Exploring The Challenges and Opportunities Of Quantum Communications And Networking

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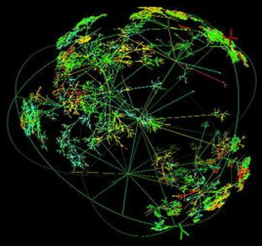
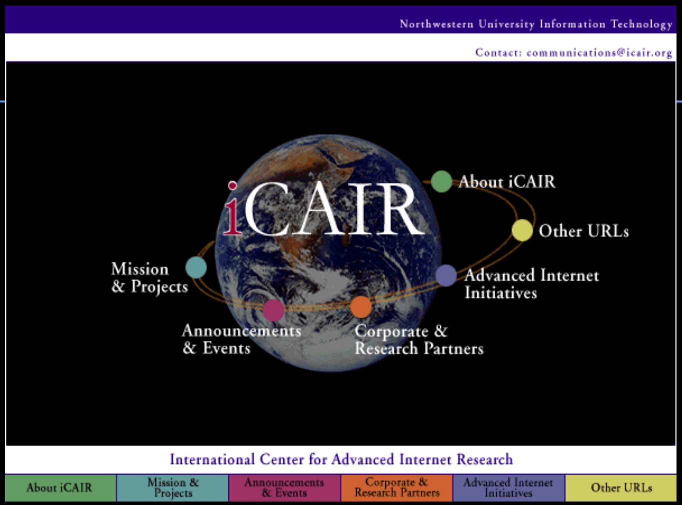
TNC Conference
Trieste, Italy
June 13-17, 2022



Introduction to iCAIR:



Accelerating Leading Edge Innovation and Enhanced Global Communications through Advanced Internet Technologies, in Partnership with the Global Community

- **Creation and Early Implementation of Advanced Networking Technologies - The Next Generation Internet All Optical Networks, Terascale Networks, Networks for Petascale Science**
- **Advanced Applications, Middleware, Large-Scale Infrastructure, NG Optical Networks and Testbeds, Public Policy Studies and Forums Related to NG Networks**
- **Three Major Areas of Activity: a) Basic Research b) Design and Implementation of Prototypes and Large Scale Research Testbeds (Currently ~ 25) c) Operations of Specialized Communication Facilities (e.g., StarLight International/National Communications Exchange Facility)**

Selected Applications

GENI
www.geni.net

GLEON
www.gleon.org

USGS EROS
www.usgs.gov/centers/eros

NEON
www.neonscience.org

Open Storage Network
www.openstoragenetwork.org

OSiRIS
www.osris.org

XSEDE
www.xsede.org

Blue Waters
bluewaters.ncsa.illinois.edu

PRAGMA
www.pragma-grid.net

CENTRA
www.globalcentra.org

OSG
www.opensciencegrid.org

GRP
theglobalresearchplatform.net/

PRP
pacificresearchplatform.org

CHASE-CI
www.calit2.net/newsroom/article.php?id=2910

SAGE2
sage2.sagecommons.org

Polar Geospatial Center
www.pgc.umn.edu

IceCube
icecube.wisc.edu

Chameleon
www.chameleoncloud.org

Jetstream
www.jetstream-cloud.org

Genomic Science Program
genomicscience.energy.gov

LSST
www.lsst.org

Pierre Auger Observatory
www.auger.org

Belle II
www.belle2.org

LBNF/DUNE/ProtoDUNE
lbnf.fnal.gov

ISS
www.nasa.gov/station

SKA
www.skatelescope.org

XENON
xenon.astro.columbia.edu

NOvA
novaexperiment.fnal.gov

Virgo
www.virgo-gw.eu

LIGO
www.ligo.caltech.edu

SDSS
www.sdss.org

ALMA
www.almaobservatory.org

LHC
home.cern/science/accelerators/large-hadron-collider

LHCONE
twiki.cern.ch/twiki/bin/view/LHCONE/WebHome

LHCOPN
twiki.cern.ch/twiki/bin/view/LHCOPN/WebHome

IVOA
www.ivoa.net

Compilation by Maxine Brown and Joe Mambretti

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Next Generation Distributed Enviroment For Global Science

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Quantum Science Research Initiatives Priority For Many Nations

- **Multiple Interdisciplinary Research Domains**
  - Physics
  - Quantum Science
  - Information Theory
  - Information Science
  - Optimization Theory
  - Materials Science
  - Quantum Components
  - Quantum Computing
  - Quantum Communications
  - Quantum Networking
  - Many, Many Other Topics
- **Undertaken By Many Organizational Cooperative Consortia**
- ***World Quantum Day: April 14th — or "4.14" — Rounded 1st 3 Digits of Planck's Constant, Value That Sets The Quantum Scale***

