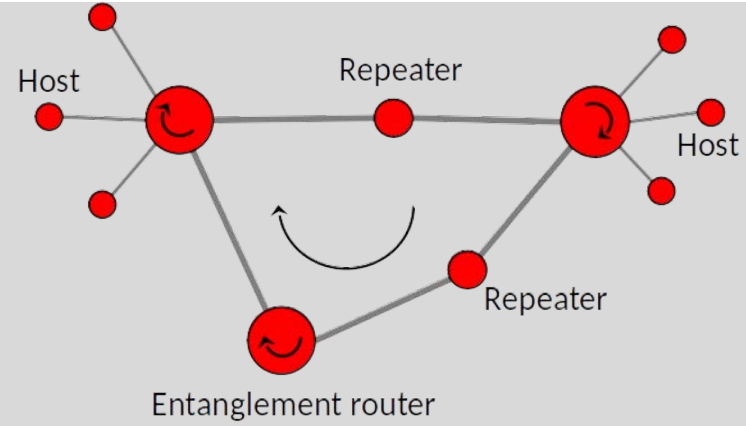
Simulation-Driven Design of Photonic Quantum Communication Networks



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SC19, Denver, CO

U.S. DEPARTMENT OF ENERGY
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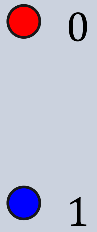
QUANTUM COMPUTING AND COMMUNICATION

<table>
<tr><th>Classical bit:</th><th>Qubit:</th><th>Multi-qubit systems:</th></tr>
<tr>
<td>
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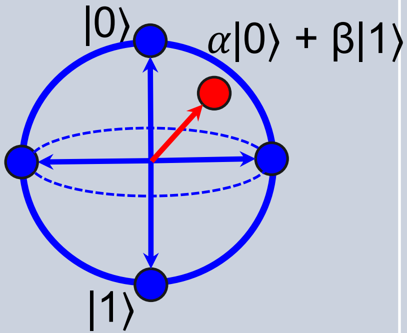
<td>
</td>
<td>2 qubits: $\alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle$

3 qubits: $\alpha|000\rangle + \beta|001\rangle + \gamma|010\rangle + \delta|011\rangle + \varepsilon|100\rangle + \zeta|101\rangle + \eta|110\rangle + \theta|111\rangle$</td>
</tr>
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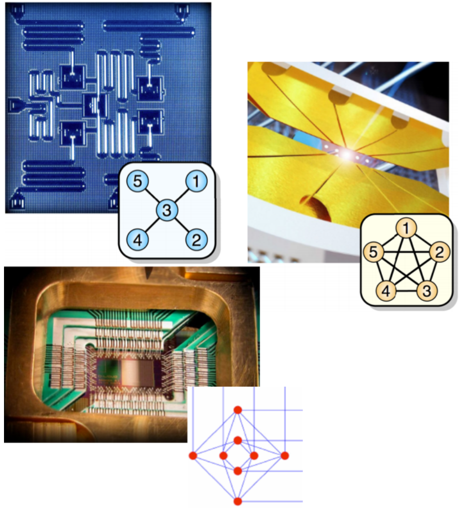
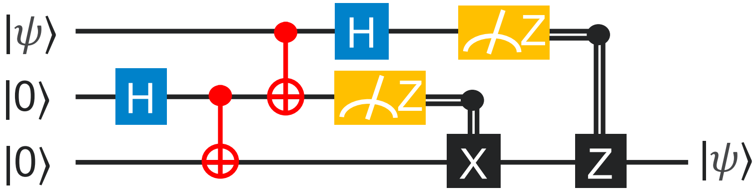
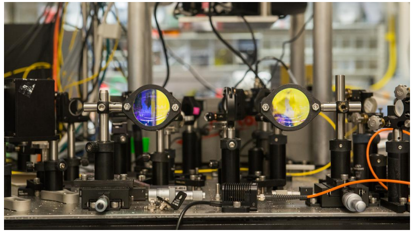
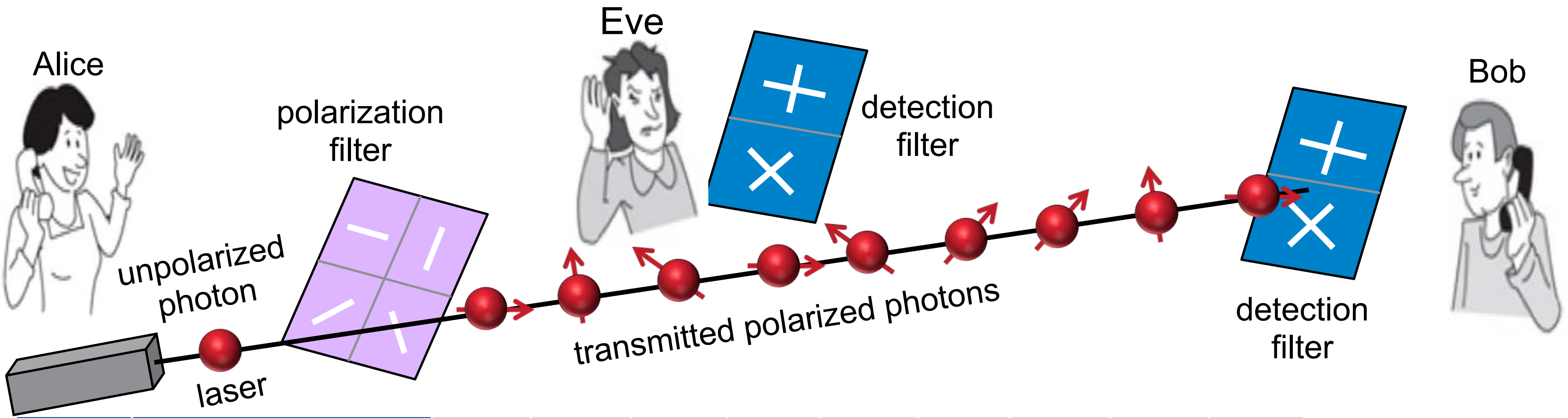


