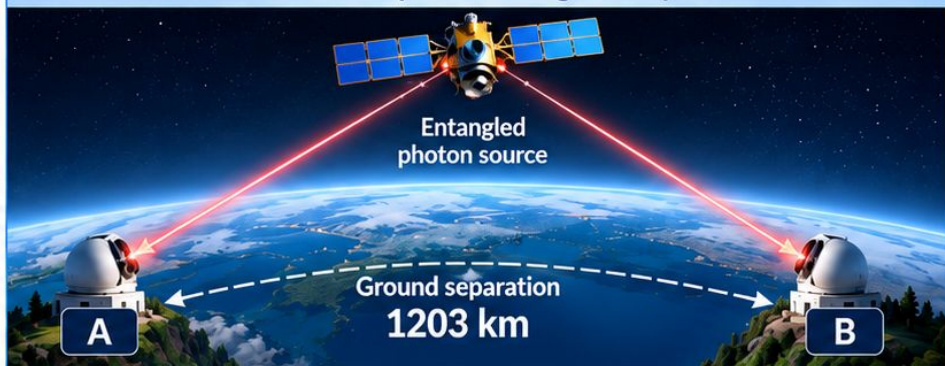
Long distance fiber suffers enormous loss



Long distance → enormous accumulated attenuation
Photons are lost in the fiber over hundreds to thousands of kilometers.

Satellite Link

Most of the path is through free space



Key challenges for satellite links



Atmospheric loss

Attenuation and turbulence are particularly severe in the lowest ~ 10 km of atmosphere.



Beam spreading

Beam diverges over distance, reducing the photon count at the ground.



Pointing / tracking

Requires precise pointing and tracking of the satellite and ground stations.



Weather

Cloud cover, rain and atmospheric conditions can block or degrade the link.



Limited availability

Link only available twice per day due to Low Earth Orbit (LEO) satellite passes.

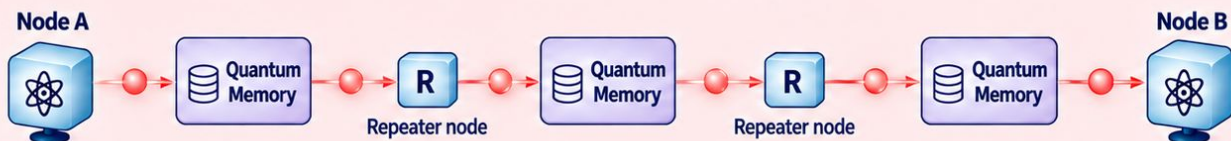


Satellites enable long-distance entanglement by avoiding thousands of kilometers of lossy fiber, at the cost of atmospheric, pointing, weather and operational constraints.

Repeater Graph States

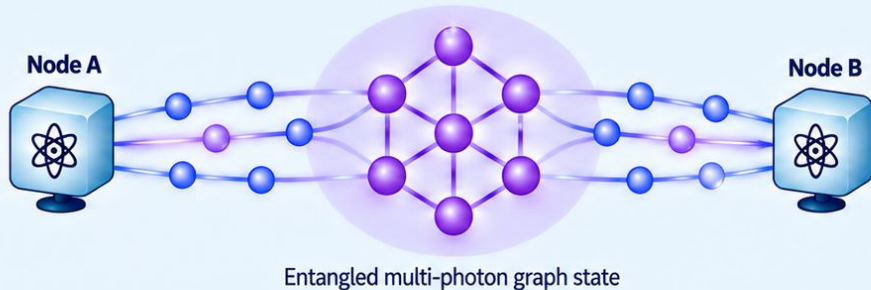
Repeater Graph States: Quantum Repeater Without Long-Lived Memory

Traditional Quantum Repeater



Long-lived quantum memory required

Repeater Graph State (RGS)