Selected NSF Quantum Research Topics

- **Quantum Fundamentals**
  - Understanding, Controlling, Minimizing Quantum Decoherence
  - Generating, Characterizing, Manipulating Quantum Entangled States
  - Characterizing, Verifying, Exploiting Quantum Algorithms
  - Discovering, Analyzing, Understanding Fundamental Properties Of Quantum Many-Body States of Matter With Exploitable Properties, e.g., Control of Many Degrees of Freedom Using High Resolution Light-Matter Interactions
- **Quantum Metrology and Control** (Enhancing Measure, Modeling, Control, And Exploiting Quantum Phenomena In Single and Multi-Particle Systems)
  - Utilizing Quantum Superposition of States, Entanglement and Quantum Squeezing in Metrology;
  - Characterizing, Minimizing Noise, Developing, Testing, Implementing Quantum Error Corrections
  - Developing Efficient High-Resolution Methods to Generate, Control, Manipulate, Read, and Write Qubits.
- **Designing Quantum Systems** - Stable, Controllable, Scalable, Error-Free, Low-Dissipation Platforms Many Types of States.
  - Interfacing Quantum & Classical Circuit & Computing Devices For Monolithic or Hybrid Systems
  - Developing Quantum Circuits, System Designs and Programming Paradigms for Quantum Sensing, Computing and Communication; Developing, Validating Platforms for Quantum testbeds for Rapid Prototyping, System Characterization, Optimization; System Integration Techniques for Combining Quantum and Classical Platforms;
  - Generating, Scalable Systems of Quantum Objects in Superposition States, Tailored for Specific Use, while Enabling Information Exchange Among Different Types of Such Objects and Across Quantum-Classical Boundaries

Quantum Communications And Networks: Motivation

- **Quantum Enables Many New Applications**
  - Security – e.g., Quantum Key Distribution (QKD), Highly Secure Information Transmission, Quantum Encryption
  - Quantum Sensors
  - Quantum – e.g., Precise Clocks
  - New Applications Derived From Unique Properties (e.g., Superposition) And Novel Quantum Devices
  - Communications Among Quantum Computers, e.g., To Address Complex Computational Science Problems Through Distributed Quantum Environments (iCAIR's Quantum Research Focus)

High Levels Of Challenges Requires Consortia

- **Northwestern University Established INQUIRE (Initiative at Northwestern for Quantum Information Research and Engineering), For Quantum Science Research**

- **This Initiative Participates in the Chicago Quantum Exchange and The Illinois Express Quantum Network, which includes the U.S. Department of Energy's Argonne National Laboratory, Fermi National Accelerator Laboratory, Multiple Research Universities, and Several Corporations.**

- **These National Laboratories, Northwestern University, Including the International Center for Advanced Internet Research (iCAIR), the StarLight International/National Communications Exchange Facility Consortium, the Metropolitan Research and Education Network (MREN), the Illinois Quantum Information Science and Technology Center (IQUIST) at the University of Illinois at Urbana-Champaign, And Other Research Partners, Including Internationally, Are Collaborating On This initiative.**

A Few Terms

- Quantum Computers Utilize Several Attributes of Quantum States, Including:
- ***Superposition:*** A State Consisting Of a Sum Of Two Or More States
- ***Interference***: Influencing Qubit Measurement To Result In One Ot More Specified States
- ***Quantum/Photonic Entanglement*** (Einstein's "Spooky Action At a Distance"): Fundamental Quantum Mechanic Effect – Physical Properties Of Interlinked Particles Can Have Perfect Correlations, Even When Separated By Large Distances

A Few More Terms

- ***Qubit, Quantum Bit*: Analog of Digital Bit, A Unit Of Information Represented By The State Of An Atom, Photon, Ion, Electron, Superconducting Circuits, Etc (e.g., Spin, Polarization, Position et al) That Can Represent Multiple Values Simultaneously, Often Described As A Two-State System (e.g., Can Be Both 1 and) vs Only the 1 or 0 Of Binary Digits)**
- ***Transduction:* - High Fidelity Transfer Of A Quantum State Among Domains, e.g., Converting Quantum Signals Among Different Modalities, Media Frequencies, Functional Devices**
- ***Quantum Teleportation:* Transferring Quantum Information From One Place To Another (Paths For "Flying Qubits")**
- ***Coherence/Decoherence: Quantum States Are Extremely Fragile, Challenging To Communicate While Maintaining High Fidelity State***

