QICK For Quantum Networks

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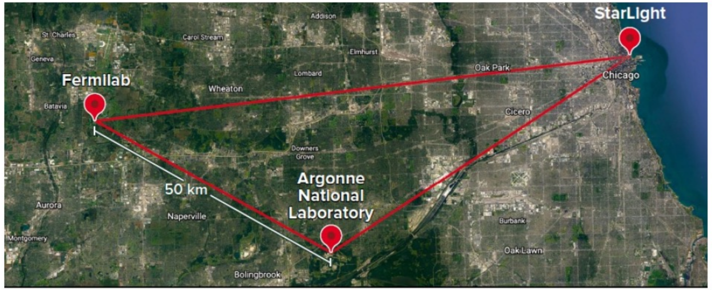
Quantum Networks: towards a quantum internet

Current focus: deploy a **multi-node, multi-user metropolitan scale quantum network** in the greater Chicago area.

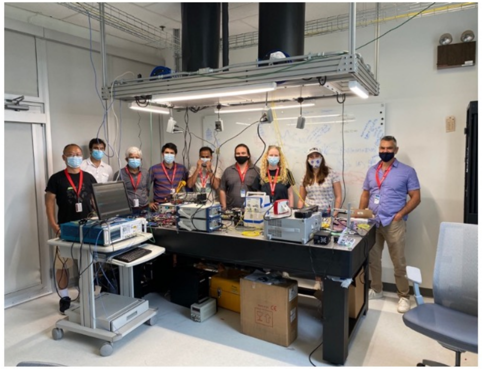
Leveraging Fermilab competencies in precision timing, controls, network architecture, and systems integration

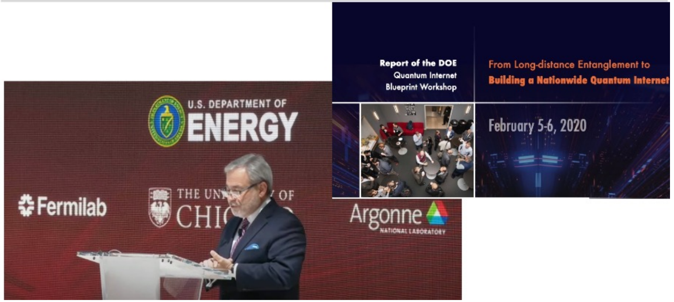


The FQNET/CQNET collaboration

The IEQNET collaboration

Long-term vision: enable security, sensor, and computing applications, following the **DOE Quantum Internet Blueprint**





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Quantum Networking Labs (Q-nodes) at Fermilab

Multiple fiber links among Q-nodes; 57 km fiber link to ANL. Routing through transparent optical switch

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Quantum Networking Functionality and Complexity

