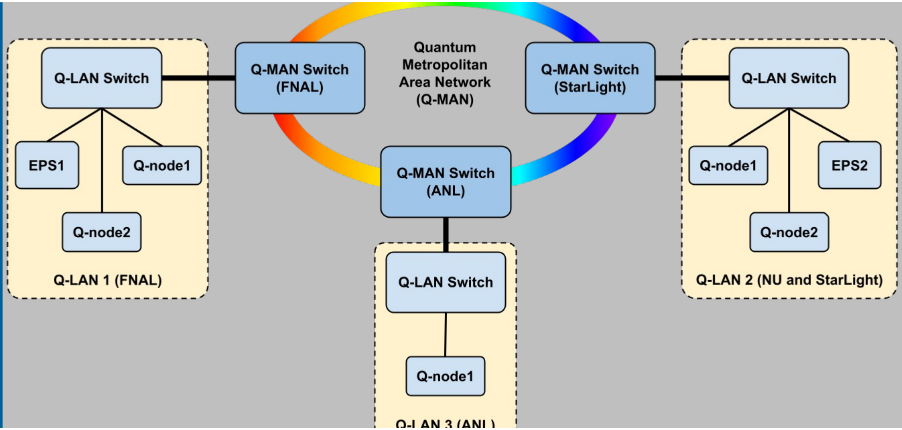
IETF 116, QIRG Meeting - March 27, 2023

Argonne NATIONAL LABORATORY

Design and Implementation of the Illinois Express Quantum Metropolitan Area Network



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U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

The IEQNET collaboration

Fermilab · Argonne · Caltech · Northwestern University · HYPERLIGHT · NuCrypt

The IEQNET Project

Illinois Express Quantum NETwork

“The Illinois Express Quantum Network (IEQNET) is a program to realize metropolitan-scale quantum networking over deployed optical fiber using currently available technology.”

Collaboration Partners:

- Two national labs
- Two universities
- Two industry partners

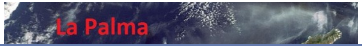
The IEQNET collaboration

J. Chung, E. M. Eastman, G. S. Kanter, K. Kapoor, N. Lauk, C. Peña, R. K. Plunkett, N. Sinclair, J. M. Thomas, R. Valivarthi, S. Xie, R. Kettimuthu, P. Kumar, P. Spentzouris, and M. Spiropulu, *“Design and Implementation of the Illinois Express Quantum Metropolitan area Network,”* IEEE Transactions on Quantum Engineering, pp. 1–20, 2022.

Motivation (circa 2019)

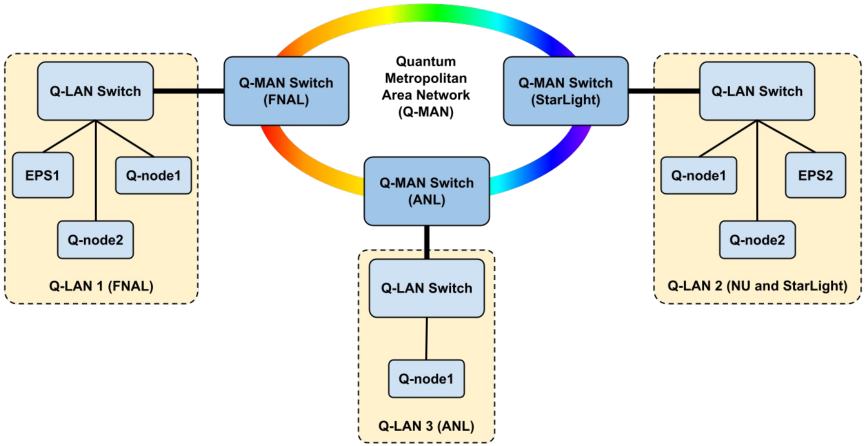
Developing a repeaterless Quantum Metropolitan Area Network

- Most quantum networking demonstra point or lir
- There is g architectu **automate** using exis demonstra **node** cap **scales** tha topologies