Flying qubits



Measurements



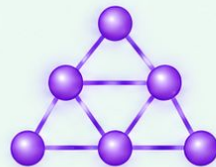
Classical feed-forward



Long-distance entanglement



Flying photonic qubits



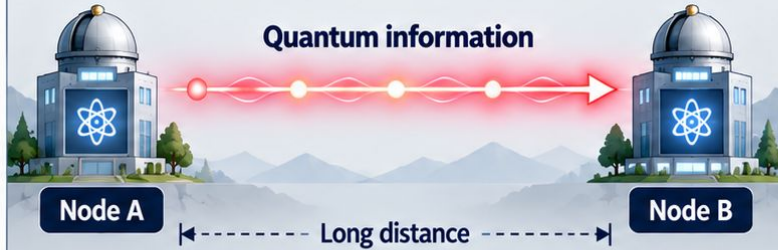
Structured graph state enables loss tolerance



Use many entangled photons and measurements instead of long-lived memory to achieve long-distance entanglement.

Sneakernet / Physical Quantum Memory Transport

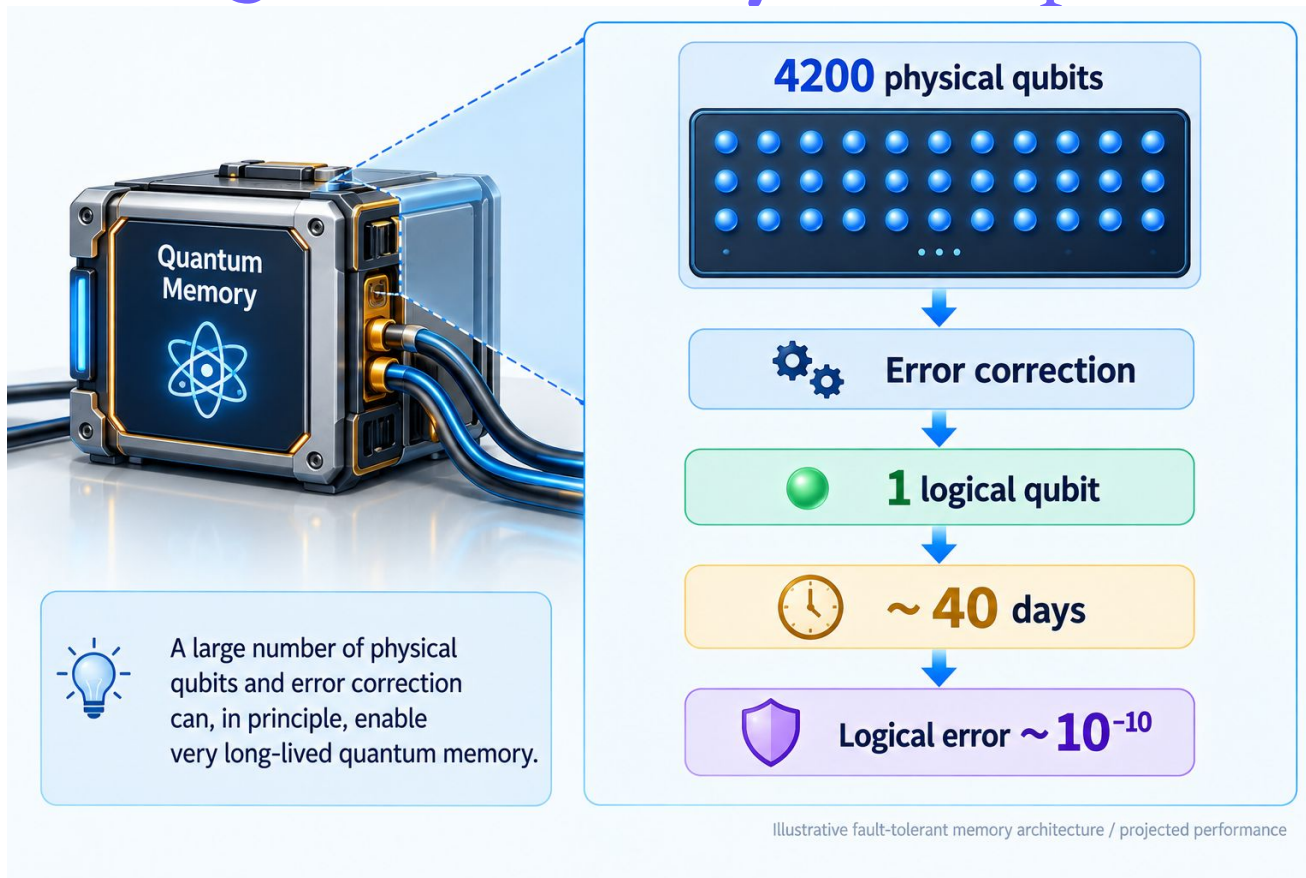
Conventional Quantum Network



Sneakernet: Physically Moving Quantum Memory



The 4200-Qubit / 40-Day Example



How Do We Identify a Physical Qubit?



Qubit address =

(Node/NIC ID, QubitIndex)

Analogous to classical networking:

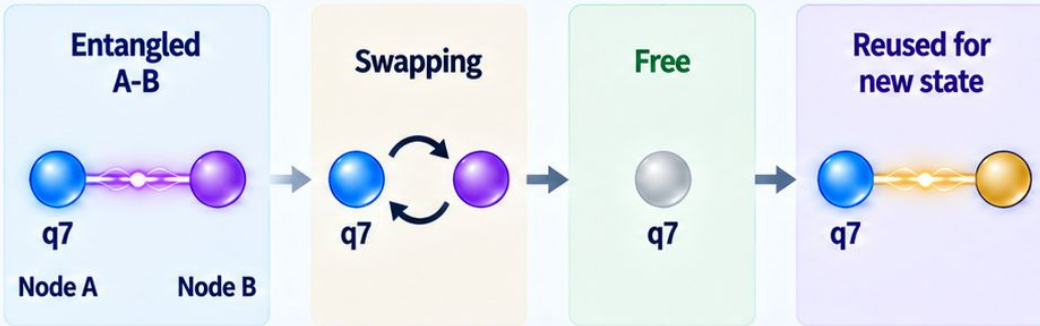
Network address +
Interface/port



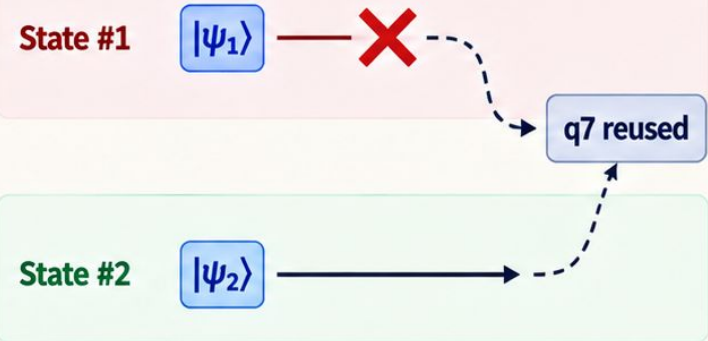
The Qubit-Reuse Problem

Node A / q7

Time →



QubitIndex = q7

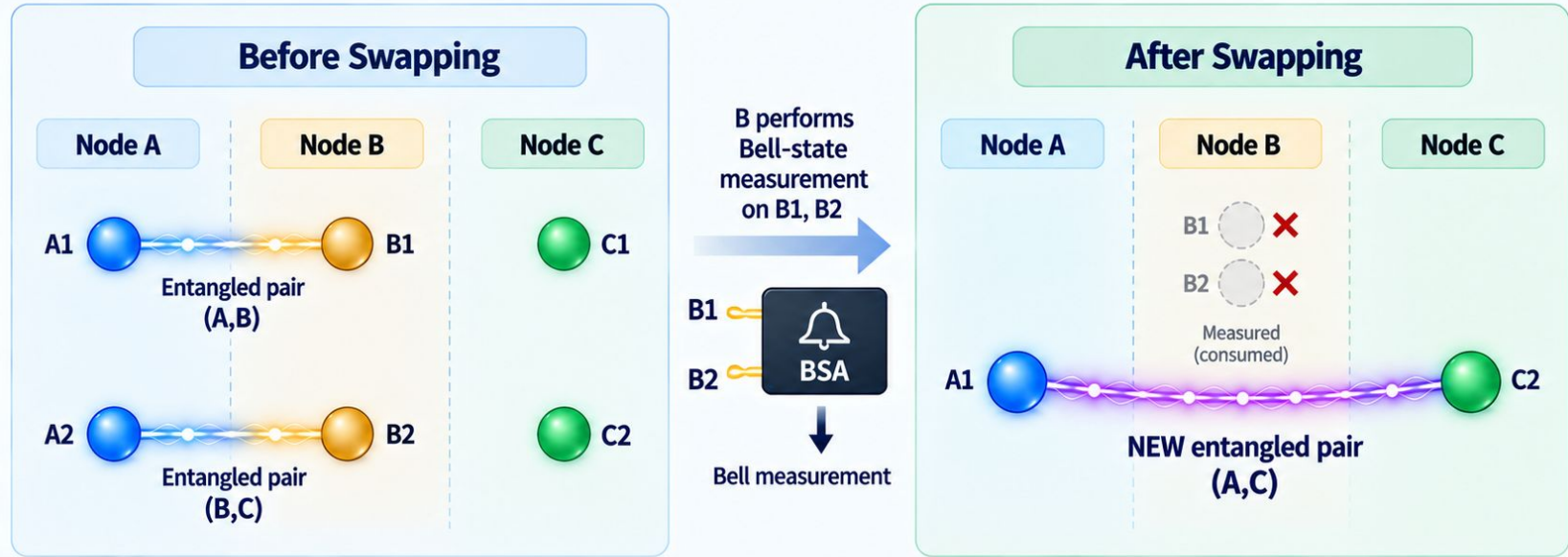


Does q7 identify the physical qubit or the quantum state that currently occupies it?



It should identify the physical resource, not permanently identify the state.

Entanglement Identity After Swapping