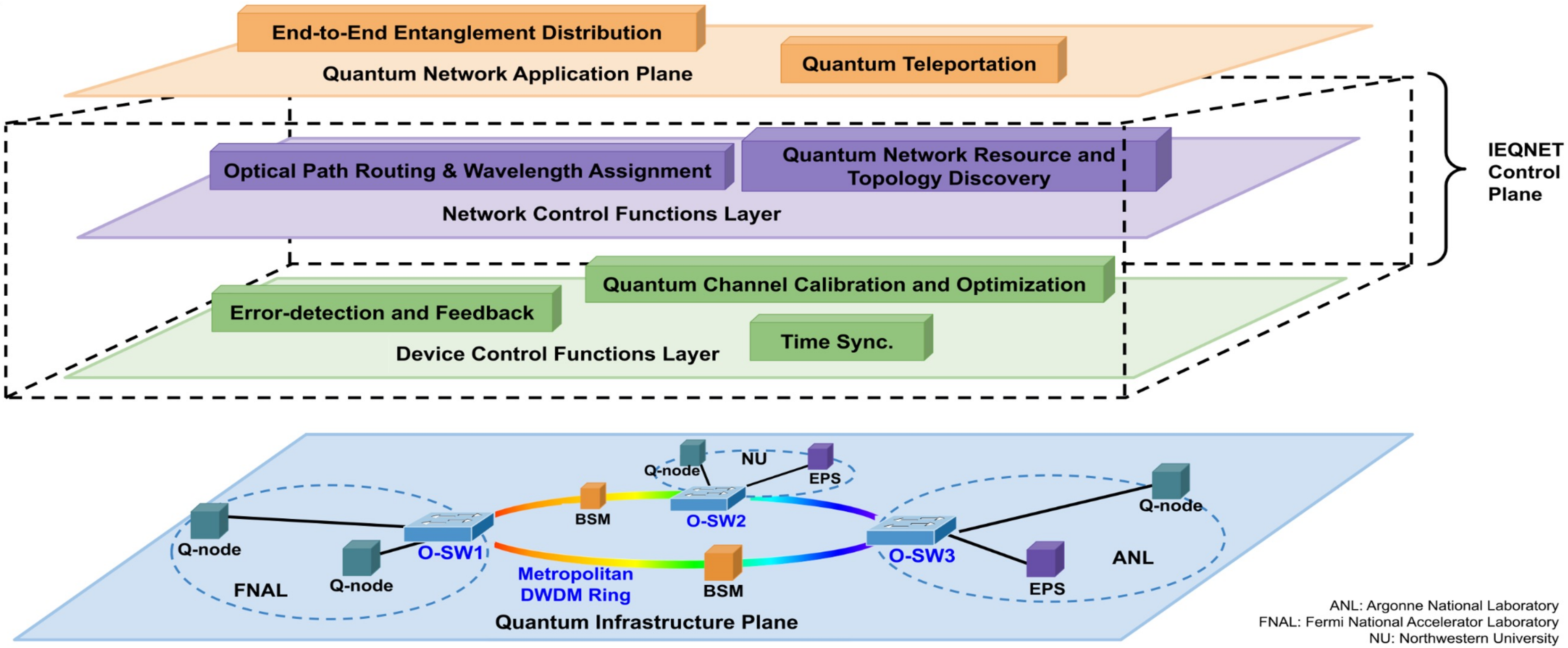

FIGURE 2. IEQNET's quantum networking architecture relies on three planes: infrastructure plane, control plane, and application. IEQNET's control plane is subdivided into