IEQNET Topology

Conceptual and Physical Diagrams

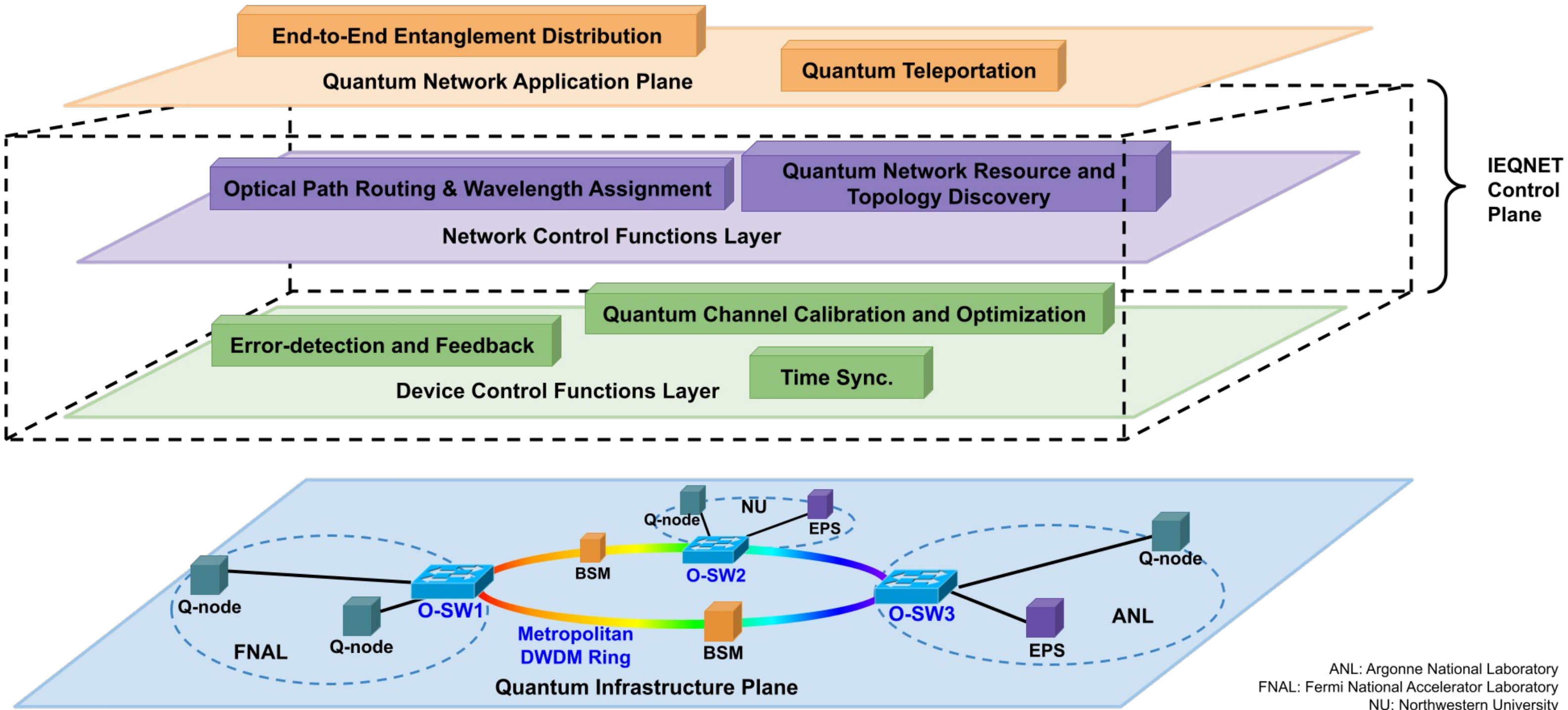


Design Considerations

- **Goal:** design and develop a **repeaterless transparent optical quantum network** in the Chicago metropolitan area to demonstrate quantum network capabilities beyond point-to-point communications.
- **Requirements:**
  - Coexistence between quantum and classical information in the same optical fibers
  - Flexibility to incorporate components developed outside IEQNET such as future quantum memories
  - Support for multi-node, multi-user operation
- **Approach:** Adopt a **layered architecture and centralized control**
  - Decouple control and data planes
  - Define control and management functions for routing and quantum channel assignment, dynamical optical path establishment, and calibration optimization functions
  - Use software-defined networking (SDN) to orchestrate optical switches and multi-wavelength entangled photon sources

IEQNET Architecture

Three-Planes Quantum Networking Architecture



ANL: Argonne National Laboratory
FNAL: Fermi National Accelerator Laboratory
NU: Northwestern University

IEQNET Control Plane Design

Control and Management Functions

- *Time Synchronization* of remote locations for distribution of entanglement and their use in subsequent applications
- *Path Routing and Wavelength Assignment (RWA)* is a fundamental network function, and multihop all-optical networks require a means of selecting lightpaths through the network
- *Quantum Channel Calibration & Optimization.* The single-photon nature of quantum communication signals makes them extremely sensitive to noise on the quantum channels

Algorithm 1: SP-RWA Algorithm.

