CSC 36000:
Modern Distributed Computing *with AI Agents*

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Today's Lecture

The Scaling Limit

The Quantum Interconnect
- Flying Qubits (Photons)
- Transduction

Distributed Quantum Protocols
- Quantum Teleportation
- Entanglement Swapping

AI Agents in the Quantum Internet

The Scaling Limit

Why Distributed Quantum Computing?

Current Quantum Processing Units (QPUs) like IBM Eagle or Google Sycamore have ~50-1000 qubits.

Cooling: Keeping large chips at nearly absolute zero (mK) requires massive dilution refrigerators.

Crosstalk: As you pack qubits closer, they interfere with each other, increasing noise (decoherence).

Control Wiring: It is physically difficult to route thousands of control wires to a single chip inside a cryostat.

The Distributed Quantum Solution

Instead of one giant 100,000-qubit chip, we use Distributed Quantum Computing (DQC).

Interconnect many smaller, high-fidelity QPUs (e.g., 50 qubits each) to function as one massive logical computer.

The Quantum Interconnect

Architecture of a Distributed Quantum Computer

Nodes (Q-Nodes): Small quantum processors (Trapped Ion, Superconducting, etc.) containing:

- Data Qubits: For computation.
- Communication Qubits: Interface with the network (usually optical).

Channels (Quantum Links):

- Fiber optic cables carrying photons ("flying qubits").
- Unlike distributed classical computing, we cannot just copy data (No-Cloning Theorem).
- We must establish Entanglement between nodes.

Stationary vs Flying Qubits

Stationary Qubits: Matter-based (Superconducting circuits, Atoms). Good for storage and gates.

Flying Qubits: Light-based (Photons). Good for travel over fiber optics.

Transduction

We need a transducer to convert the state of a stationary qubit (microwave freq) to a flying qubit (optical freq) without destroying the quantum state.

Analogy: Like a Modem converting digital signals to analog for phone lines, but preserving quantum superposition.

Distributed Quantum Protocols

Quantum Teleportation

Problem: We cannot physically send a matter qubit from Node A to Node B easily.

Mechanism: Quantum Teleportation.

1. Entanglement: Node A and Node B share an entangled pair of particles (Bell pair).
2. Local Operation: Node A performs a measurement on its qubit and the qubit it wants to send.
3. Classical Communication: Node A sends 2 classical bits of measurement results to Node B.
4. Correction: Node B applies a gate (Pauli-X/Z) based on those bits to recover the original state.

Key Takeaway: The "Quantum Information" is transferred, not the particle itself.

Entanglement Swapping

Distance Limit: Photons are lost in fiber optics over long distances (attenuation). Classical repeaters (amplifiers) destroy quantum states (No-Cloning).

Quantum Repeaters:

- If Node A is entangled with Repeater R, and R is entangled with Node B...
- R performs a Bell State Measurement (BSM) on its two qubits.
- Result: Node A becomes entangled with Node B, even though they never interacted directly.
- This "swaps" the entanglement to span the full distance.

Distributed Quantum Gates

Non-Local Gates:

- To run a distributed algorithm (like Shor's), we often need a CNOT gate where the Control is on Node A and the Target is on Node B.

Telegate:

- We consume one pre-shared entangled pair (an "ebit") to perform one cross-node gate.
- Cost: Distributed gates are expensive! They require consuming entanglement resources and classical communication time (latency).
- Optimization: Algorithms must minimize the "cut" across nodes (minimize non-local gates).

AI Agents in the Quantum Internet

The Complexity of Management

Quantum networks are fragile. Links (entanglement) degrade within microseconds (decoherence).

Resources (Bell pairs) are consumed immediately upon use.

AI Agent Roles

Entanglement Routing: Agents decide the optimal path to "swap" entanglement to connect Alice and Bob before the qubits decohere. (Reinforcement Learning).

Fidelity Estimation: Agents monitor the noise levels of links and route around "noisy" channels.

Purification Scheduling: Agents decide when to sacrifice two low-fidelity pairs to create one high-fidelity pair (Entanglement Purification).

Converging on Modern Distributed Computing

Modern Distributed Computing is evolving from sending bits to sending qubits.

Similarities: We still face latency, bandwidth, and consistency (fidelity) issues.

Differences:

- No-Cloning (cannot copy data for backup).
- Teleportation requires both quantum and classical channels.

Future: Hybrid Cloud-Quantum centers where AI Agents orchestrate the flow of classical and quantum data.

Questions?