- Secure communication and teleportation:



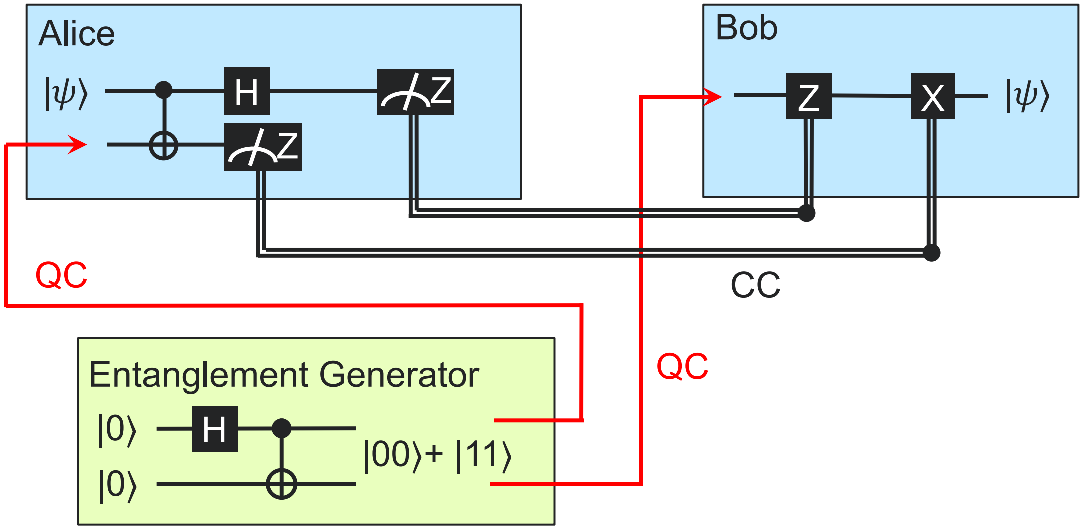


BB84 PROTOCOL – BENNETT & BRASSARD, 1984



Step 1	Alice’s bit	0	1	1	0	1	0	0	1	0
Step 2	Alice’s random basis	+	+	x	+	x	x	x	+	+
Step 3	Alice’s polarization	→	↑	↖	→	↖	↗	↗	↑	→
Step 4	Bob’s random basis	+	x	x	x	+	x	+	+	x
Step 5	Bob’s measurement	→	↗	↖	↗	↑	↗	↑	↑	↗
Step 6	Public discussion	Determine which bases match and only retain the corresponding bits								
Step 7	Shared secret key	0		1			0		1	

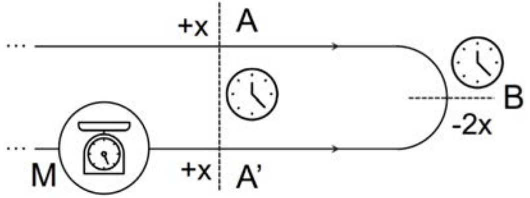
QUANTUM TELEPORTATION NETWORKS

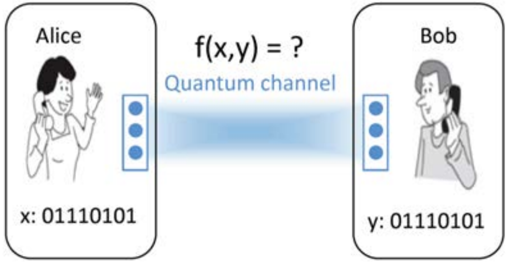


- Teleportation of quantum state $|\psi\rangle$ from Alice to Bob using a quantum channel (QC) and a classical channel (CC)
- Quantum communication does not require a quantum channel between Alice and Bob