Q-Node and Network control functions planes. See text for further description.

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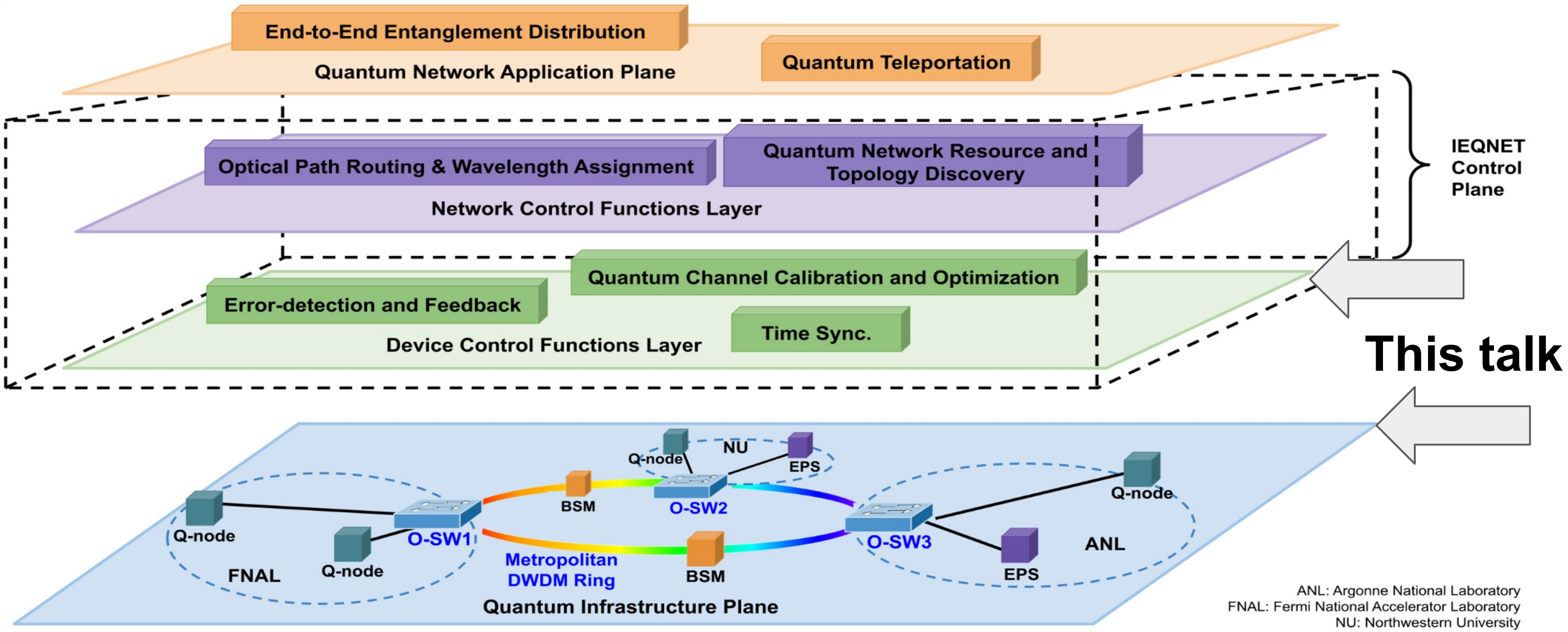
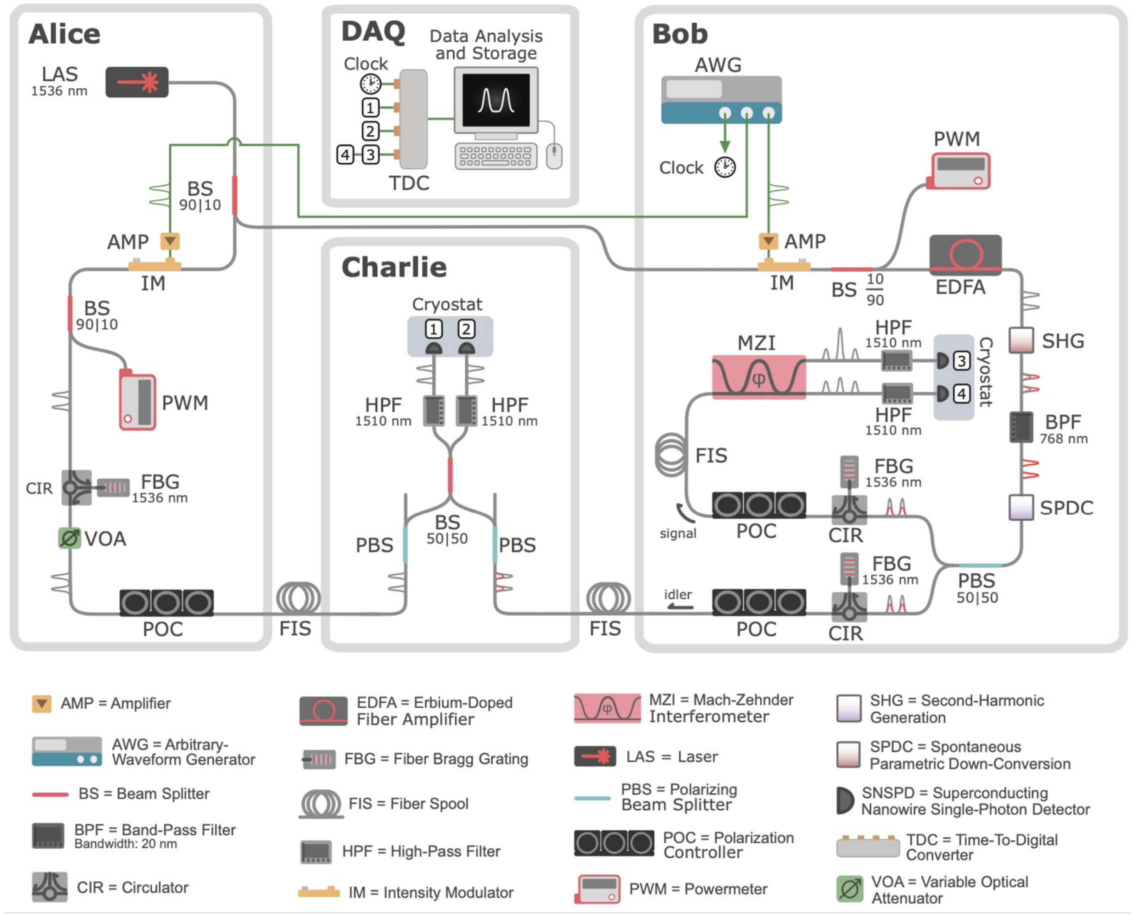