Quantum Transduction

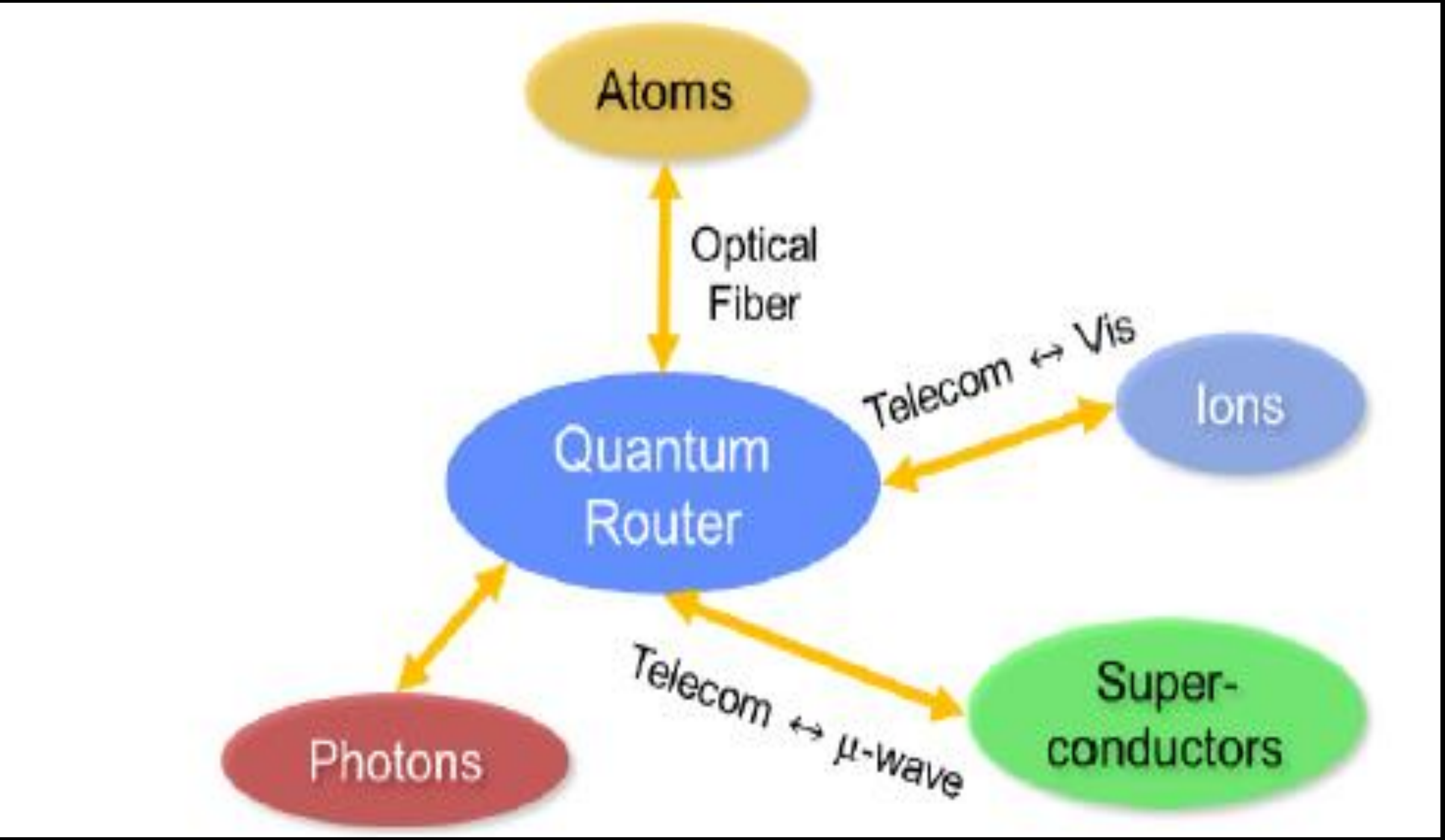


Image Source: Prem Kumar, Northwestern
Center for Photonic Communication And Computing

Quantum Network Layers

- • ***Quantum Service Layer***

  - Quantum Entanglement Discovery And Distribution Service: e.g., Entangled Photonic Generation, Management, Distribution

- • ***Quantum Networking Layer***
- - SDN Control Functions, e.g., Wavelength Routing, Wavelength Assignment, Path Topology Creation Among Quantum Nodes, Related Devices
- ***Quantum Link Layer***
  – Protocol Layer Manages Quantum signals and Messages Transmitted Through Quantum Channels Among Q-nodes, Monitors Quantum Link Status
- • ***Quantum Physical Layer***
  – Physical Connectivity (e.g., Optical Fiber)/Communication Among Quantum Nodes, Determines Quantum Channel Frequencies, Signal Rates, Photon Pulses Used For Quantum Signals et al