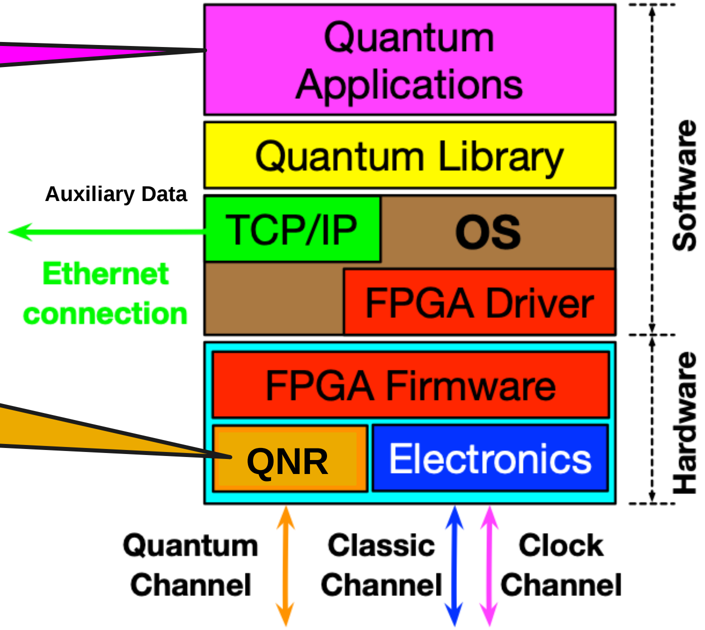
```
Input: G(V, E), src, dst, k, R ▷ G(V, E) is a graph
    representing the network topology. src and dst are
    the source and destination Q-nodes, respectively. k
    represents the number of paths and wavelengths to
    be found and R represents the entanglement
    distribution requirements.
Output: route ▷ Optimal lightpath between source
    and destination for entanglement distribution.
route ← NULL
paths ← FINDANDSORTPATHS(G, src, dst, k, R)
if paths is NULL then
    return "Request Rejected"
end if
for each path in paths do
    wavelengths ← SORTWAVELENGTH(path, R)
    for each wl in wavelengths do
        if wl is available then
            route ←
            ASSIGNWAVELENGTHTOPATH(path, wl)
            break
        end if
    end for
    if route is not NULL then
        return route
    end if
end for
return "Request Rejected"
```

IEQNET Q-Node Design

Q-Node = communication parties in the quantum network

Quantum applications will initially include entanglement distributions and quantum teleportation

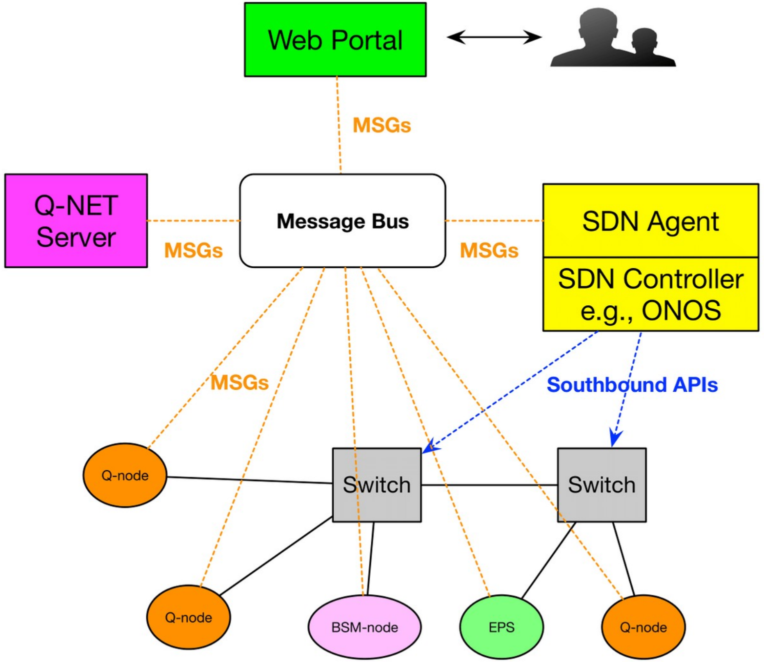
The quantum functions that a node can execute depend on the quantum resources available in the node (e.g., EPS, SNSPD, BSM, etc.)