NEW QUANTUM NETWORK APPLICATIONS

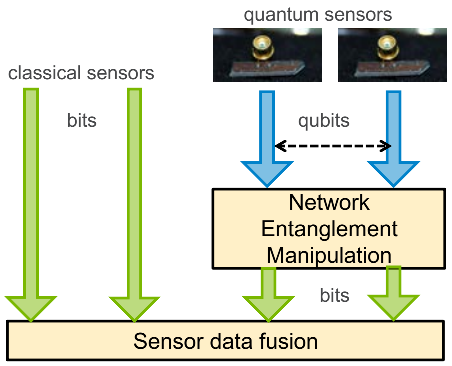
clock synchronization



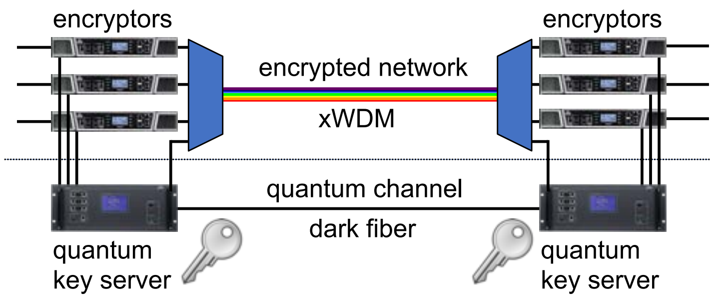


distributed computing

quantum sensing

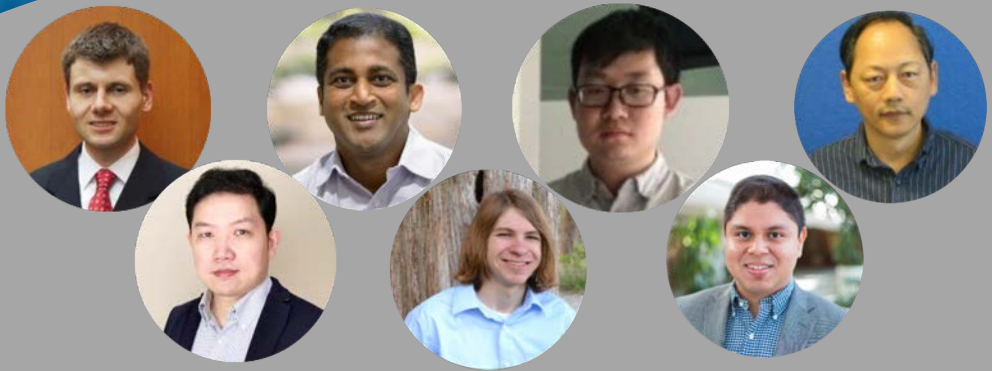


- Heterogeneous applications – each with different specialized function
- Bandwidth, latency and security requirements vary
- Many applications require long-distance communication
- Challenge as well as opportunity



quantum key distribution

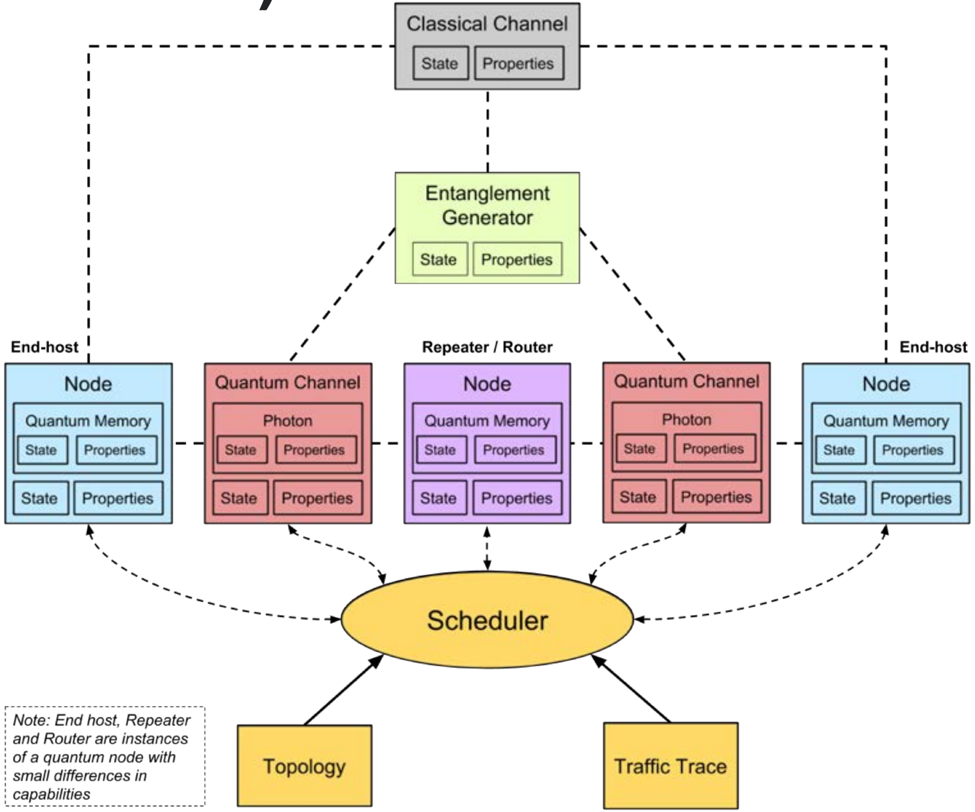
SIMULATIONS OF QUANTUM NETWORKS



Quantum Network Simulation Team

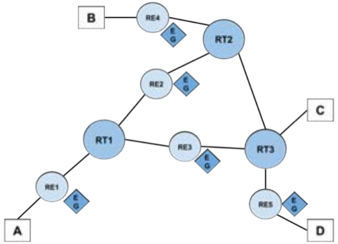
SIMULATOR OF QUANTUM NETWORK COMMUNICATION (SeQUeNCe)

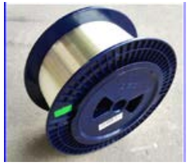
- Modularized discrete event simulator with a scheduler and entanglement manager
- Simulates quantum communication at photon-level with picosecond accuracy
- Models of light sources, SPDCs, quantum and classical channels, single photon detectors, beam splitters, interferometers, BSMs
- Simulations with different parameters, protocols, topologies, and network architectures



SPECIFYING PARAMETERS OF A SIMULATION

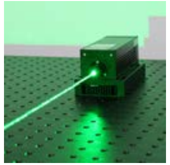
1. Network topology specification:

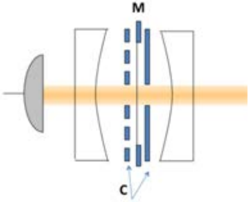




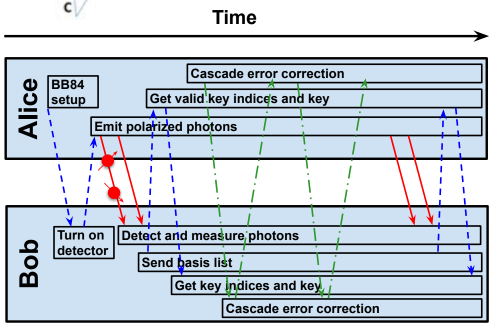

```
"RE1": {"neighbors": [{"A": {"qc": {"distance": "70km",
                                    "attenuation": "0.1db/km",
                                    "bandwidth": "80MHz"},
                             "cc": {"latency": "10ms",
                                    "bandwidth": "1G"}}
       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


2. Properties of optical components:

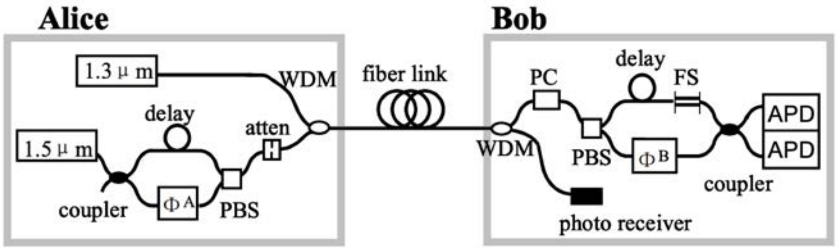




3. Choose quantum network protocols from a library:



SIMULATING QUANTUM KEY DISTRIBUTION

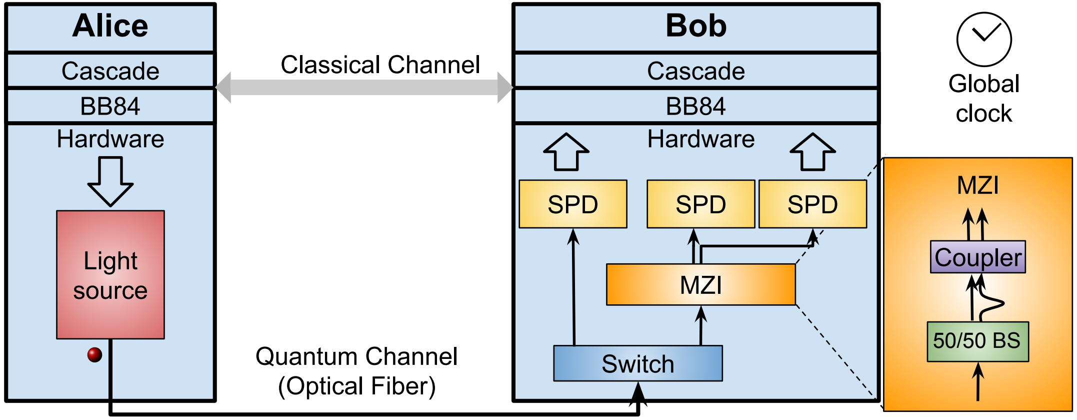


Original experimental setup:

- *Gobby et al., "Quantum key distribution over 122 km of standard telecom fiber"*

Our simulation setup:

- Implements BB84 and CASCADE with time-bin encoded qubits
- Simplified models of optical components
- Tracks individual photons with picosecond accuracy



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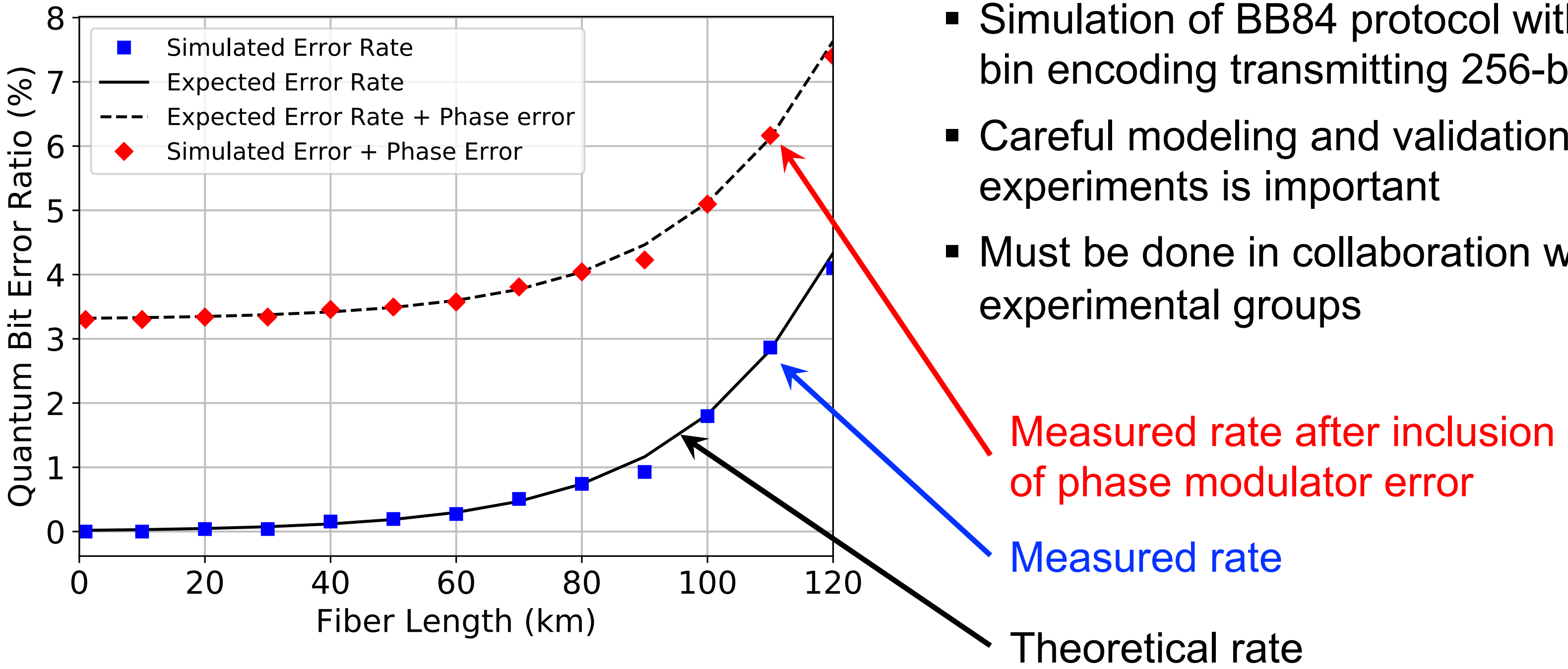
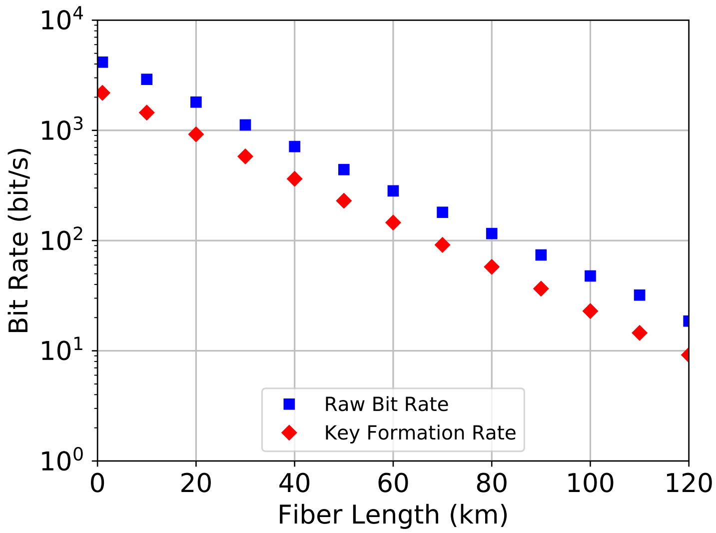
SIMULATIONS TO VALIDATE OR PREDICT EXPERIMENTAL RESULTS

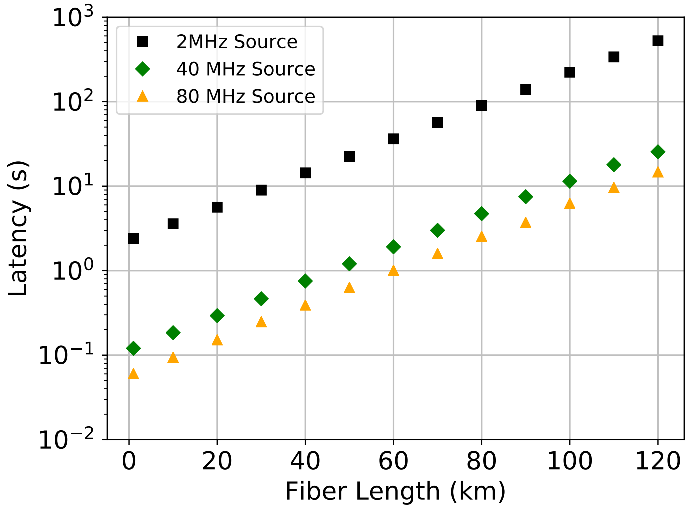


- Simulation of BB84 protocol with time bin encoding transmitting 256-bit keys
- Careful modeling and validation against experiments is important
- Must be done in collaboration with experimental groups

SIMULATIONS TO VALIDATE OR PREDICT EXPERIMENTAL RESULTS

- The raw bit rate (throughput of BB84) and the key formation rate (throughput of the Cascade protocol) decrease exponentially with increasing distance





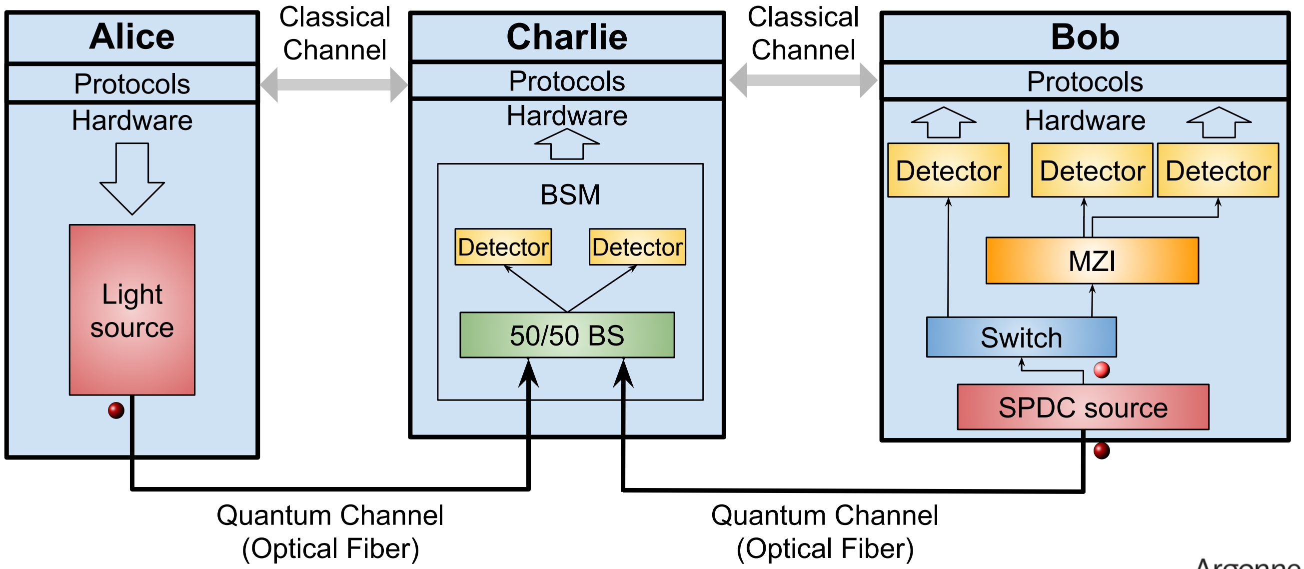