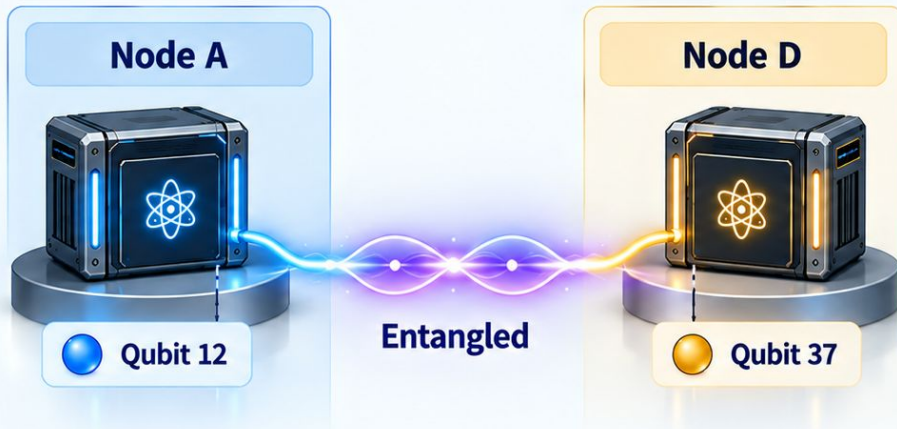


**Physical-qubit identity
≠ entangled-state identity.**



- Entanglement swapping creates a new entangled pair (e.g., A and C).
- The original physical qubits at B can be measured and consumed.
- Qubit identifiers refer to physical resources, not to a specific entangled state.

How Do We Name a Distributed Quantum State?



A distributed identifier tracks the entangled state across network nodes.