Example Issues In Quantum Communications & Networking

- Designing Specialized Architecture, e.g., Customized For Applications
- Delineating Quantum "Services"
- Quantum Information Distribution, Specialized Carriers (e.g., Qubits, Entangled Photons)
- Determining What Functions Should Be Placed At What Level With What Components
- Topologies, Algorithms, Interfaces and Protocols? (No "Quantum TCP or "Quantum IP" Exist)
- Quantum Memory, Switching/Routing
- *Because No Repeaters Exist Yet*, Distances Are Limited (Rate Declines Exponentially With Photon Transmission Probability – 150-200 Km Max)
- Quantum Network Management, Control, And Data Planes
- Space vs Time Domains
- Integration With Classical Networks
- Quantum Measurements, Quantum Error Correction
- Fiber Types e.g., SMF-28 vs Hollow Core, Impedances, Wavelengths (Lightpaths) vs Dedicated Fiber, db Loss, etc.

Qubit Transmission

- Photons Require Exceptionally High Fidelity Transmission – From Source To Destination
- When They Arrive At Their Target, The Quality Of Their Entangled State Should Be Perfect
- One Challenge: Implementing A High Quality Spectrally Un-Entangled Source
- Goal: Qubits Entangled With A Single Degree of Freedom
- Multiple Degrees of Freedom Diminish Hong-Ou-Mandel Interference (H-O-M Effect)

H-O-M Effect

- H-O-M Effect: Two-Photon Interference Demonstrated (1987) By Chung Ki Hong, Zheyu Ou, and Leonard Mandel, University of Rochester Physicists.
- Two identical Single-Photon Waves Can Be Sent Through A 1:1 beam Splitter, Each In One Input Port Resulting In A Temporal Overlap
- Under Ideal Conditions, The Photon Temporal Overlap Will Be Perfect.
- Two Photons Exit The Beam Splitter With An Identical Output Mode
- (50% Probability)

Transitioning Qnets From Concepts And Lab Experiments To Field Trials

- Research in Quantum Communications and Networking Requires Real World Testbeds Supporting Empirical Experiments
- Currently, A Distance Limitation Exists On Communicating High Fidelity Qubits Over Fiber (No Quantum Repeaters)
- Consequently, Various Metro Scale Quantum Networking Testbeds Have Been Created
- Previously, iCAIR developed a Dedicated Fiber Quantum Testbed That Supported Experimentation In Photonic Entanglement and Quantum Key Distribution.
- With Consortium Partners, iCAIR Is Participating Design And Development Metro Scale Quantum Networking Testbeds, Particularly To Interconnect Quantum Computers, Eventually Quantum Clouds
- A Potential Exists For Extending These Testbeds To International Sites Via Satellite (Line-of-Sight Optics), Eventually “Quantum Repeaters”

Quantum Networking Testbed Building Blocks

- Advanced Networking And Exchange Facilities
- Architecture (Defining QNode Capabilities, QNet Topology Discovery, Path And Wavelength Assignment, Clock Distribution, Entanglement Distribution Protocols)
- Heterogeneous Components
- High Quality Dedicated Fiber
- Management And Control Planes Based On Classical Networking (*<u>Software Defined Networking Techniques</u>*)
- Interfaces, Protocols, Algorithms
- Low db Loss Optical Switches
- Quantum Memories As Proxies For Quantum Computers
- Measurement⬄Management Integrations

StarLight – "By Researchers For Researchers"

StarLight: Experimental Optical Infrastructure/Proving Ground For Next Gen Network Services Optimized for High Performance Data Intensive Science

Multiple 100 Gbps (80+ Paths)