- Cascade suffers from large latency due to the need to construct a 10,240-bit frame before error correction can begin
- Use of light source with higher frequencies dramatically improves latency

SIMULATING QUANTUM TELEPORTATION

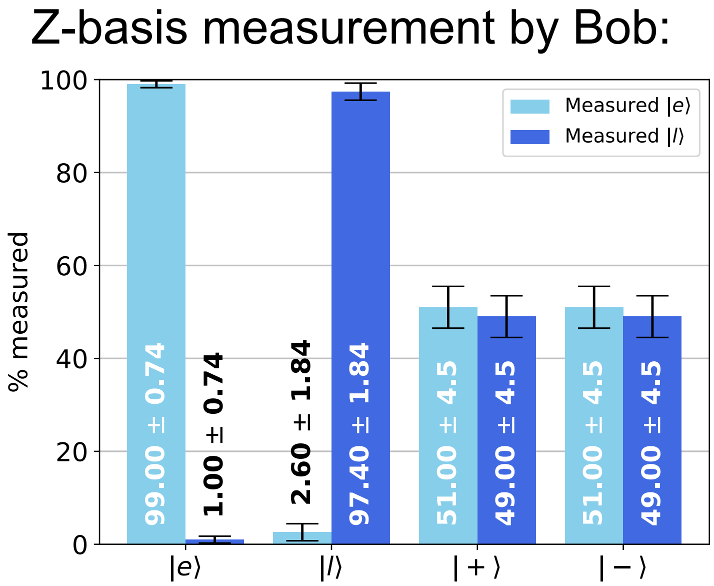
Calgary experiment:

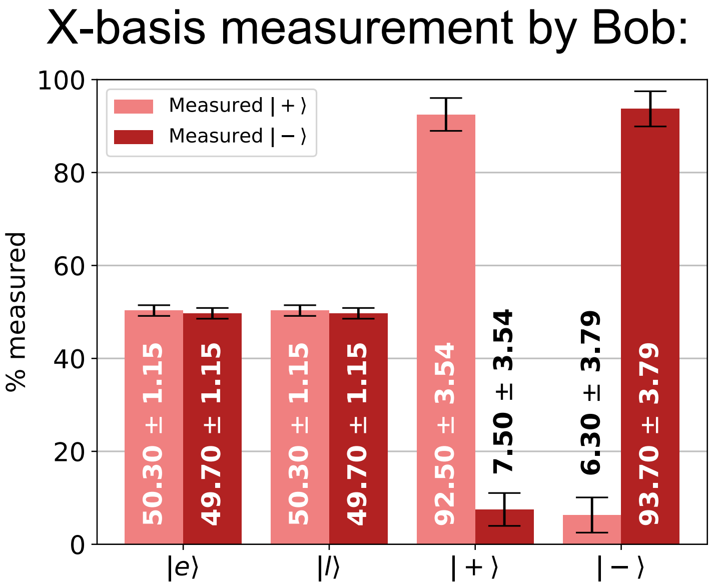
- *Valivarthi et al., "Quantum teleportation across a metropolitan fibre network"*

Our simulation setup:



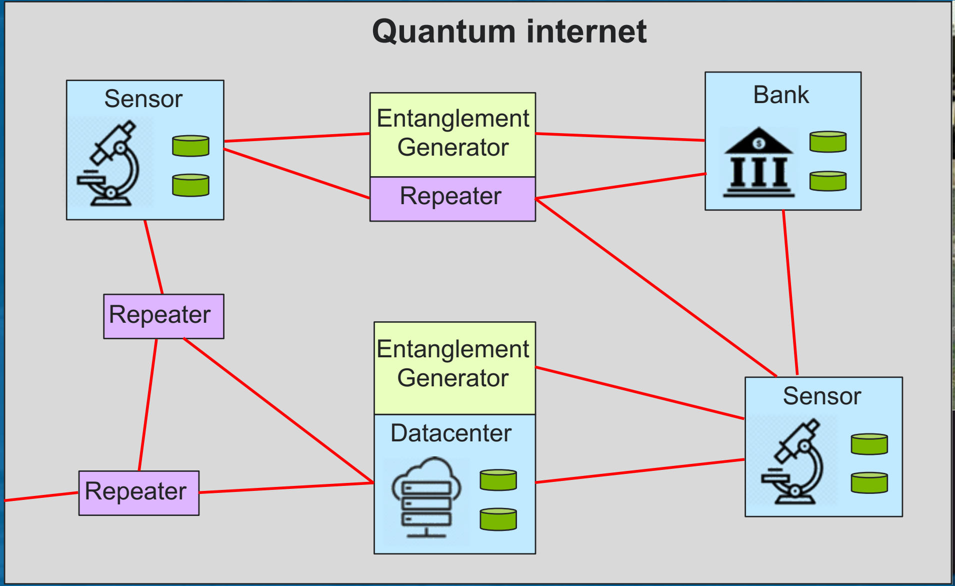
RESULTS – TELEPORTATION SIMULATION

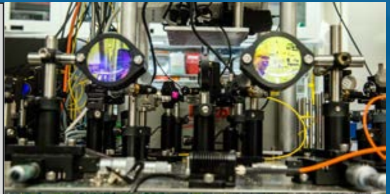


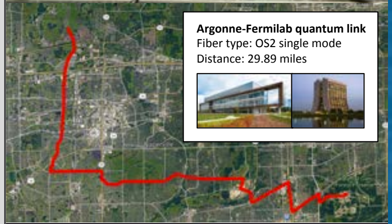


- Lower fidelity for X-basis measurement due to errors in the interferometer and use of two single-photon detectors

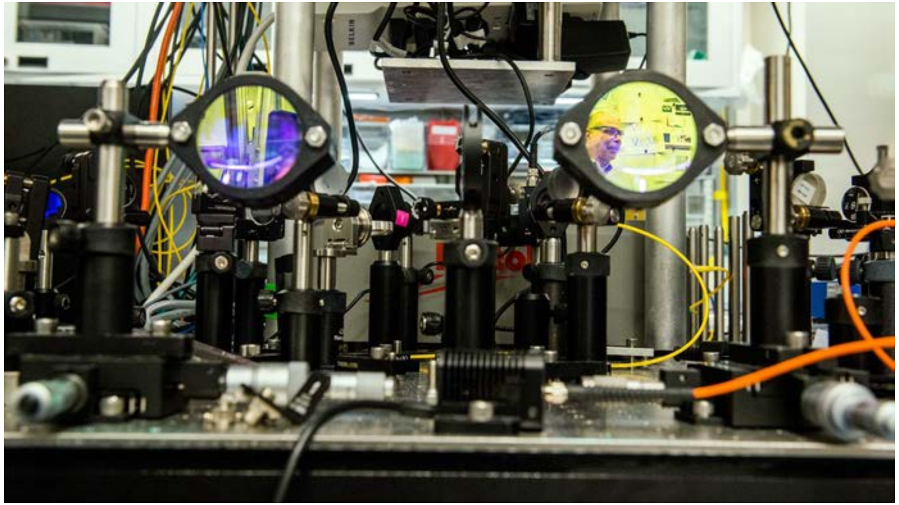
BUILDING THE QUANTUM INTERNET