QNR: quantum network resources
FPGA: field programmable gate array

IEQNET Implementation Plan

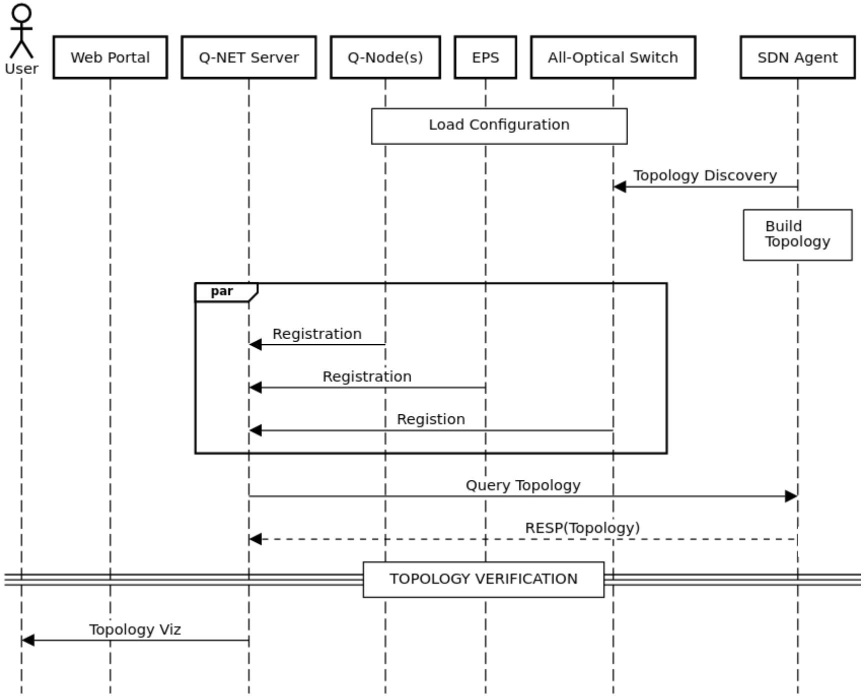
Centralized Control Framework



- **Web Portal:** allows user to access IEQNET services, browse topology, and monitor status
- **Q-NET Server:** manages and controls quantum network resources and provisions quantum networking services
- **SDN Agent:** maintains optical network topology, set up and tear down paths
  - **SDN Controller** (e.g. ONOS)
- **Message Bus** (e.g. MQTT)

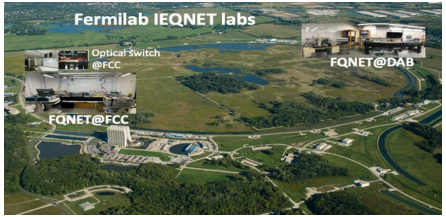
Control Protocol Example

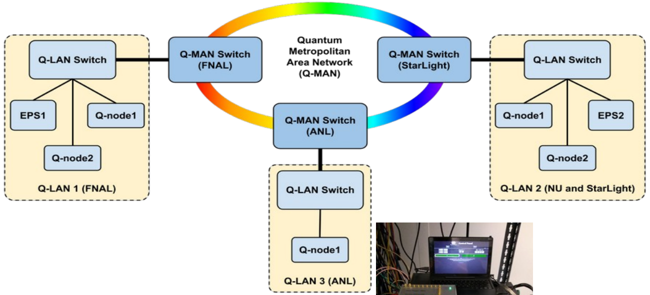
Quantum network resource and discovery protocol