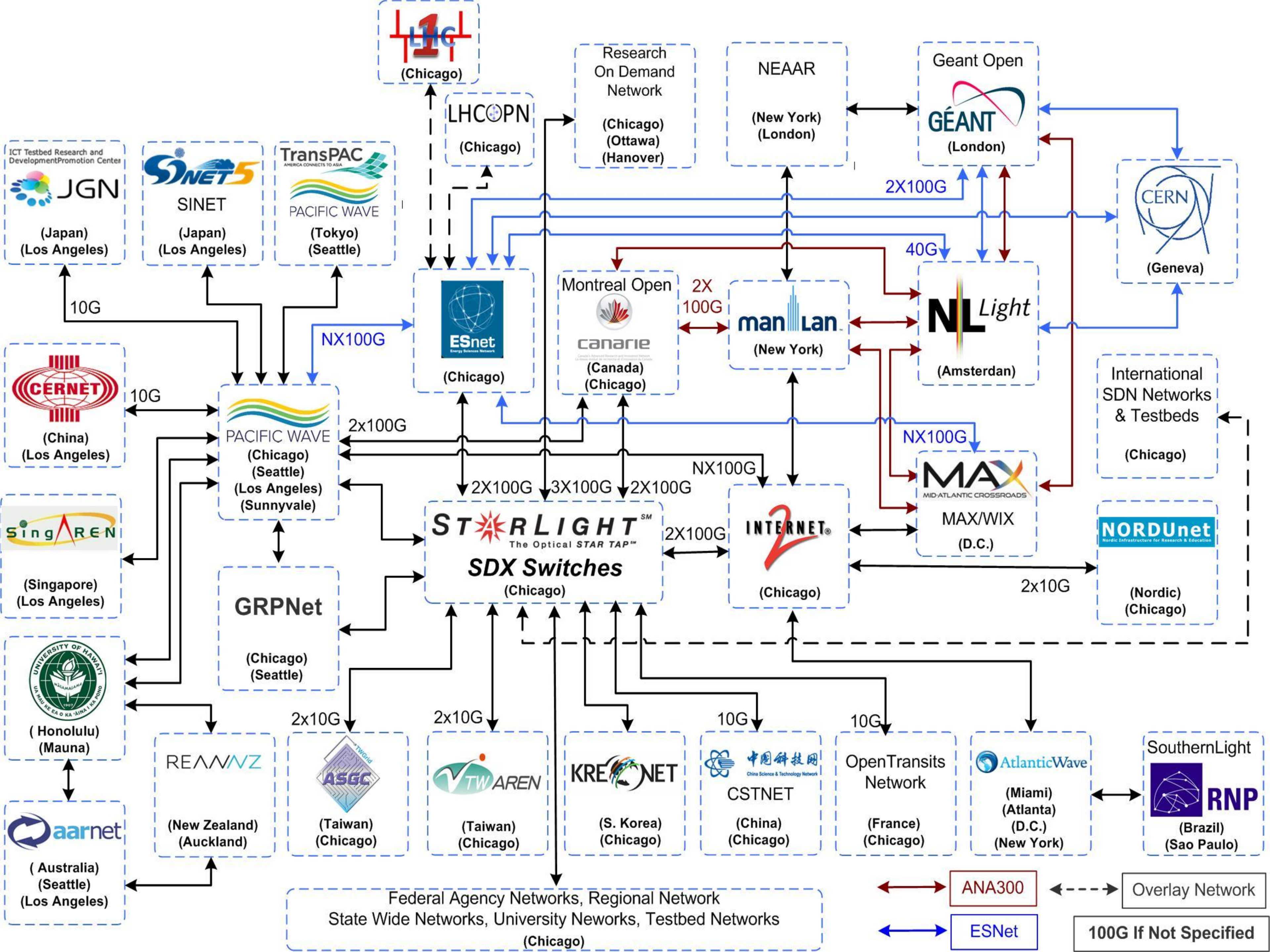
StarWave 100 G Exchange

World's Most Advanced Exchange

Multiple First of a Kind Services and Capabilities

View from StarLight

Abbott Hall, Northwestern University's Chicago Campus



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(Auckland)
ASGC
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KREONET
(S. Korea)
(Chicago)
CSTNET
(China)