FIGURE 2. IEQNET's quantum networking architecture relies on three planes: infrastructure plane, control plane, and application. IEQNET's control plane is subdivided into Q-Node and Network control functions planes. See text for further description.

Entanglement-based Protocol: Quantum Teleportation

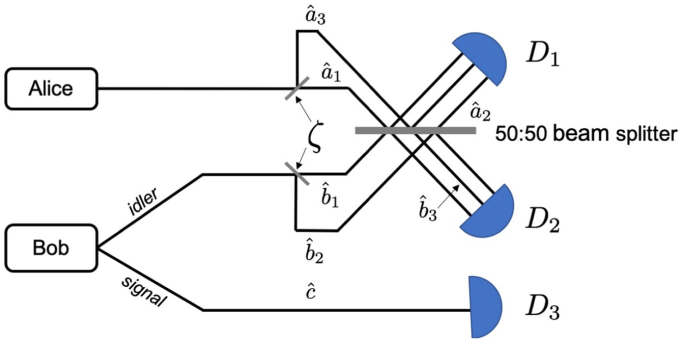
Tasks:

- Qubit preparation & stability control
- Entanglement generation & stability control
- Time synchronization
- Bell State measurement
  - Timestamping & Correlation
- Polarization control
- Laser & IM control



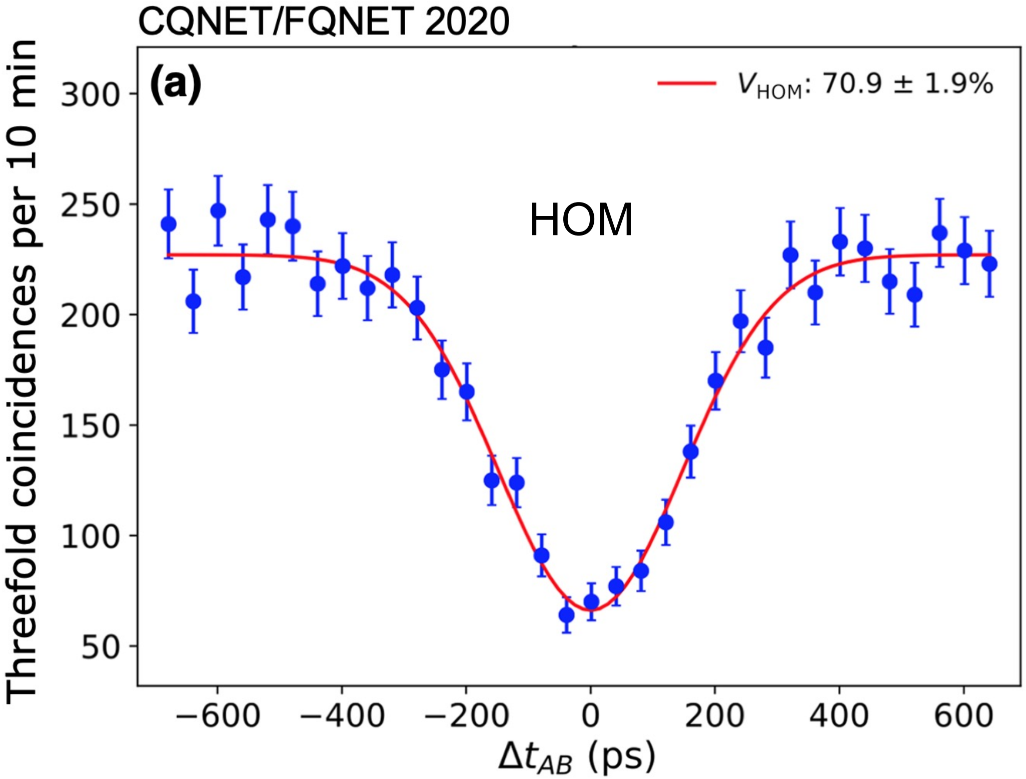
PRX Quantum **1**, 020317 – December 2020