Entanglement Record



State ID: **E-10482**



Endpoint 1: **(Node A, q12)**



Endpoint 2: **(Node D, q37)**



State: **Bell pair $|\Phi^+\rangle$**



Fidelity: **0.93**



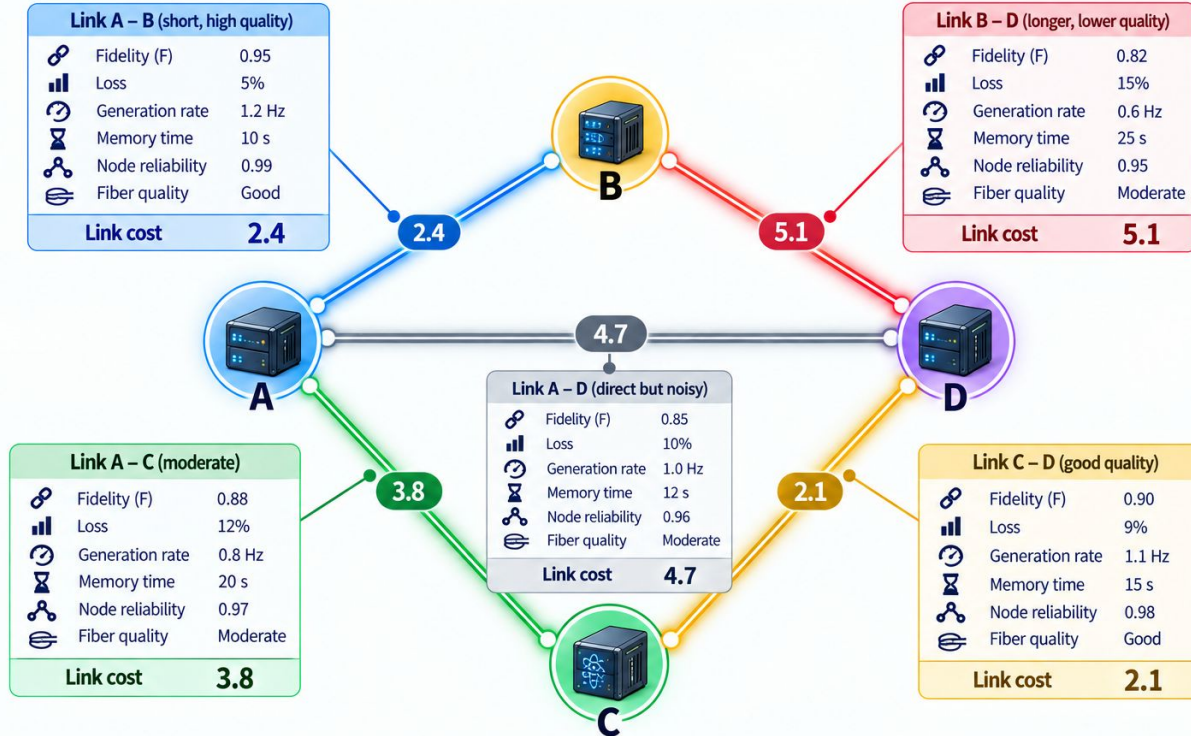
Created: **t_0**



Expires / coherence: **$t_0 + T$**

Quantum Network Routing — Q-Dijkstra

Each link has multiple quantum metrics, and the link cost is computed from them.



Quantum Link Metrics



Link fidelity (F)

Probability that entanglement is correct



Loss

Photon loss in fiber / free space



Entanglement generation rate (R)

Rate of successful entanglement (Hz)



Memory coherence time (T)

Time qubits can be stored



Fiber / channel quality

E.g., attenuation, noise, turbulence



Node reliability (N)

Uptime and success probability of intermediate nodes



Other factors

Queueing / congestion, wavelength availability, stability, etc.

Quantum Network Routing — Q-Dijkstra

Path Comparison (Example)

Path	Links (sum of costs)	End-to-end fidelity ($\approx$ product)	Generation rate (min)	Memory time (along path)	Node reliability ($\approx$ product)	Total path cost	Remarks
A $\rightarrow$ B $\rightarrow$ C	2.4 + 5.1 = 7.5	0.91×0.82 = 0.75	0.8 Hz	5 s	0.99×0.95 = 0.94	7.5	Higher loss, lower rate, shorter memory time
A $\rightarrow$ D $\rightarrow$ C	3.8 + 2.1 = 5.9	0.88×0.90 = 0.79	1.1 Hz	15 s	0.97×0.98 = 0.95	5.9	Better overall performance
A $\rightarrow$ C	4.7	0.85	1.0 Hz	12 s	0.96	4.7	Direct but lower fidelity

