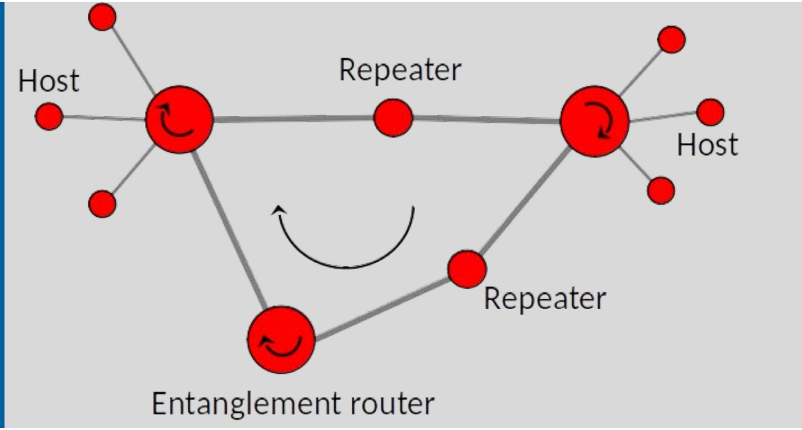


# SeQUeNCe – Simulator of Quantum Network Communication


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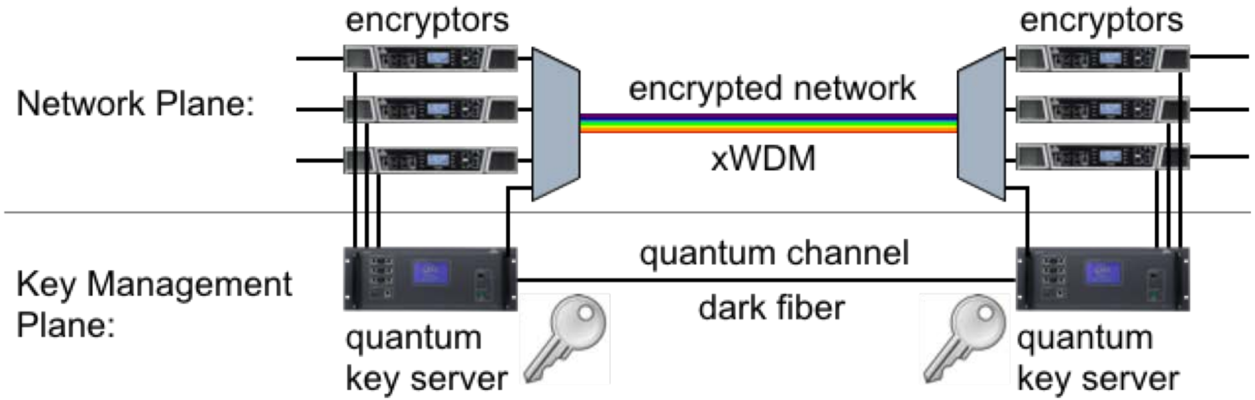
Argonne, IL

# QUANTUM KEY DISTRIBUTION NETWORKS

- Distributes secret key securely for use with private-key cryptography, offers "perfect" security guarantee