Entanglement-based Protocol: Quantum Teleportation



Photon arrival time is critical for quantum indistinguishability

Determines the teleportation and swapping fidelities



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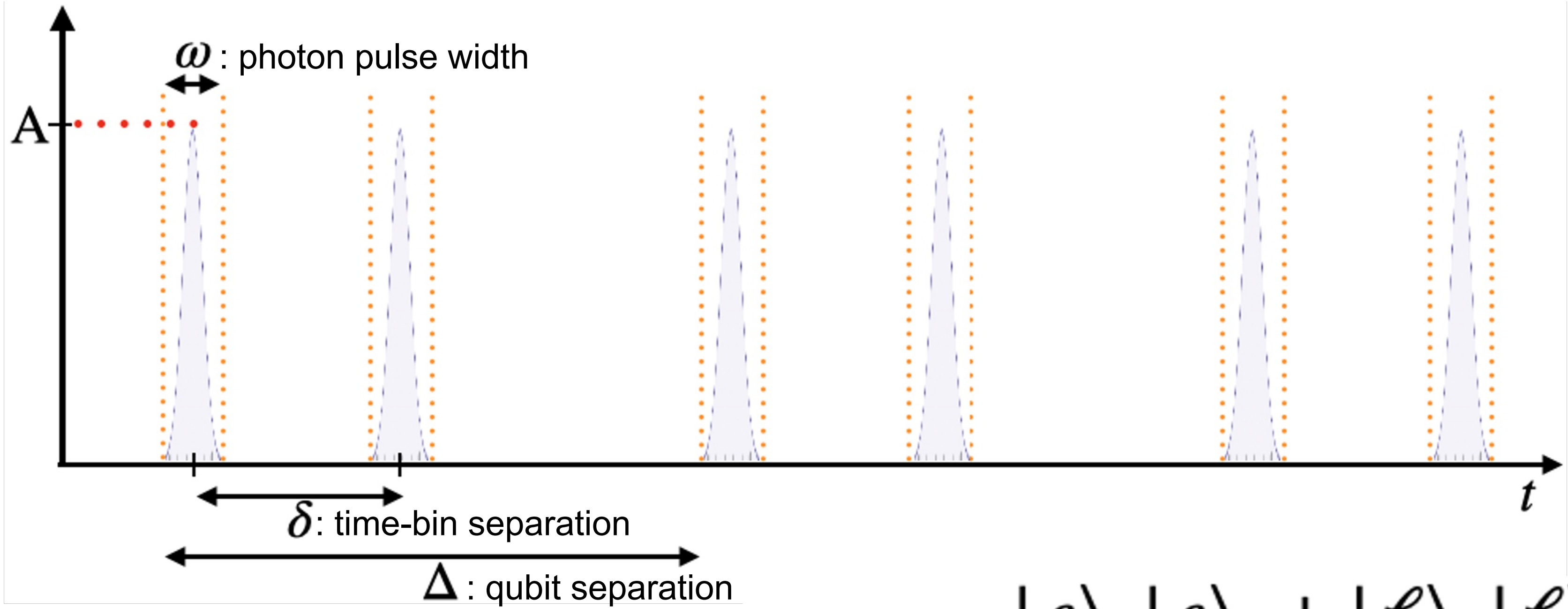
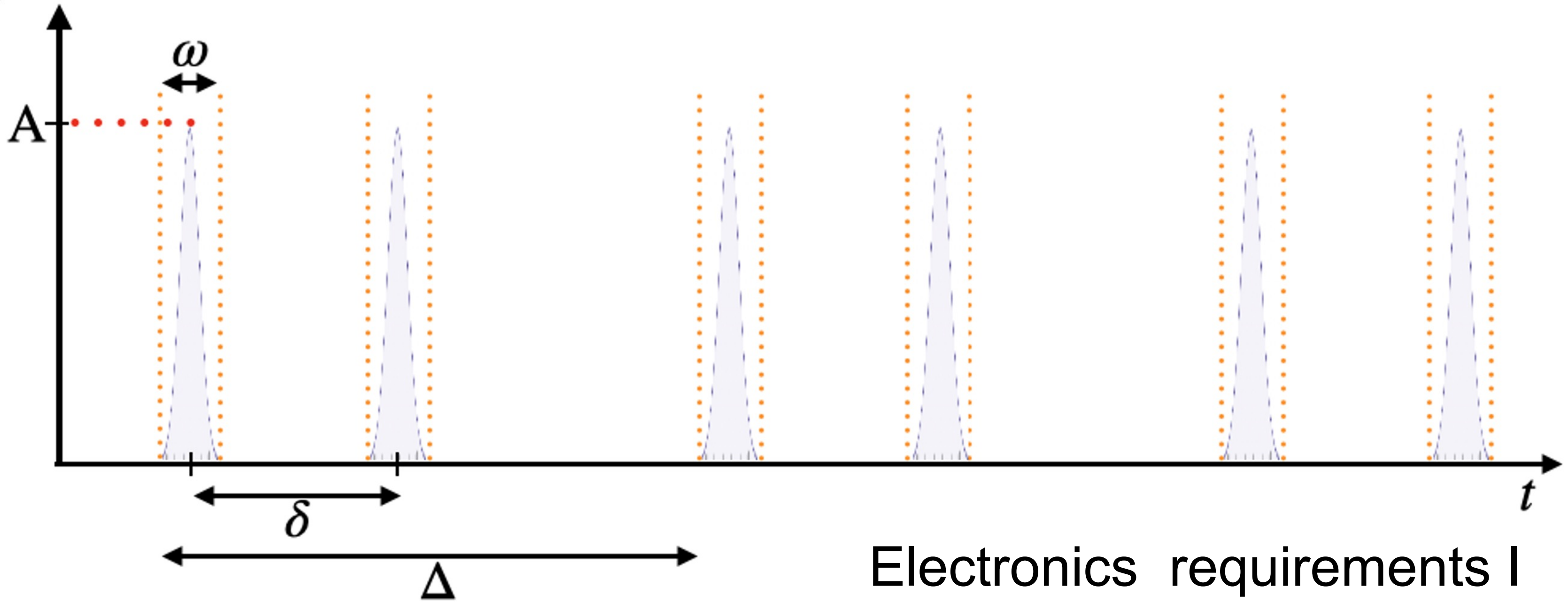
Fiber-based quantum networks: time-bin entanglement