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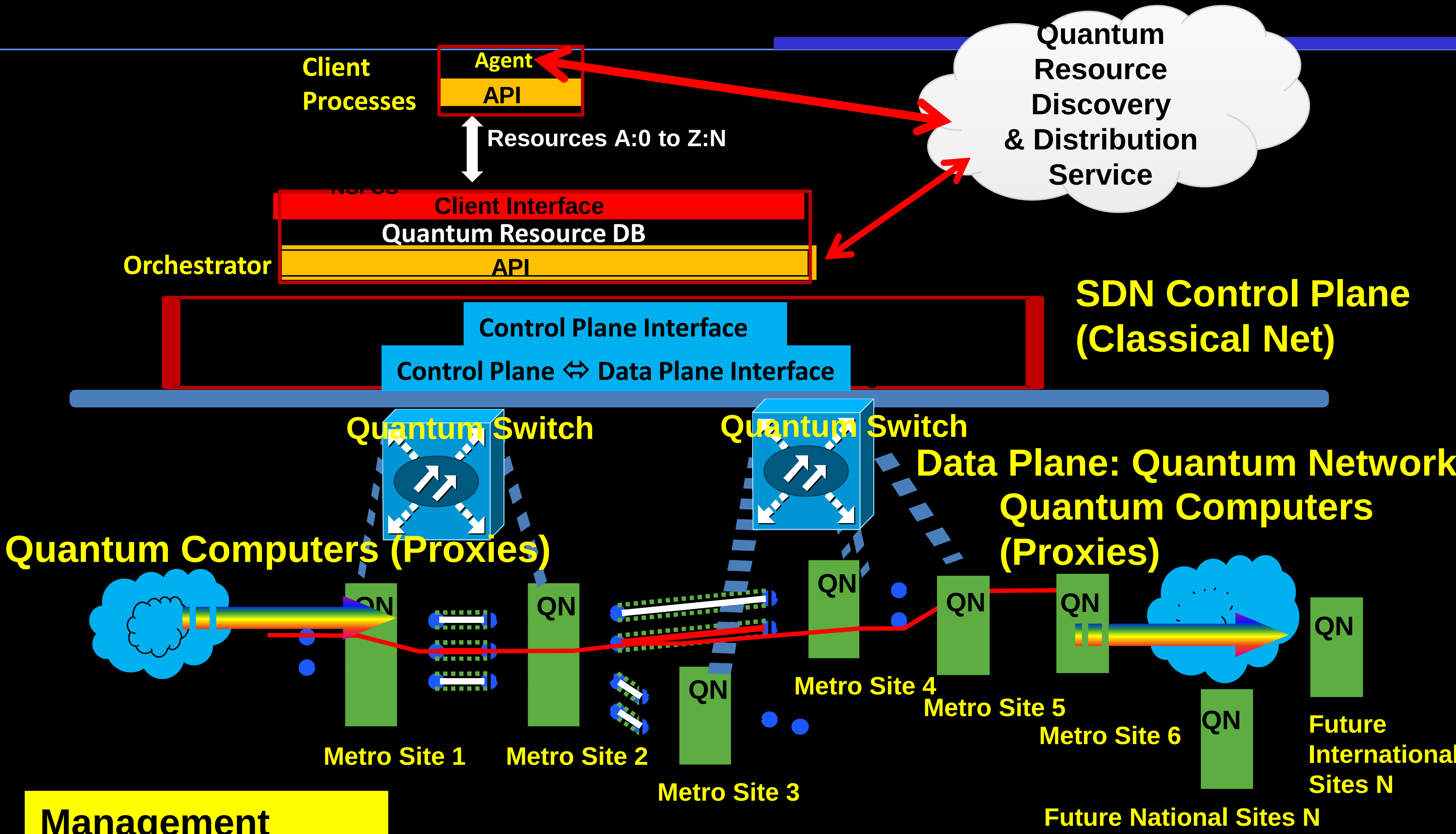
OpenTransits
Network
(France)
(Chicago)
AtlanticWave
(Miami)
(Atlanta)
(D.C.)
(New York)
SouthernLight
RNP
(Brazil)
(Sao Paulo)
aarnet
(Australia)
(Seattle)
(Los Angeles)
Federal Agency Networks, Regional Network
State Wide Networks, University Neworks, Testbed Networks
(Chicago)
ANA300
Overlay Network
ESNet
100G If Not Specified