Beijing-Shanghai QKD Backbone

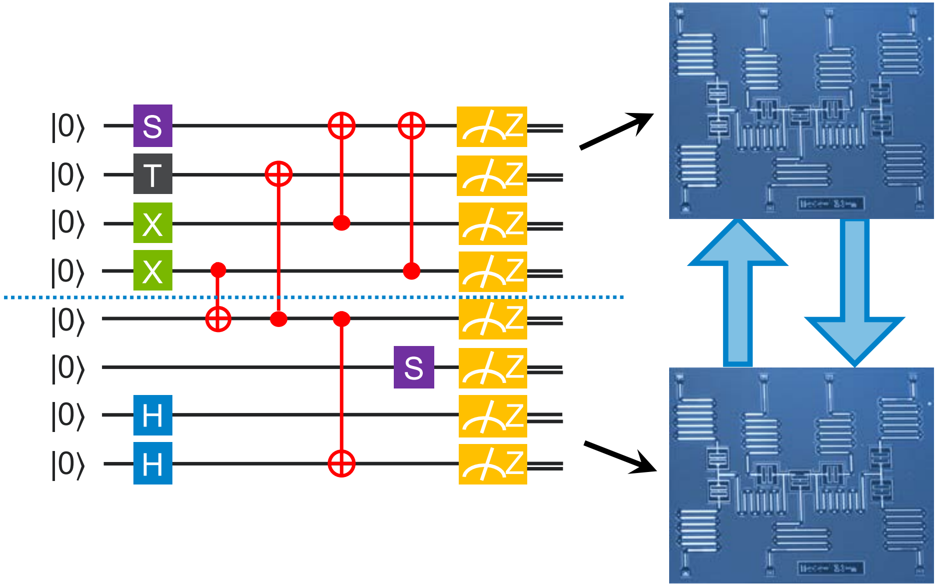
SwissQuantum Network


Tokyo QKD Network

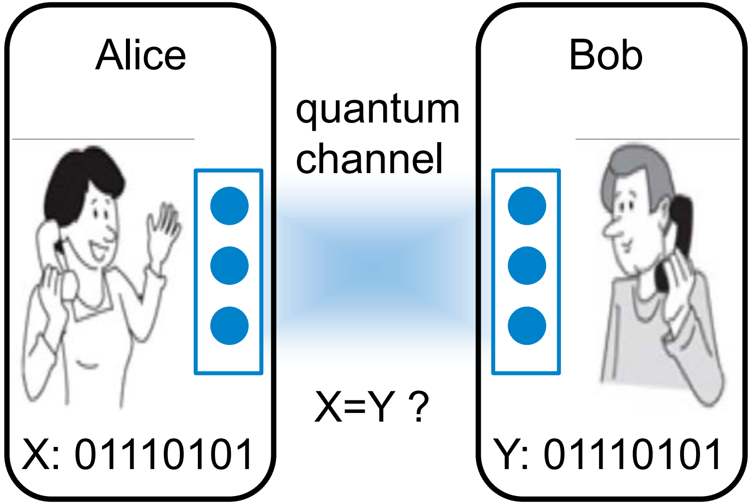
Battelle QKD Network, Columbus, OH

# QUANTUM NETWORK APPLICATIONS: DISTRIBUTED COMPUTATION

- Connecting small quantum processors allows solving larger problems:



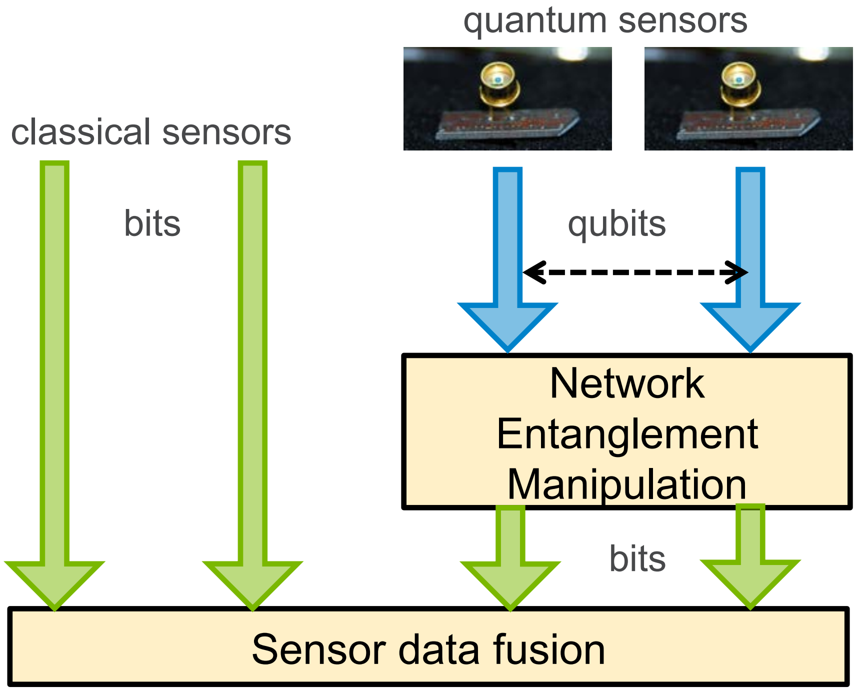

- Some distributed problems can be solved with exponential speedup:




Promise: Hamming distance n/2 or 0

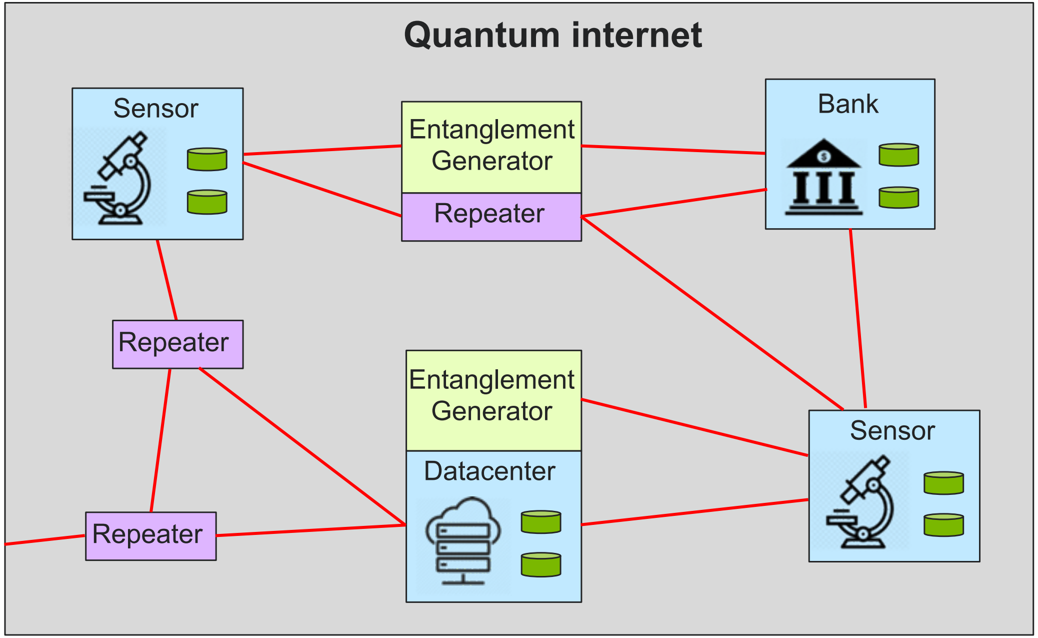
# QUANTUM NETWORK APPLICATIONS: SENSING

- Quantum sensing uses individual particles (photons, electrons) as sensors in measurements of forces, gravitation, electric fields etc.
- Heisenberg's uncertainty principle limits the precision; precision is enhanced by shifting the uncertainty to another variable (known as a squeezed state)
- Networked sensors exploit entanglement



# THE QUANTUM INTERNET

- Connected quantum sensors, accurate clock synchronization, secure delegated Quantum computing
- Bandwidth, latency and security requirements vary
- These applications require long-distance communication
- Multiple repeaters and entanglement generators are used



# QUANTUM TELEPORTATION NETWORKS

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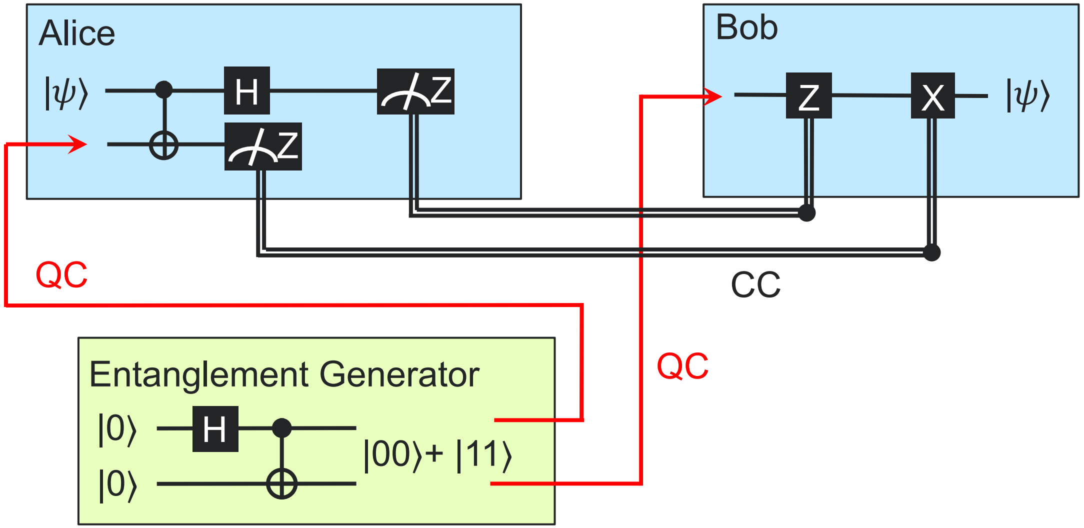
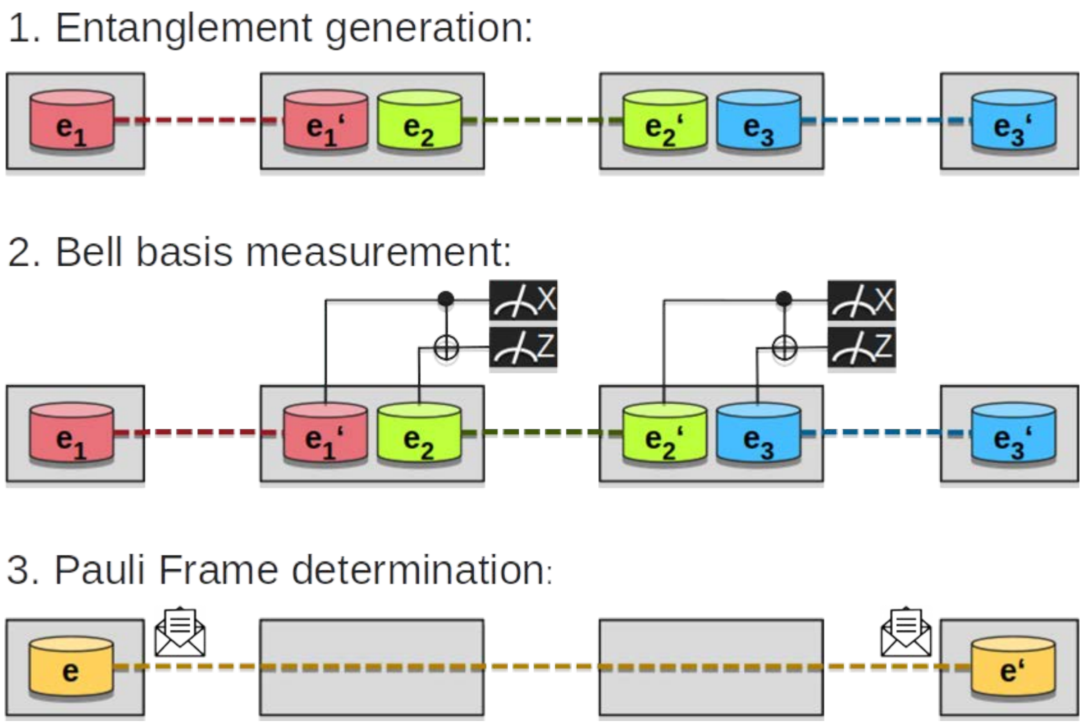