Entanglement encoded photon arrival time

$$|\psi\rangle_{12} = \frac{|e\rangle_1|e\rangle_2 + |\ell\rangle_1|\ell\rangle_2}{\sqrt{2}}$$

Fiber-based quantum networks: time-bin entanglement



Electronics requirements I

ω ~ [**10**-100] ps

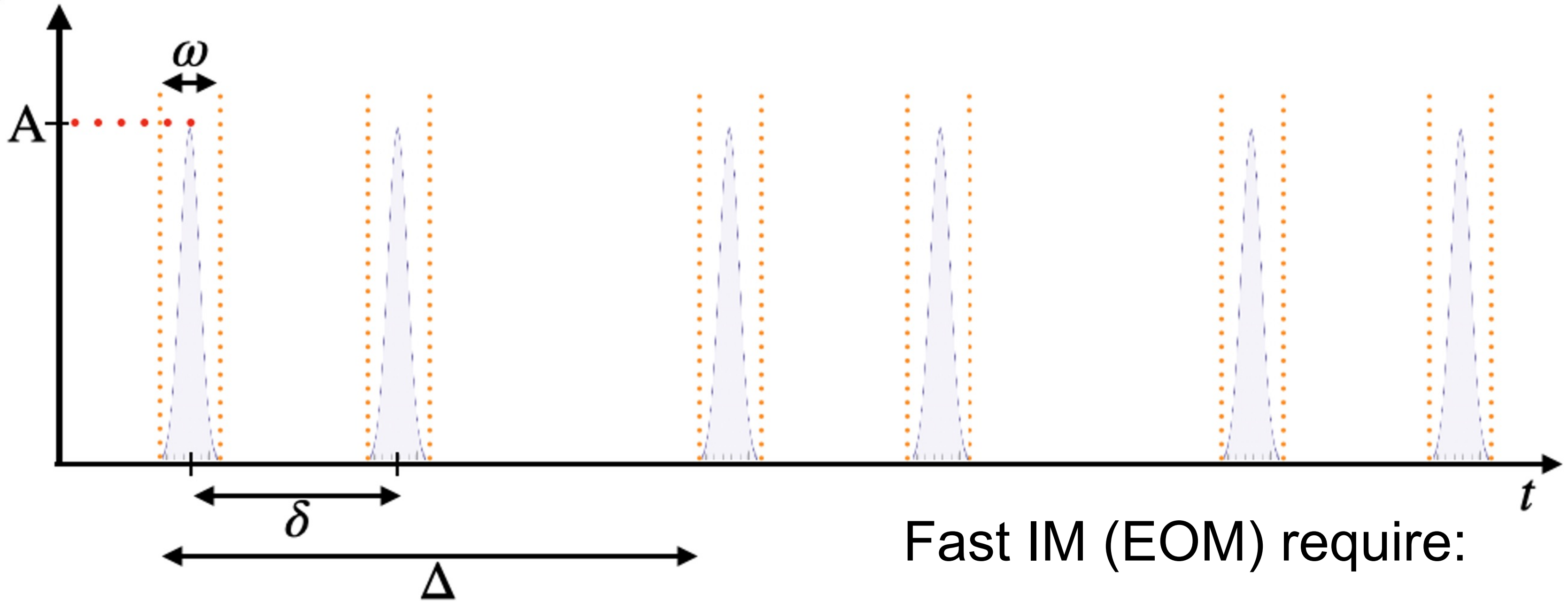
δ ~ [**50**-1000] ps

Δ ~ [**100**-2000] ps

Goal: Fast repetition rate

Additionally eases interferometric requirements

Fiber-based quantum networks: time-bin entanglement

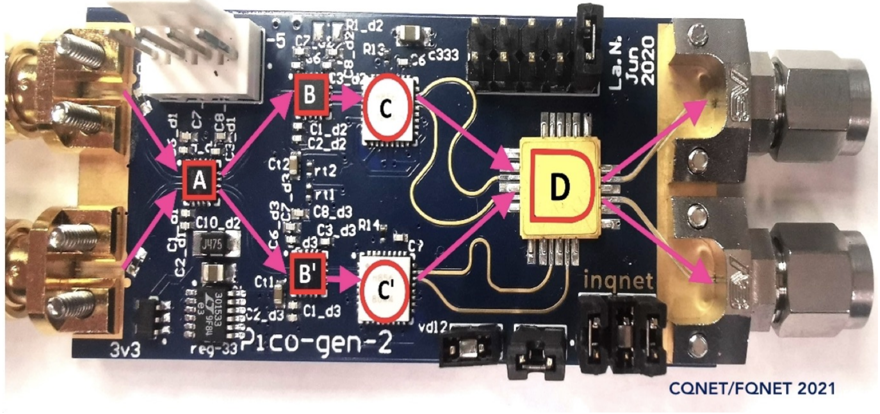


Fast IM (EOM) require:

Electronics requirements II

- A ~ [1-10] V (coarse)
- Fine adj. ~5-10% of A
- 4 channels with adjustable phases (ps jitter)

Dedicated (in house) electronics for qubit generation



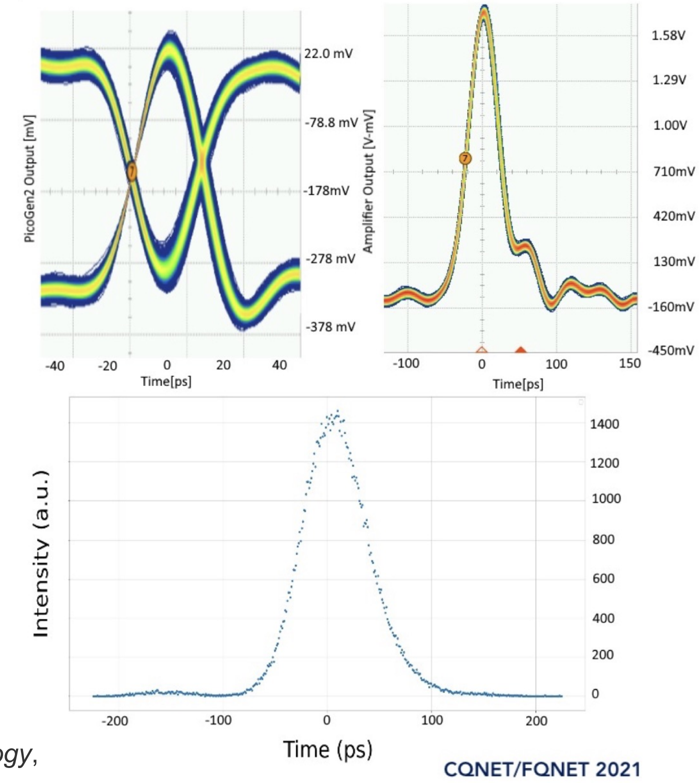
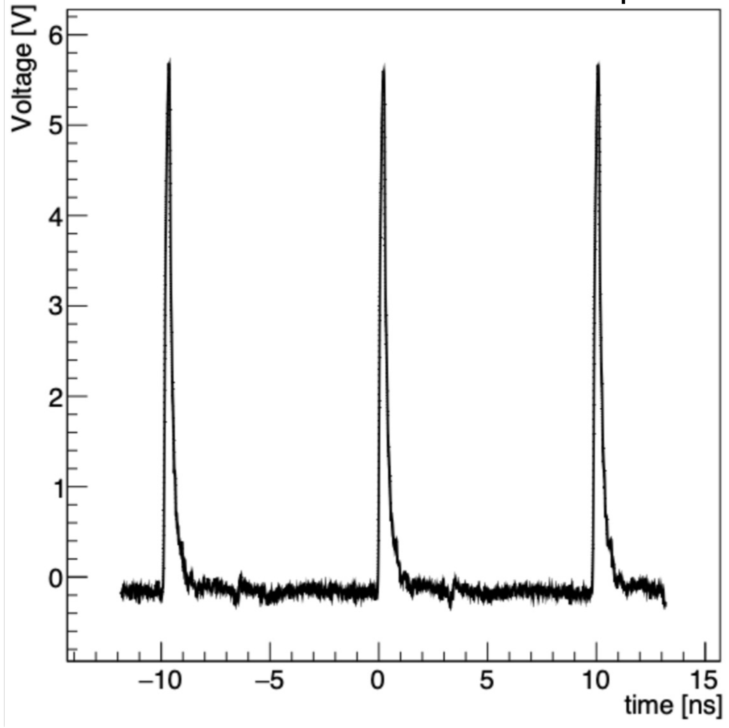