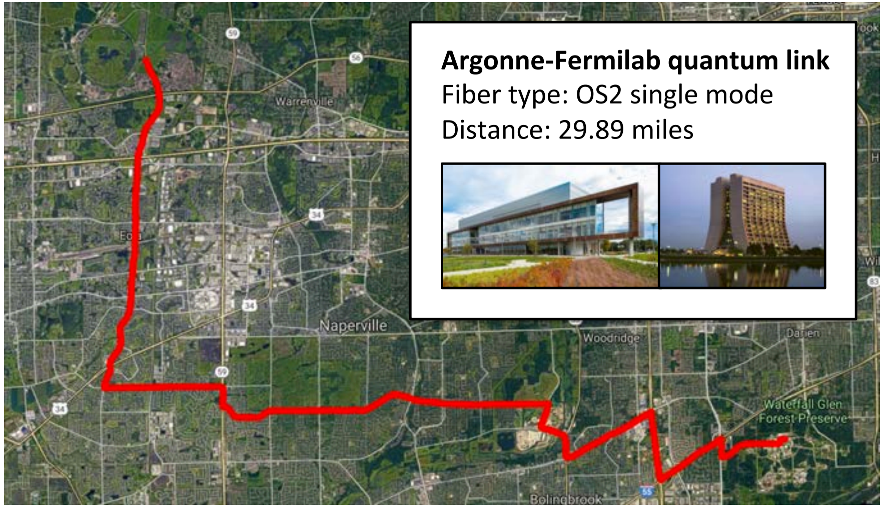




QUANTUM TELEPORTATION AT THE CHICAGO QUANTUM EXCHANGE

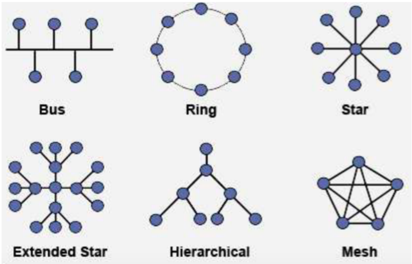


Optical table demonstrating the principles of quantum teleportation in the Awschalom Lab (University of Chicago and Argonne)

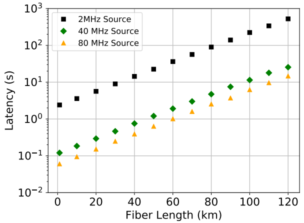


Quantum teleportation allows transmission of quantum states between two network hosts (Argonne and Fermilab)

WHAT ARE QUANTUM NETWORK SIMULATIONS USEFUL FOR?

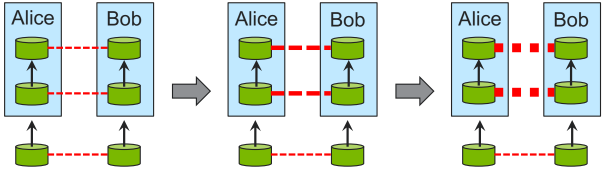


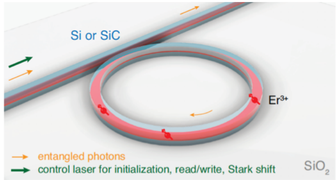
- Network architecture design – topology and architecture that allows scalability and long-distance communication



- Experiment planning and validation – facilitate system integration with hundreds of optical components, allow easy parameter tuning, predict and validate results