Quantum Testbed Design Architecture



Management Plane: Classical Net

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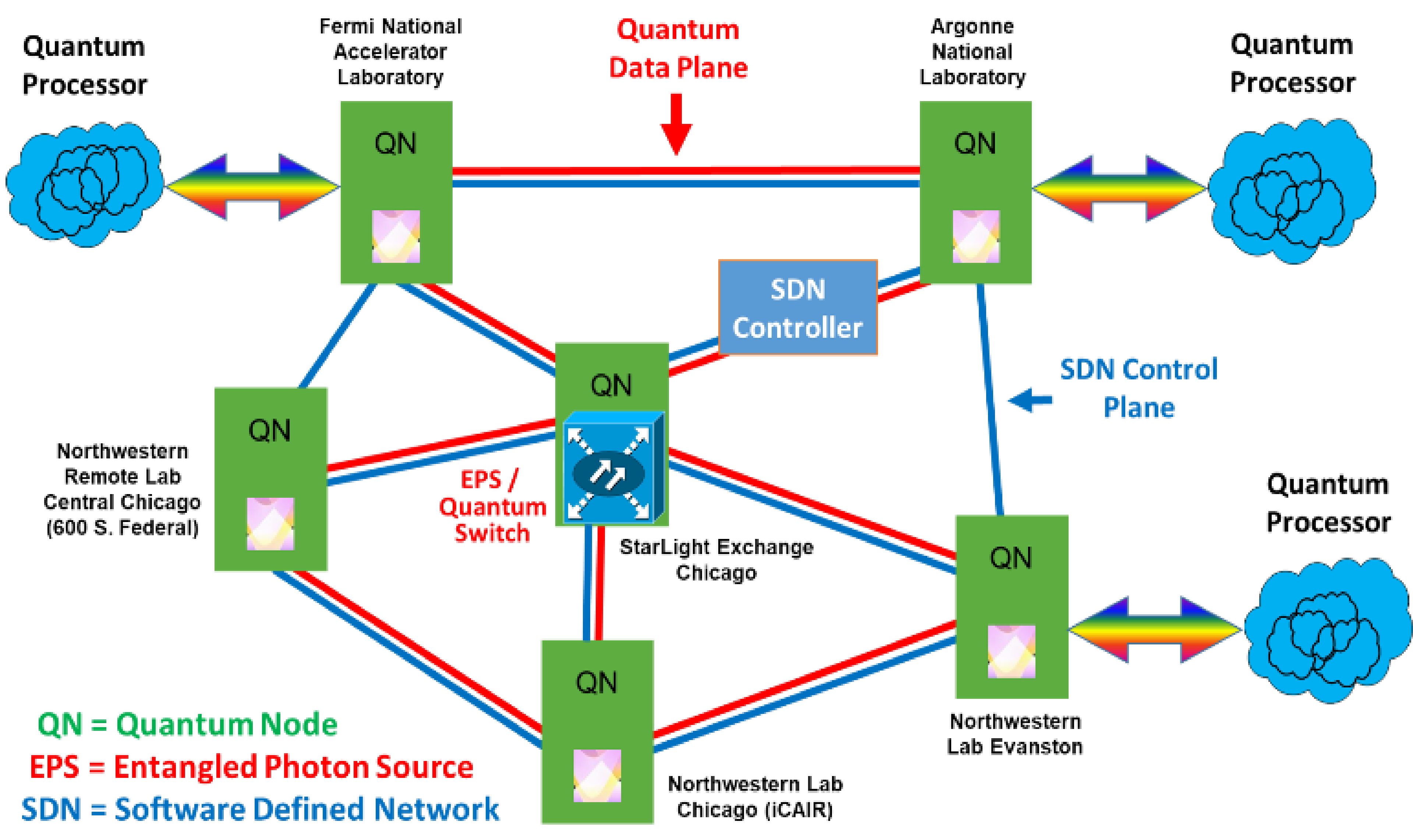
Emerging Chicago Quantum Exchange Testbed