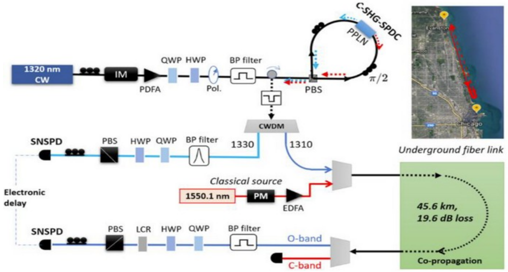


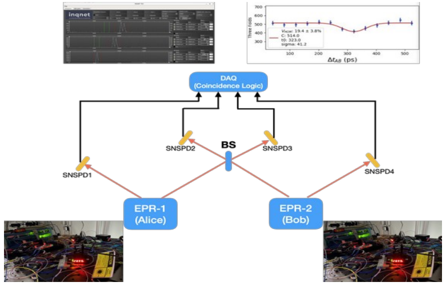
Algorithm 2: Quantum Network Resource and Topology Discovery Protocol.

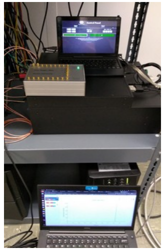
```
@ all Q-Nodes
INITIALIZE(config_file)
@ SDN Agent
topo ← NULL
for each switch in switches do
    neighbors ← QUERYNEIGHBORS(switch)
    topo ← UPDATETOPO(switch, neighbors)
end for
@ all Q-Nodes ▷ in parallel
SENDREG(q_node_info, QNETServer_address)
@ Q-NET Server
while RegistrationEvent do
    quantum_resources ←
    UPDATEQRESOURCES(q_node_info)
end while
QUERYTOPO(SDNAgent_address)
@ SDN Agent
SENDTOPO(topo, QNETServer_address)
@ Q-NET Server
for each q_node in quantum_resource do
    topo ← VERIFYCONNECTIVITY(q_node_info,
    SDNAgent_address)
end for
SENDTOPO(topo, WebServer_address)
@ Web Server
BUILDTOPOVISUALIZATION(topo)
```


Fermilab IEQNET labs
Optical switch
@FCC
FQNET@DAB
FQNET@FCC


Quantum
Metropolitan
Area Network
(Q-MAN)
Q-LAN Switch
Q-MAN Switch
(FNAL)
Q-MAN Switch
(StarLight)
Q-LAN Switch
EPS1
Q-node1
Q-node2
Q-LAN 1 (FNAL)
Q-MAN Switch
(ANL)
Q-node1
EPS2
Q-node2
Q-LAN 2 (NU and StarLight)
Q-LAN Switch
Q-node1
Q-LAN 3 (ANL)


1320 nm
CW
IM
PDFA
QWP
HWP
Pol.
BP filter
PBS
C-SHG-SPDC
PPLN
π/2
CWDM
SNSPD
PBS
HWP
QWP
BP filter
1330
1310
Underground fiber link
Electronic
delay
Classical source
1550.1 nm
PM
EDFA
45.6 km,
19.6 dB loss
SNSPD
PBS
LCR
HWP
QWP
BP filter
O-band
C-band
Co-propagation


DAQ
(Coincidence Logic)
SNSPD2
BS
SNSPD3
SNSPD1
SNSPD4
EPR-1
(Alice)
EPR-2
(Bob)
Δt_AB (ps)