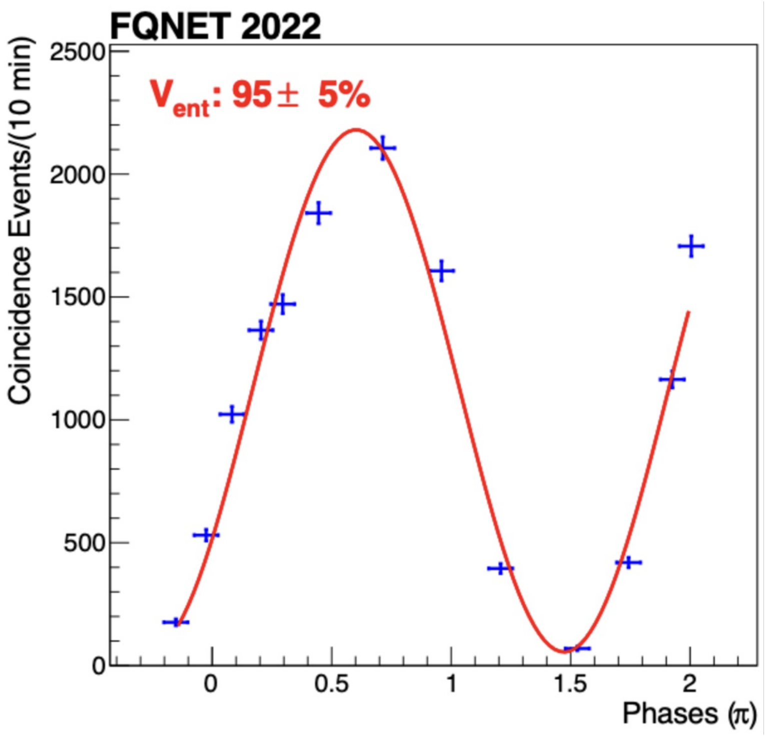
Fig. 4. TOP LEFT: A 25 ps-duration differential output pulse from the Picoshort pulse shortener. TOP RIGHT: A 47 ps-duration, 1.88 Vp-p, output pulse from the Picoamp amplifier. BOTTOM: Attenuated optical pulse measured after the MZM using an SNSPD. Pulse duration is 74 ps and has an extinction ratio of 28 dB. Time is measured relative to the maximum amplitude of the pulse.

"Picosecond Synchronization System for Quantum Networks," *Journal of Lightwave Technology*, vol. 40, no. 23, pp. 7668-7675, 1 Dec.1, 2022, doi: 10.1109/JLT.2022.3194860.

RFSoC Pulse Generation for Networking

~10 GS/s RFSoC DAC + Amp

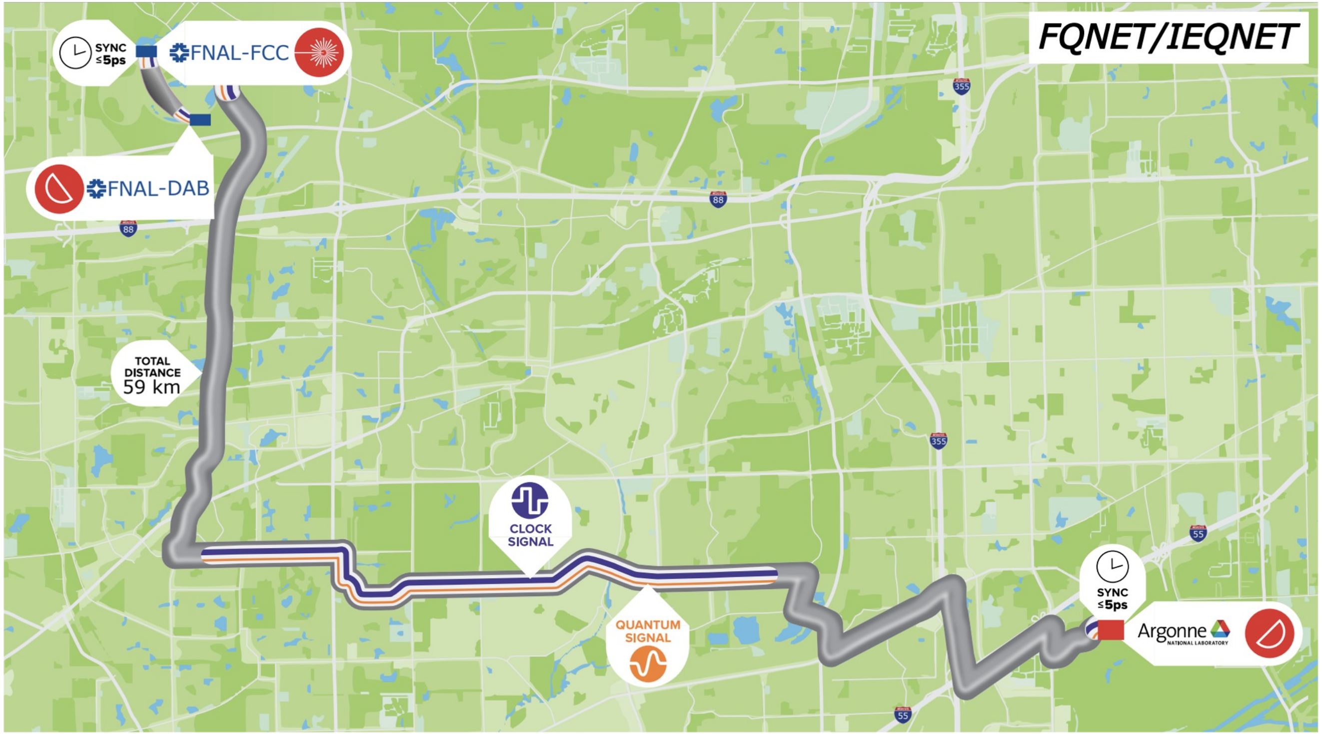




RFSoC DAC yields high entanglement visibility for current quantum network configuration