- Teleportation of quantum state $|\psi\rangle$ from Alice to Bob uses a quantum channel (QC) and a classical channel (CC)
- Photons must be tracked at the individual particle level, requiring a great level of coordination

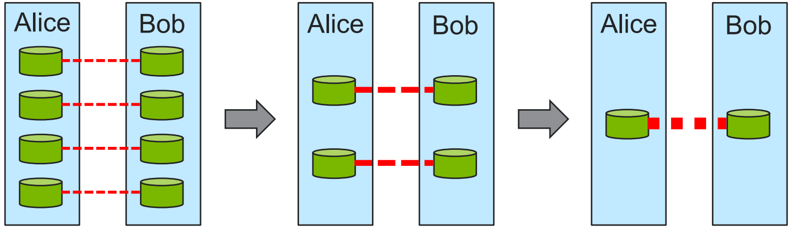
# ENTANGLEMENT SWAPPING

- Used to obtain long-distance entanglement
- Distribution of entangled photons only between nearest neighbors
- Photons stored in memories until they are consumed
- Optional purification techniques to improve fidelity

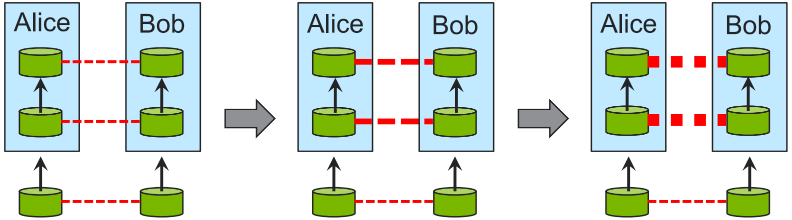


# ENABLING RELIABLE COMMUNICATION

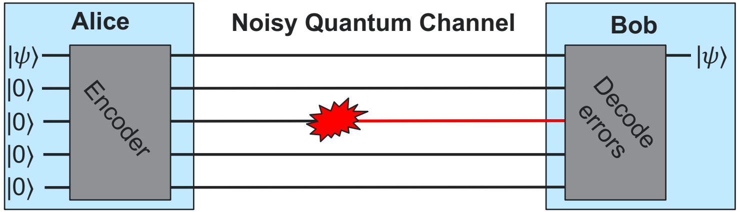
- Entanglement purification – uses n weakly entangled pairs to distill a high-quality entangled pair:



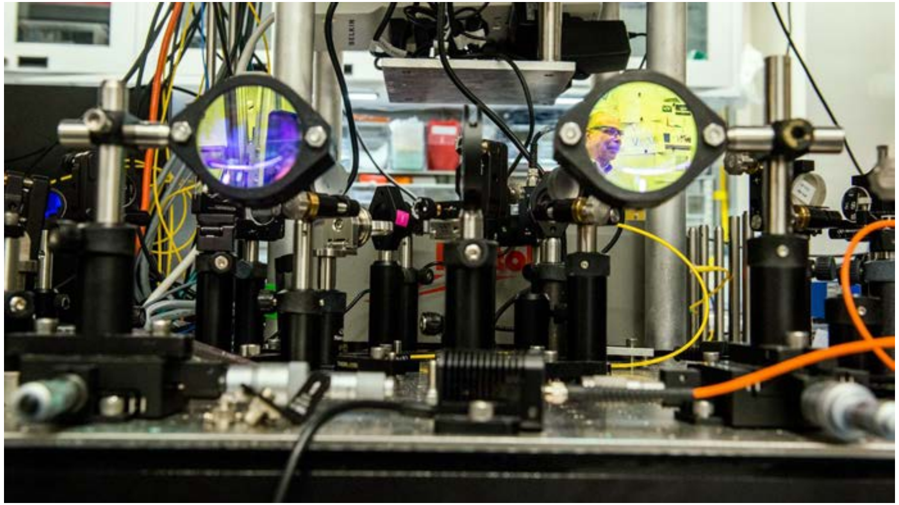

- Entanglement pumping – gradually improves entanglement quality by using additional weakly entangled pairs:



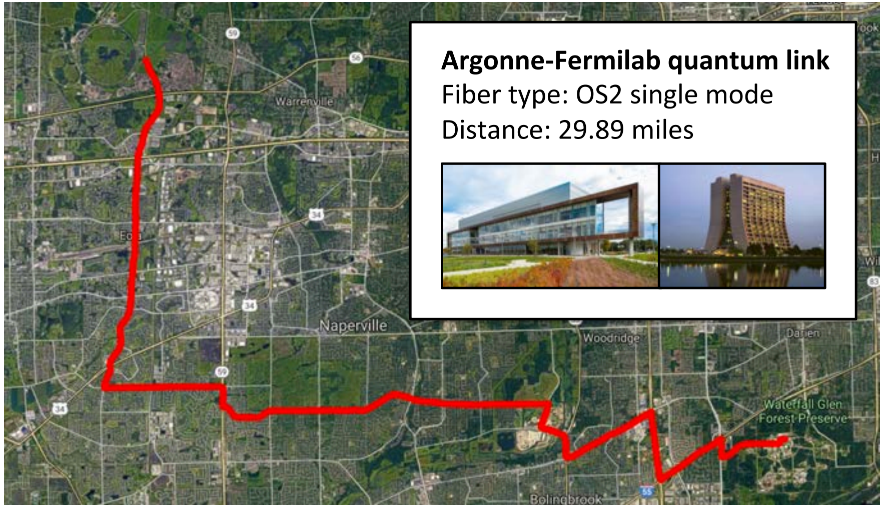

- Error correction – encodes the transmitted states into multiple qubits and no entanglement is required:



# QUANTUM TELEPORTATION AT THE CHICAGO QUANTUM EXCHANGE



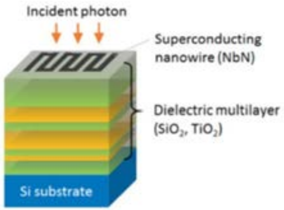
Optical table demonstrating the principles of quantum teleportation in the Awschalom Lab (University of Chicago and Argonne)




Quantum teleportation allows transmission of quantum states between two network hosts (Argonne and Fermilab)

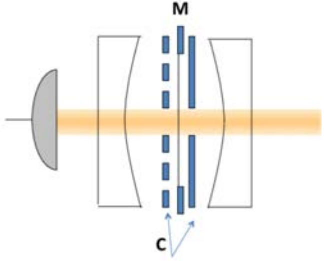
# ARGONNE-FERMILAB QUANTUM NETWORK

- Experimental realization of quantum teleportation at telecom wavelength using optical fiber
- Experiment requires:
  - Communication on dedicated dark fiber near telecommunication wavelength ~1532 nm
  - Entanglement generation
  - Single photon detection
  - Precise coordination and timing
- Future extensions driven by technology:
  - Quantum memories will allow building a quantum repeater
  - Frequency conversion and transduction