IEQNET Topology

Quantum Networking Resources

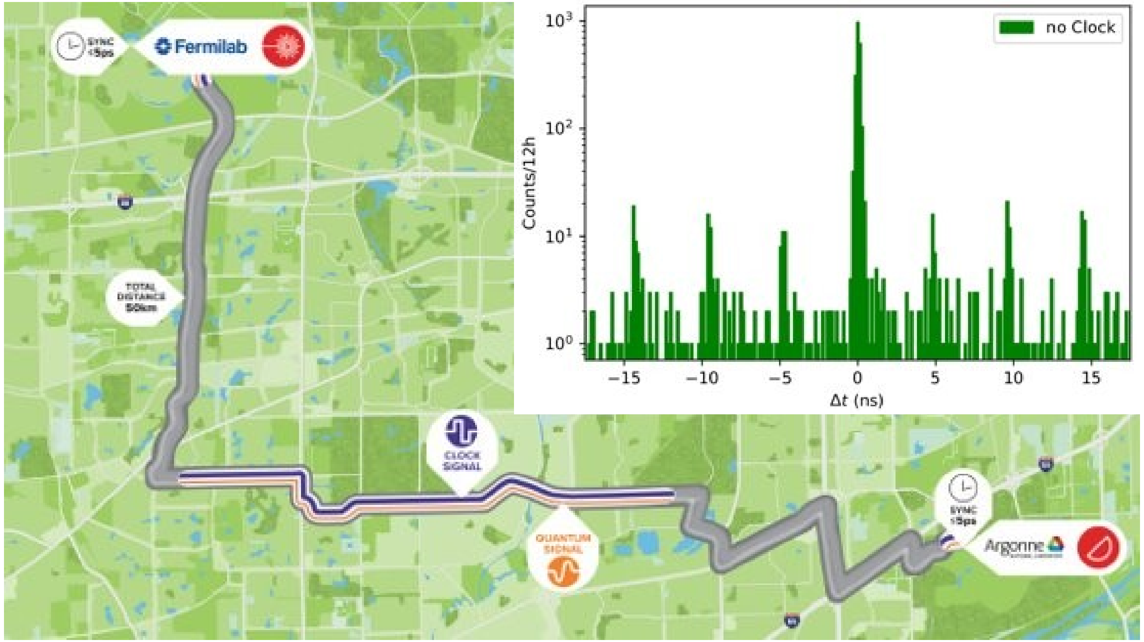
Time-bin qubits
SNSPDs
EPS
Clock source
Polatis 16x16 all-optical switch

Polarization qubits
SNSPDs
EPS
2 Polatis 8x8 all-optical switches

Polarization qubits
SNSPDs
EPS (NuCrypt)
Clock source
Polatis 16x16 all-optical switch

Coexistence of Qubits with Clock Signals

Between Q-LAN1 (Fermilab) and Q-LAN3 (Argonne)



We demonstrate a three-node quantum network for **C-band photon pairs using 2 pairs of 59 km of deployed fiber** between Fermi and Argonne National Laboratories. The C-band pairs are directed to nodes using a standard telecommunication switch and the detection system is synchronized to picosecond-scale timing resolution using a **coexisting O- or L-band optical clock distribution system**. We measure a reduction of coincidence-to-accidental ratio **(CAR) of the C-band pairs from 51 ± 2 to 5.3 ± 0.4 due to Raman scattering** of the O-band clock pulses. Despite this reduction, the CAR is nevertheless suitable for quantum networks.

K. Kapoor, S. Xie, J. Chung, R. Valivarthi, C. Peña, L. Narváez, N. Sinclair, J. P. Allmaras, A. D. Beyer, S. I. Davis, G. Fabre, G. Iskander, G. S. Kanter, R. Kettimuthu, B. Korzh, P. Kumar, N. Lauk, A. Mueller, M. Shaw, P. Spentzouris, M. Spiropulu, J. M. Thomas, and E. E. Wollman, "Picosecond synchronization system for the distribution of photon pairs through a fiber link between fermilab and argonne national laboratories," IEEE Journal of Quantum Electronics, pp. 1–1, 2023.

Future Work

1. **Infrastructure Plane:**
   - Demonstrate entanglement between Q-LAN2 (NU/StarLight) and Q-LAN3 (Argonne)
   - Implement conversion between time-bin and polarization qubits (and vice versa)
2. **Control Plane:**
   - Prototype implementations of both Q-Node and IEQNET Controller
3. **Application Plane:**
   - Demonstrate entanglement distribution automatically controlled by IEQNET control plane, assisted by Q-Nodes

Thanks!