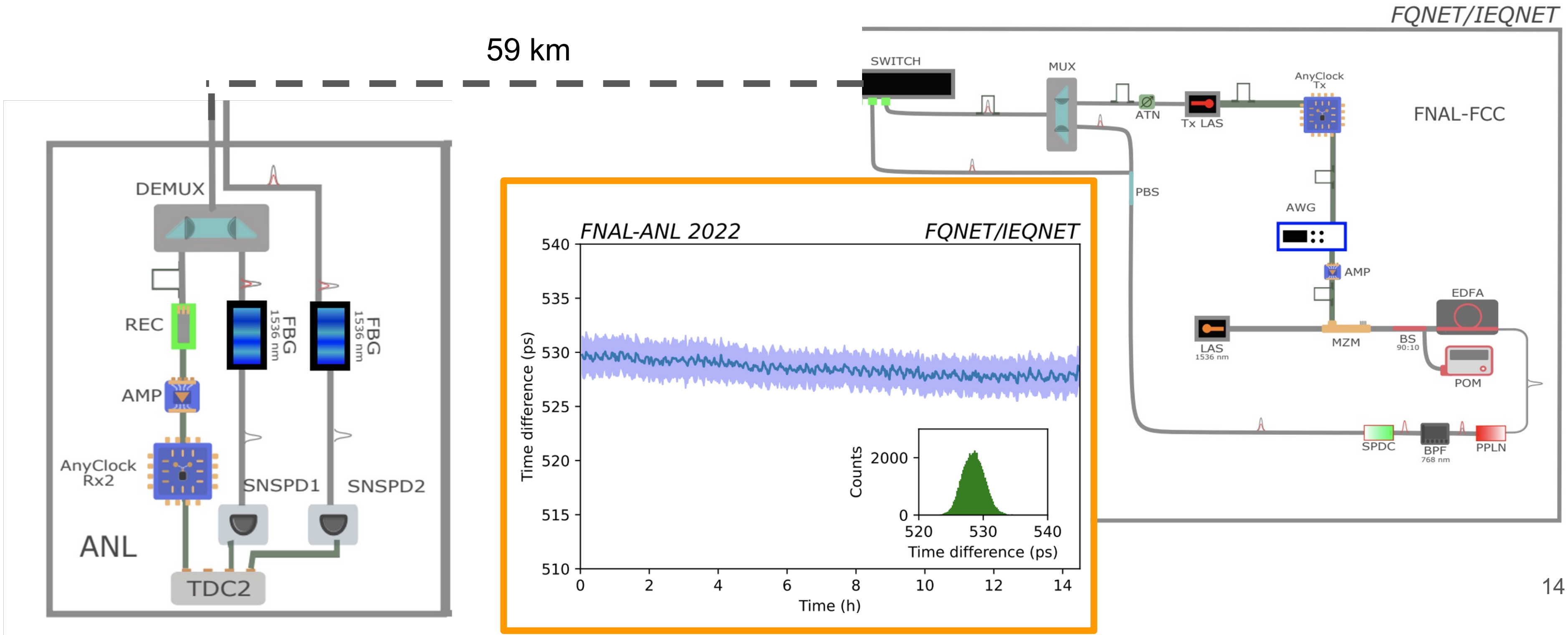
Multi-node Synchronization

- All Q-nodes of the network must be time-synchronized to few ps level
- Time synchronization must be achieved across distances of tens of miles



Multi-node Synchronization

- Currently achieved with AnyClock + 1610/1310 laser coexisting on fiber carrying quantum signals; **Demonstrated 3 ps sync over 59 km link**



Multi-node Synchronization

- Requirements:
  - Clock distribution through optical fiber with <3ps jitter
    - Produce RF & optical clock signals in 1300-1600nm range
    - Ability to lock to reference RF & optical clocks on fibers coexisting with quantum signals @ 1536nm
  - Minimizing background rates on quantum channels are of paramount importance, and have identified as important control parameters:
    - Optical clock duty cycle
    - Amplitude and wavelength of clock signal
  - Automated time synchronization monitoring and feedback control for time drift

Future needs for more advanced Q-Network protocols

- Control framework is needed to “operate” the future networks:
  - Teleportation/Swapping control: BSM logic, feed-forward logic, etc
  - Control for Q-repeater functionality: BSM logic, Q-memory control, etc
  - Feedback controls on various system components : Intensity Modulators, Polarization controllers, HOM logic & time delay controllers, etc.
  - Automated Q-link diagnostics : testing standard protocols across network links, measure standard fidelities, and initiate automatic warnings or corrections