- New protocol and control plane design – evaluate performance of specialized network protocols for e.g. entanglement purification



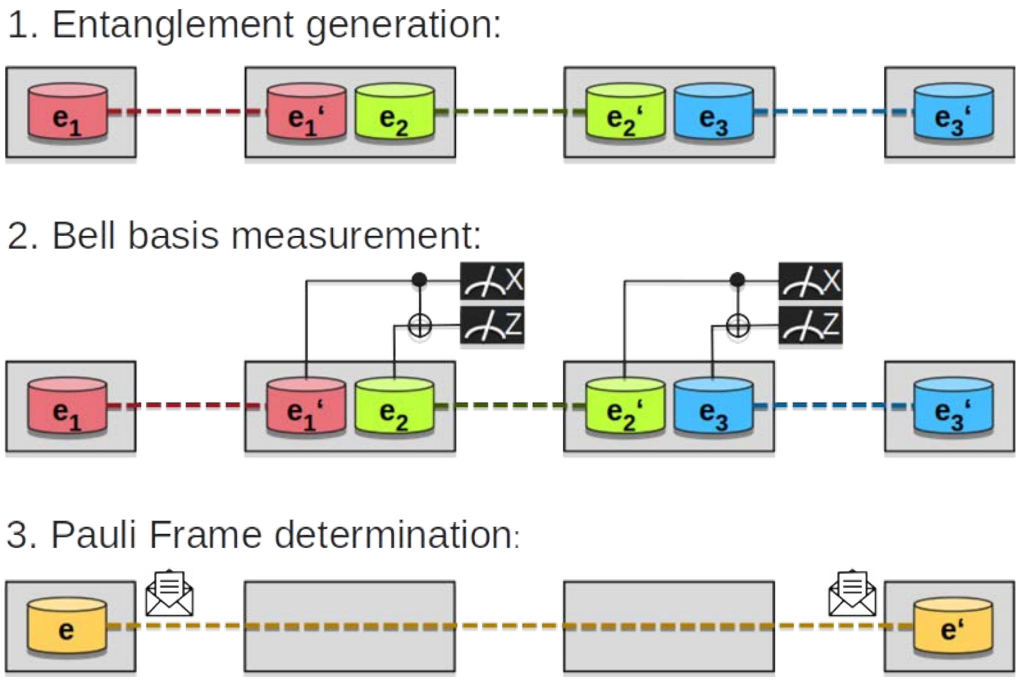


- Motivate experimental advances – what are the benefits of building better detectors, memories, or light sources?

THANK YOU!

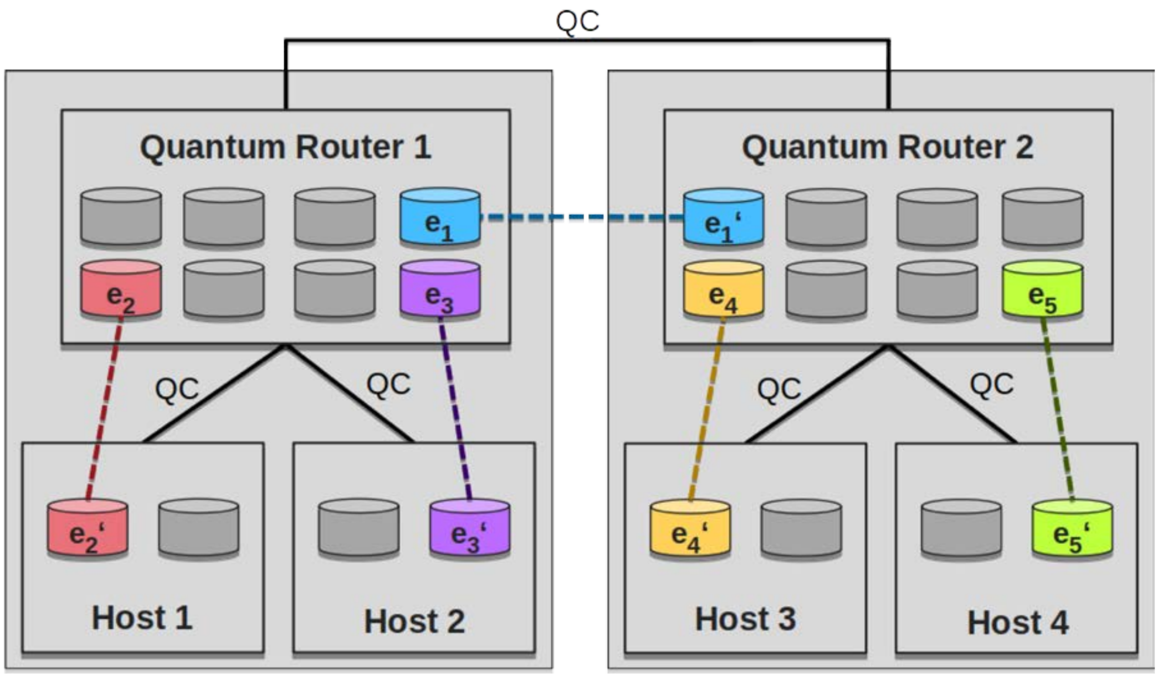
ORCHESTRATION - ENTANGLEMENT SWAPPING

- Distribution of entangled photons only between nearest neighbors, or not?
- Photons stored in memories until they are consumed
- Optional purification techniques to improve fidelity
- Requires careful orchestration at the individual photon level!
- Different paradigm: need to rethink network architecture



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



➢Control plane protocols will be needed for networks with 3 or more nodes