Q&A

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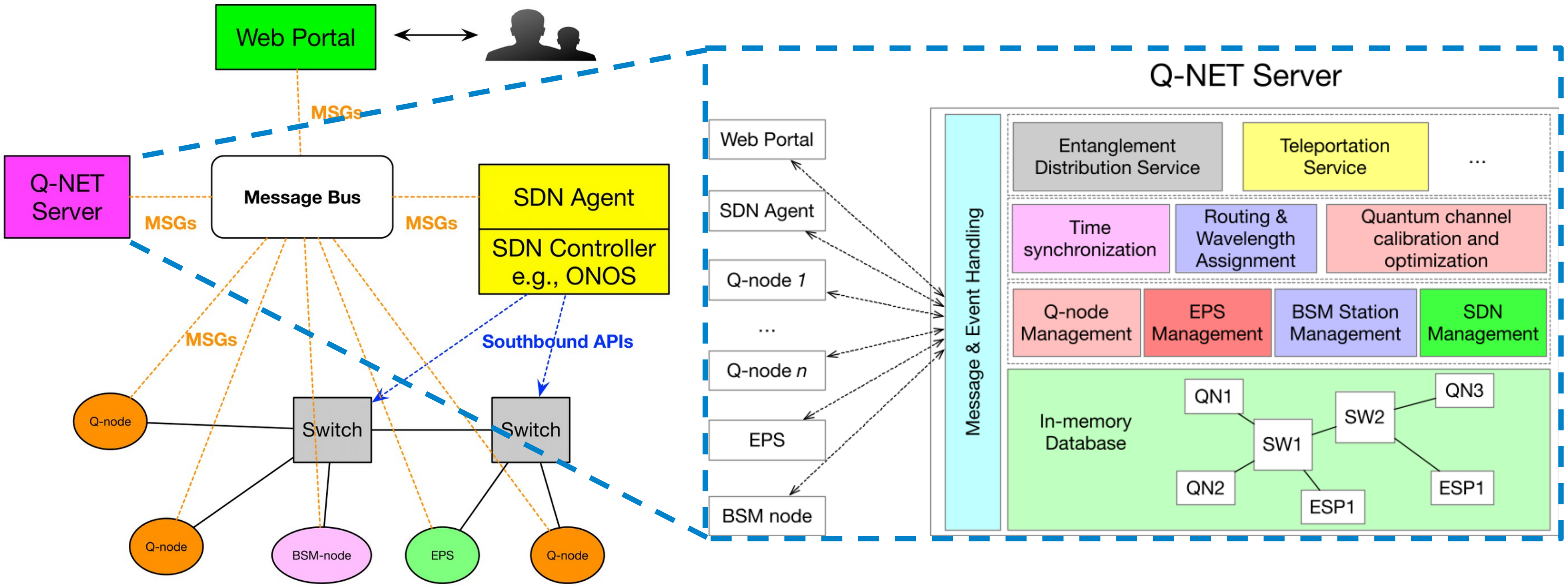
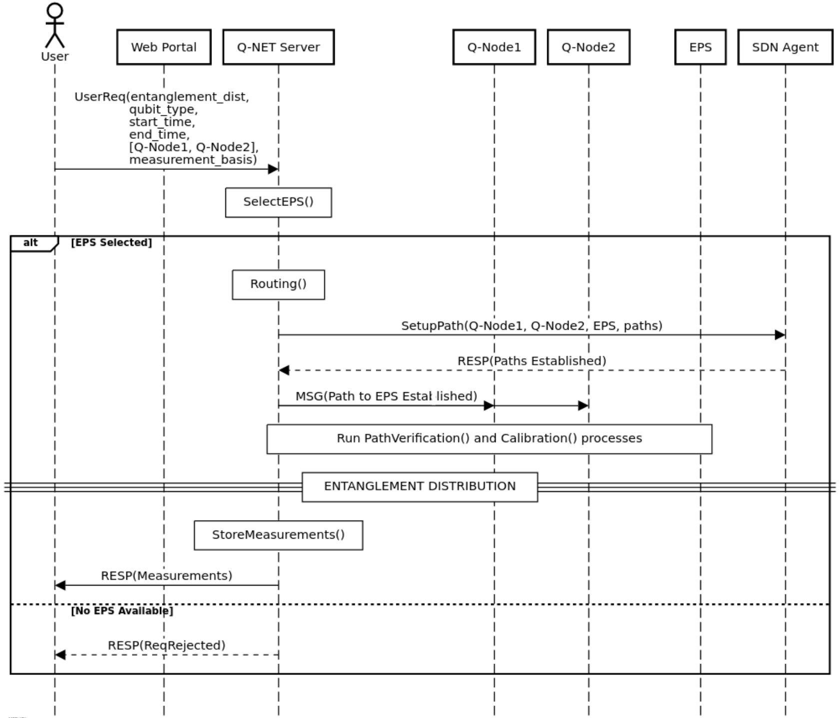
Control Plane Implementation