Superconducting nanowire single photon detector

Fabry-Perot cavity used to create entanglement



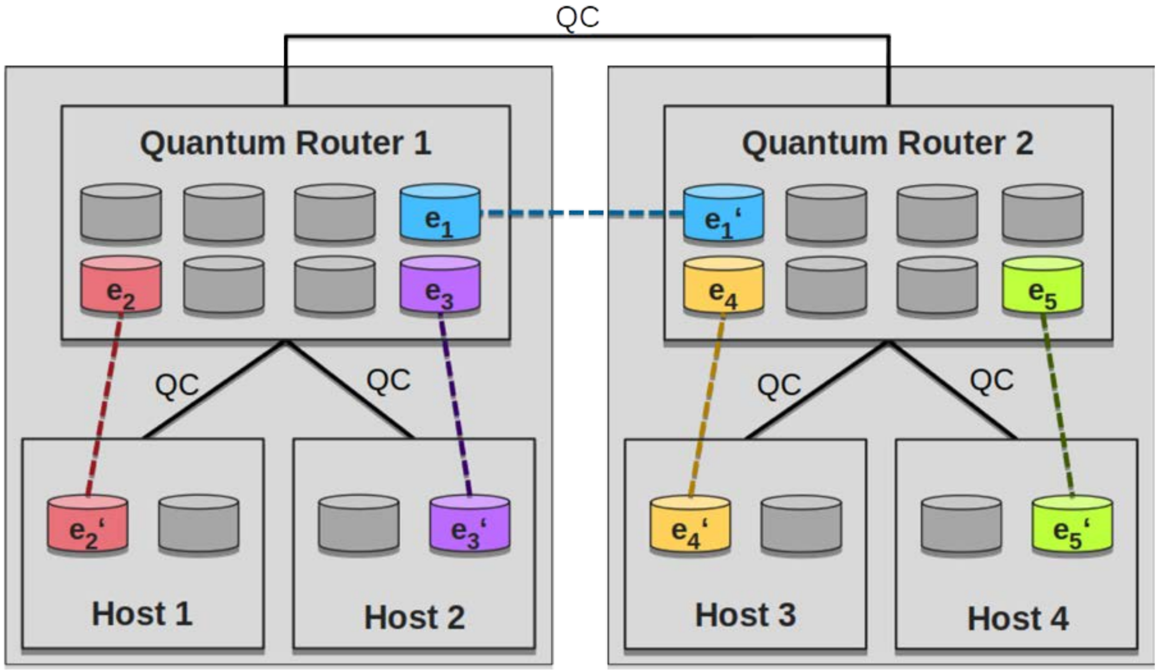


Multimode quantum memory based on rare-earth doped crystals

# SIMULATIONS OF QUANTUM NETWORKS

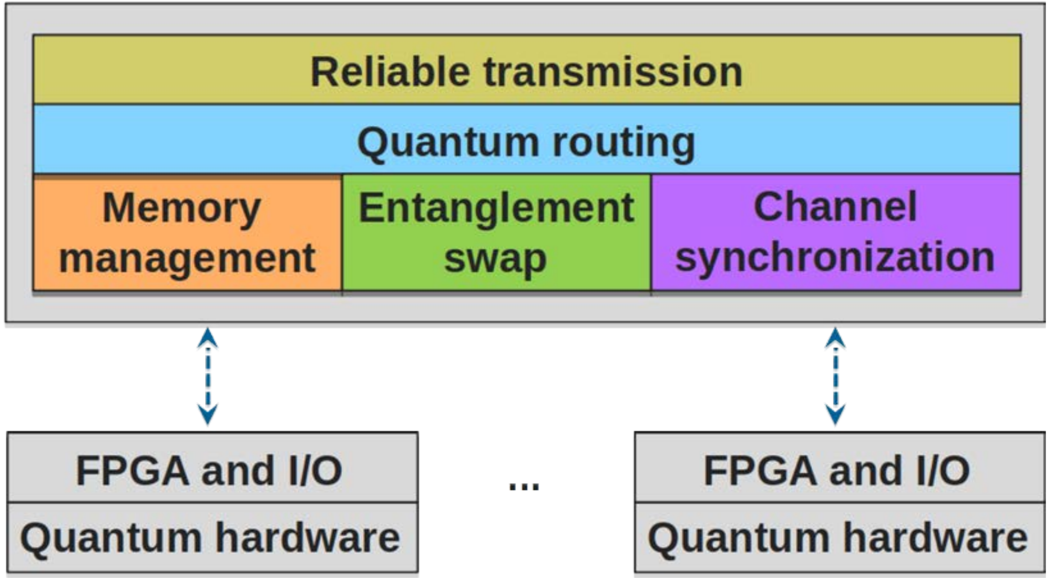
# MULTI-NODE QUANTUM NETWORK ARCHITECTURE

- Reconfigurable quantum nodes
  - Memory, photon pair source, BSM unit
- Coherent quantum materials and photonics
  - Long coherence memory, classical control of photon
- Control plane determines role and action of nodes