Example Link Cost Function

$$C_{i,j} = w_1(1 - F_{i,j}) + w_2 L_{i,j} + w_3 \frac{1}{R_{i,j}} + w_4 T_{i,j} + w_5(1 - N_j) + w_6 Q_{i,j}$$

$F_{i,j}$: link fidelity

$L_{i,j}$: loss (e.g., dB or %)

$R_{i,j}$: entanglement generation rate

$T_{i,j}$: memory time

N_j : node reliability

$Q_{i,j}$: fiber / channel quality

$w_1 \dots w_6$: weighting
factors (tuned
per application)

Optimal Route

A $\rightarrow$ D $\rightarrow$ C

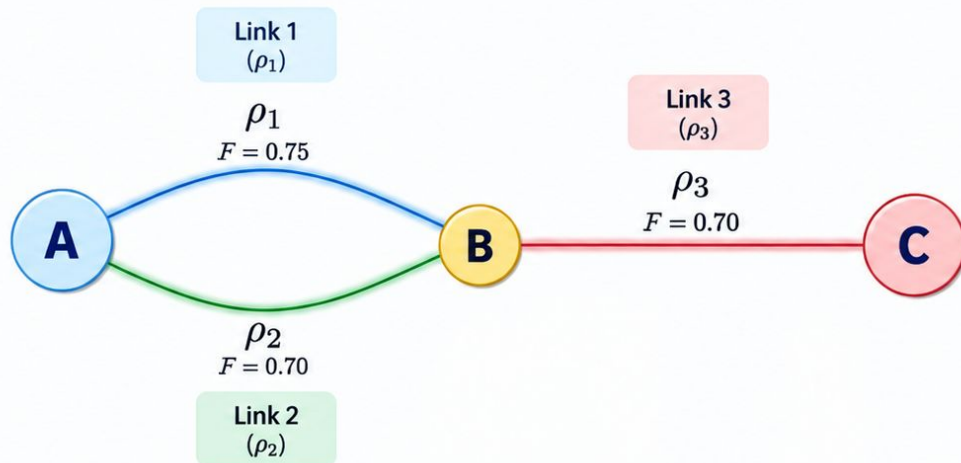
Selected path with the lowest total cost
based on quantum link metrics,
not just the fewest hops.

Local Optimum vs Global Optimum

Quantum Routing: Local Optimum $\neq$ Global Optimum

An apparently better sub-path may not lead to the best end-to-end fidelity!

(Di Franco and Ballester, 2012)



$$\rho_1 = \rho_Z(0.75)$$

$$\rho_2 = \rho_X(0.70)$$

$$\rho_3 = \rho_X(0.70)$$

A, B, C : Network nodes

ρ_i : Quantum channel on link i

F : Fidelity after entanglement swapping

Naïve expectation (local view)

Since $\mathcal{F}(\rho_1) > \mathcal{F}(\rho_2)$, you would expect

$$\mathcal{F}(\rho_1 + \rho_3) > \mathcal{F}(\rho_2 + \rho_3)$$

Actual result (global view)

$$\text{Path A} \rightarrow \text{B} \rightarrow \text{C} \quad (\rho_1 + \rho_3) \quad \mathcal{F}(\rho_1 + \rho_3) = 0.525$$

$$\text{Path A} \rightarrow \text{B} \rightarrow \text{C} \quad (\rho_2 + \rho_3) \quad \mathcal{F}(\rho_2 + \rho_3) = 0.580$$

Thus,

$$\mathcal{F}(\rho_2 + \rho_3) > \mathcal{F}(\rho_1 + \rho_3)$$

The path with the locally worse link (ρ_2) gives a higher end-to-end fidelity!

Building the Quantum Network of Tomorrow

Heterogeneous | Scalable | Fault-Tolerant



Connect.



Preserve.



Route.



Compute.

Towards a globally interconnected Quantum Internet.

"The future of quantum networking will not be defined by a single technology, but by how effectively we connect them into one intelligent, scalable quantum infrastructure."

Thank You

Questions?