Quantum networking control hardware - report from breakout session

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Moon shot goal(s)

1. “On demand teleportation of quantum states between any two nodes in a quantum network with at least ten nodes with high fidelity (95%, 99.9%, …)”

- Complex network topology, multi-path
- Data rate: >10 Hz, scale to kHz, …
- Without repeaters, 20 km, 5 y goal
  - With any technology, scalable or not
    - Dil fridge networks, rack mounted, not out of the question, ?
- With repeaters, 100+ km, 10 y goal
  - Hetero-qubit (e. g. SC-RF to ion traps to color enters to atomic)

- 2. Long term goal: Teleportation based gates, multipartite entanglement, distributed QC, …
- Work in progress, …

To reach this we need (probably)

- Quantum memory
  - Coherence time, fidelity requirements
- Quantum repeaters
  - Type 1 type, 2, …
- Synchronization
  - classical - quantum to tag and quantum – quantum to swap
- Network protocols for both
  - w/w-out q-repeater based
- **Network characterization**
  - classical – quantum, tracking and tomography, test, design, methods for benchmarking, figures of merit [analog to QC benchmarking, gate set tomography and result check], entanglement quantification, tracking/trouble shooting (noise sources, …)
    - Hard ware specific and higher level design rules
- Transduction
  - matter-photon, photon – photon
- Multiplexing optical channel
  - time – frequency
- Quantum – classical signal and control integration
- Control electronics and hardware, quantum switch, quantum router
  - Advanced material and device fabrication for non-linear optics, …

Let’s establish **metrics** for scalable quantum networks

- Science vs. market metrics (vs. timeline, roadmap, TRL, …)
- End to end, node characterization, link by link
- Quantum network volume
  - Number of gates before error, number of teleportation events before error, …
- Fidelity
  - 95% → 99.95
  - Threshold for error correction
- Connectivity
- Complexity
- Success rate, efficiency
- Authentication (hardware/software, timing, security characterization, track performance, …)
- SWAPs, CSWA
  - Challenge driven, efficiency, market value, quantum state transfer/$; science applications vs. early market adapters, …
- For early high impact use cases, e. g. sensor network, …
- Quantum supremacy metrics for a “useful application”
  - Sensing: rate vs. precision, sensitivity

Links – range

- Short range
  - On chip
  - Chip to chip
  - Fridge to fridge in lab

- Long
  - City
  - Area, state – state
  - Coast to coast
  - Global
  - Space

Metric for supremacy of a quantum network

- Sensing
  - Squeezing, …
  - Clock synch
- Distributed QC
- Secure communication ?

- Algorithms
- Purification protocols

- Application specific network controls

- Quantum switching, routing, decision making with and without quantum repeaters

Hardware integration

- Classical – quantum

- **Hardware needs**: better methods to fabricate nonlinear devices and optics

- Meaningful engineering solutions for impactful network
- **Metrics:** a goal and full stack system analysis; define and measure
- **Quantum transduction – optical-microwave-optical – frequency conversion. Also used within a band.**
- **Scalable repeaters and technologies**
- **Quantum memories (for repeaters and transduction); includes classical memory. How much do we need?**
- Processor-photon interfaces and quantum gates
- Teleportation gates
- **Hardware needs**: better methods to fabricate nonlinear devices and optics
- Frequency conversion

- Quantum memories
- Quantum repeaters
- Distributed systems
- Space-ground communication

- Algorithms
- Purification protocols

- Build-outs

- **Multiplexing technologies – signal sharing with classical communication. Scaling challenges?**
- **Quantum switching, routing, decision making with and without quantum repeaters**
- **Encoding on quantum signals, some fiber-compatible and some not. What are the balances?**
- **Quantum switching, pathways, and control; error-corrections**
- **What is future optical network? Old or new fiber networks?**
- **Quantum intranet: connecting two chips, two machines – huge impact.**
- Resource allocation: chip packaging and interconnects (boring but vital)
- Pick a wavelength (standards)
- **Synchronization challenges and phase-stabilized networks and relationships. Could this help classical networks?**
- Sharing classical communication pathways
- Networks: not 2D grids for the future. Better to break long-range interactions and having different types of connectivity. Networks also include chip- and fridge-scale systems that dramatically impact performance. Hardware, algorithms.
- **Quantum CDMA – spread spectrum with orthogonal signals/multiplexing; coherent filtering; demultiplexing**

- **Goals**
  - Entanglement distribution
  - Quantum repeaters
  - Entangled sensor networks
  - Space-based communication
  - Multi-hop ground communication

Other items:

- Networking – not about hardware but about interconnections; about resource management in an interconnected way. From chip scale to national scales.
- Beyond hardware – protocol stack. Points in the network are likely to be very different objects.

- Challenge of coming up with two or three applications that are vital: scientific or otherwise. QKD,
- **Goal: arbitrary teleportation protocol on demand ~6 nodes on demand using a network. An arbitrary quantum state. One-time shot. High fidelity.**
- **What does it take to do a fault-tolerant quantum state transmission? Often requires 99% fidelity for most steps. Challenging for a network….**
- Connect across the labs and within the labs

- **Need: quantum memory;**
- **Need: synchronization;**
- **Need: metrics;**
- **Need: repeater;**
- **95% fidelity A to B; rate that beats the repeaterless bound; cannot be achieved by direct photon transmission.**

- Incorporate ideas from statistical networking to quantum networking. Statistical errors on-chip alone will apply constraints.