# THE CONTROL PLANE

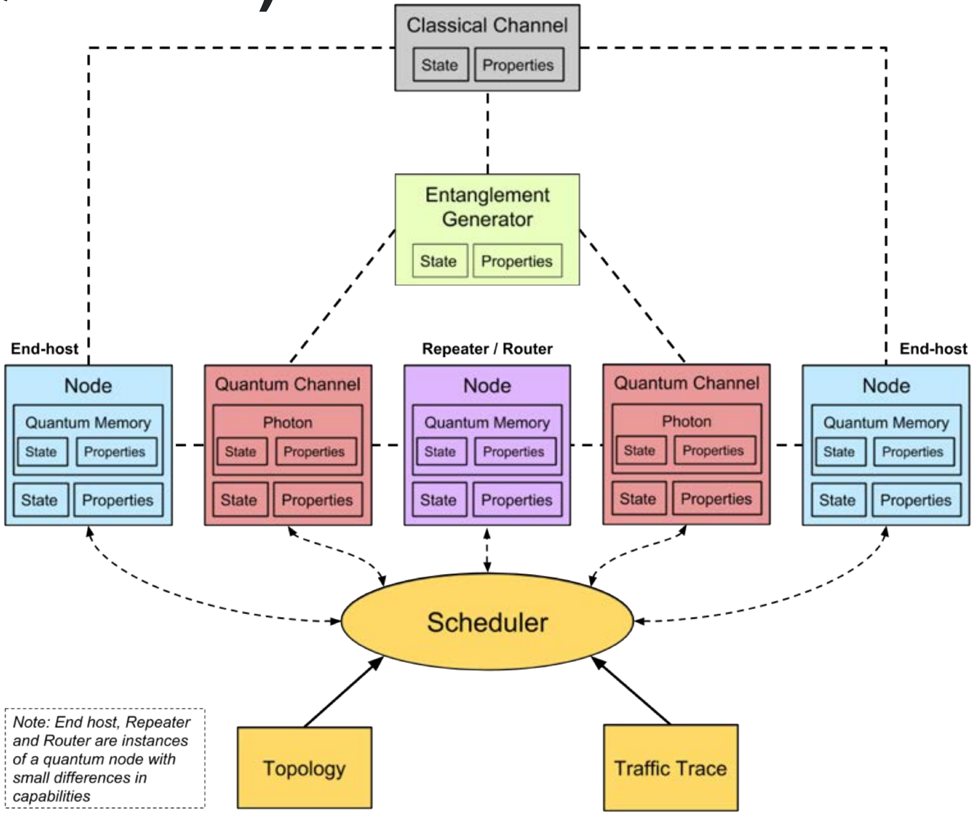
- Quantum nodes integrate with control plane via FPGA & fast I/O
- Layered control plane stack – lowest layer controls hardware, highest layer provides service to applications
- Routing – identify route, perform entanglement swapping, communicate Pauli frame
- SeQUeNCe will be used to verify the correctness of the control protocol implementation



# SIMULATOR OF QUANTUM NETWORK COMMUNICATION (SeQUeNCe)

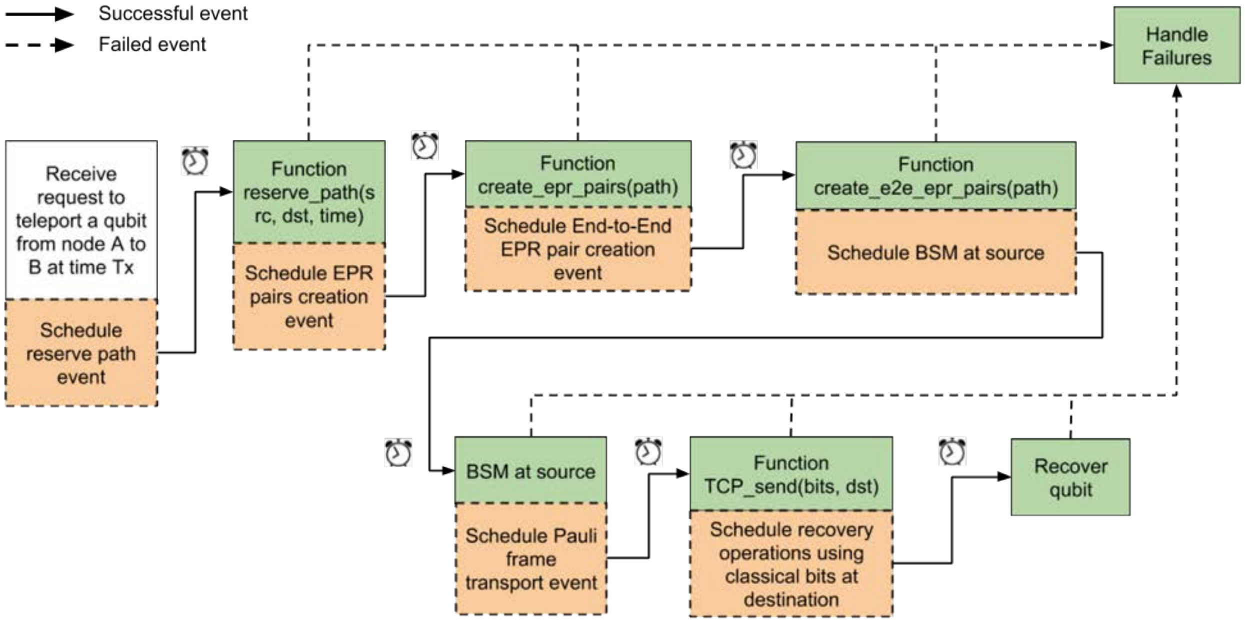
- Modularized discrete event simulator with a scheduler
- Simulates quantum communication at photon-level
- Other simulators:

1. A. Dahlberg & S. Wehner, SimulaQron—a simulator for developing quantum internet software
2. B. Bartlett, "A distributed simulation framework for quantum networks and channels”
3. The Network Simulator for Quantum Information using Discrete events, https://netsquid.org/