Quantum Network (Q-NET) Server



Control Protocols

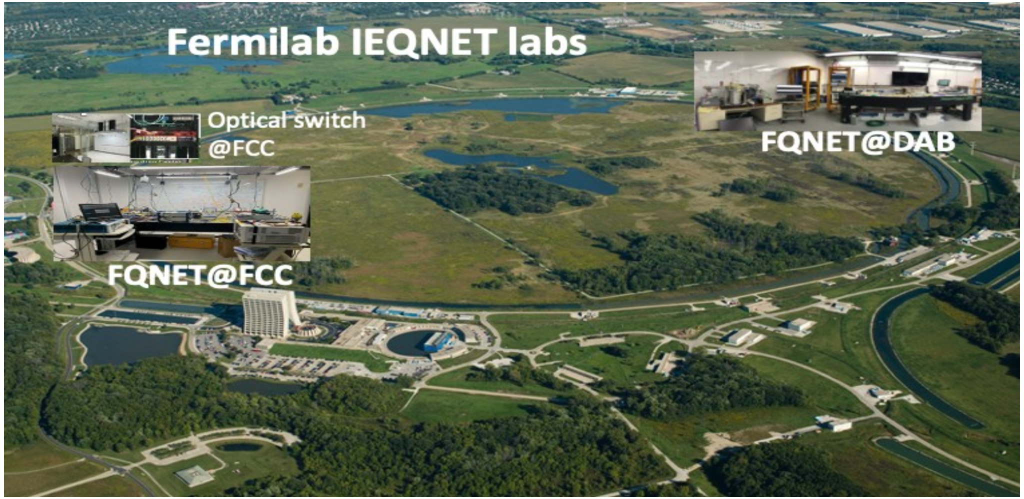
The protocol for handling entanglement distribution requests

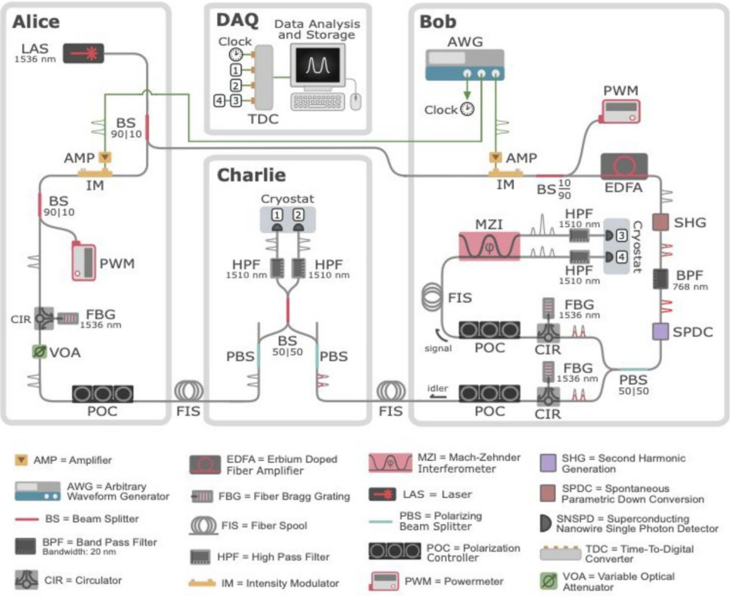


1. User issues entanglement distribution request
2. Q-NET server selects an EPS that meets requirements
3. Upon request acceptance, Q-NET server executes RWA and requests paths setup from SDN agent
4. Q-NET server initiates path verification, calibration and optimization
5. Q-NET server starts entanglement distribution process
6. Q-NET server stores measurements and makes them available to user

Quantum Teleportation of Time-bin Qubits

@ Q-LAN1 (Fermilab)





Demonstration of a quantum teleportation protocol in which a photonic qubit (provided by Alice) is interfered with one member of an entangled photon-pair (from Bob) and projected (by Charlie) onto a Bell-state, whereby the state of Alice's qubit can be transferred to the remaining member of Bob's entangled photon pair.

Experiment Demonstration

Experimental Setup and Coexistence Results in QLAN-2 (NU)