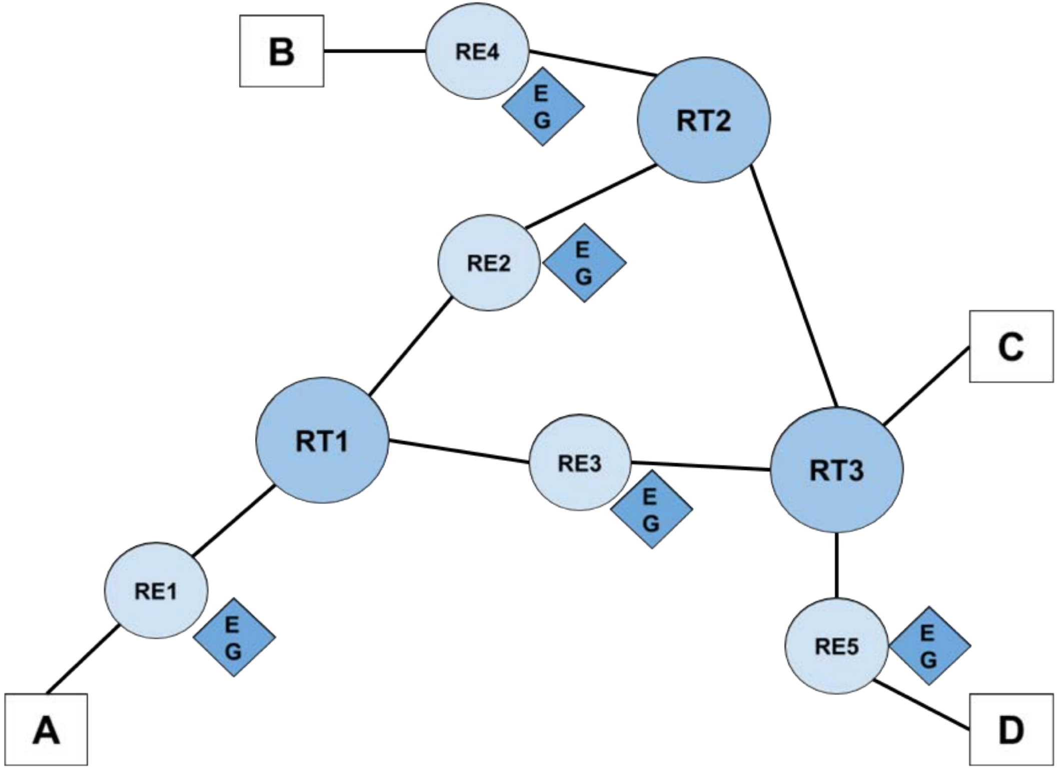


# DISCRETE EVENT SIMULATION OF TELEPORTATION

- Discrete event simulator models the operation of a system as a discrete sequence of events in time
- Simulation jump in time from one event to next
- Events generated upon a request or at the end of a certain activity
- Event is associated with a time and a function to invoke



# SAMPLE QUANTUM NETWORK TOPOLOGY



# TOPOLOGY REPRESENTATION

**End-host snippet:**

- Only have one neighbor
- Properties of quantum and classical channel
- Number of quantum memories


```
"A": {"neighbors": [{"RE1": {"qc": {"distance": "70km",
                                     "attenuation": "0.1db/km",
                                     "bandwidth": "80MHz"},
                              "cc": {"latency": "10ms",
                                     "bandwidth": "1G"}}
                     }],
      "quantum_mem": 4
},
```


**Repeater snippet:**

- It have 2 neighbors
- Properties of quantum and classical channels
- Number of quantum memories is a multiple of number of quantum links


```
"RE1": {"neighbors": [{"A": {"qc": {"distance": "70km",
                                    "attenuation": "0.1db/km",
                                    "bandwidth": "80MHz"},
                             "cc": {"latency": "10ms",
                                    "bandwidth": "1G"}}
                      },
                      {"RT1": {"qc": {"distance": "70km",
                                      "attenuation": "0.1db/km",
                                      "bandwidth": "80MHz"},
                               "cc": {"latency": "10ms",
                                      "bandwidth": "1G"}}
                      }],
        "quantum_mem": 8
    },
```

# SUMMARY

- Majority of prior work focuses on point-to-point quantum communication
- CQE aiming to experimentally realize a multi-node network architecture
- Systematic design that leverages experience from traditional networking
- Classical control software to enable rapid experimental progress
- Discrete event simulator to verify scalability, performance of the network
- Quantum networks rely on early generation hardware components
- SeQUeNCe to quantify benefits, understand value of improvements
- SeQUeNCe to verify correctness, understand security of network designs

# THANK YOU!

U.S. DEPARTMENT OF ENERGY

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