Argonne National Laboratory QILab Testbed Architecture

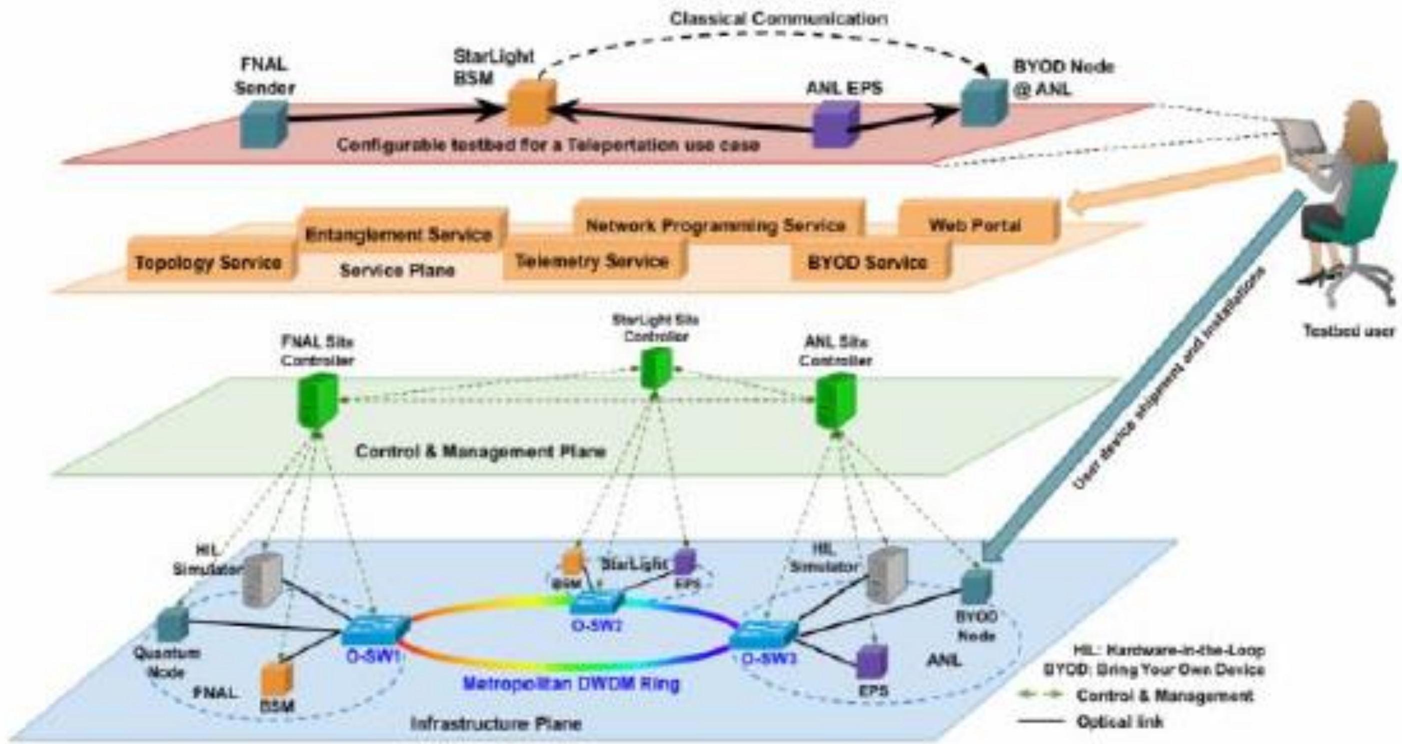
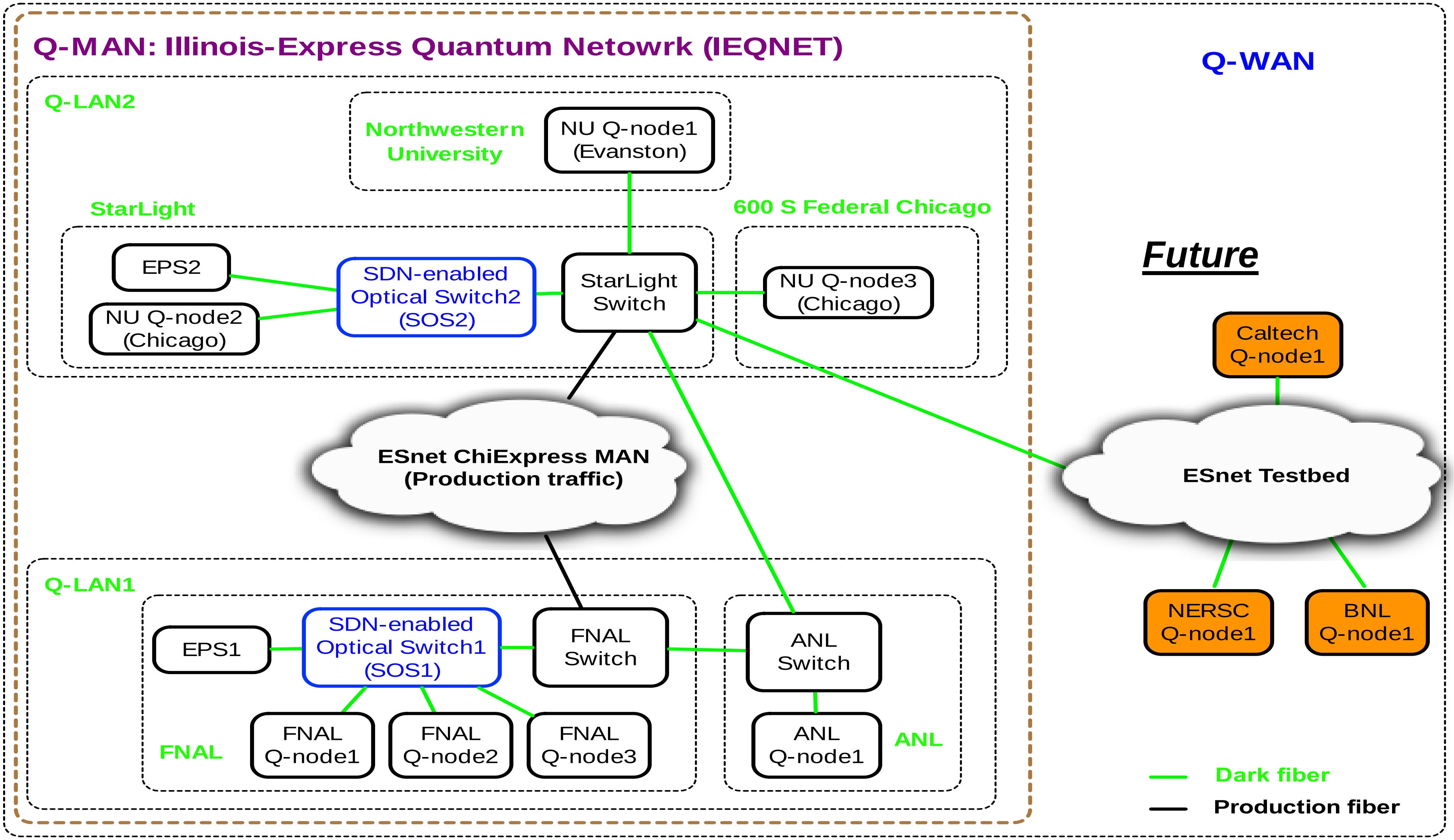


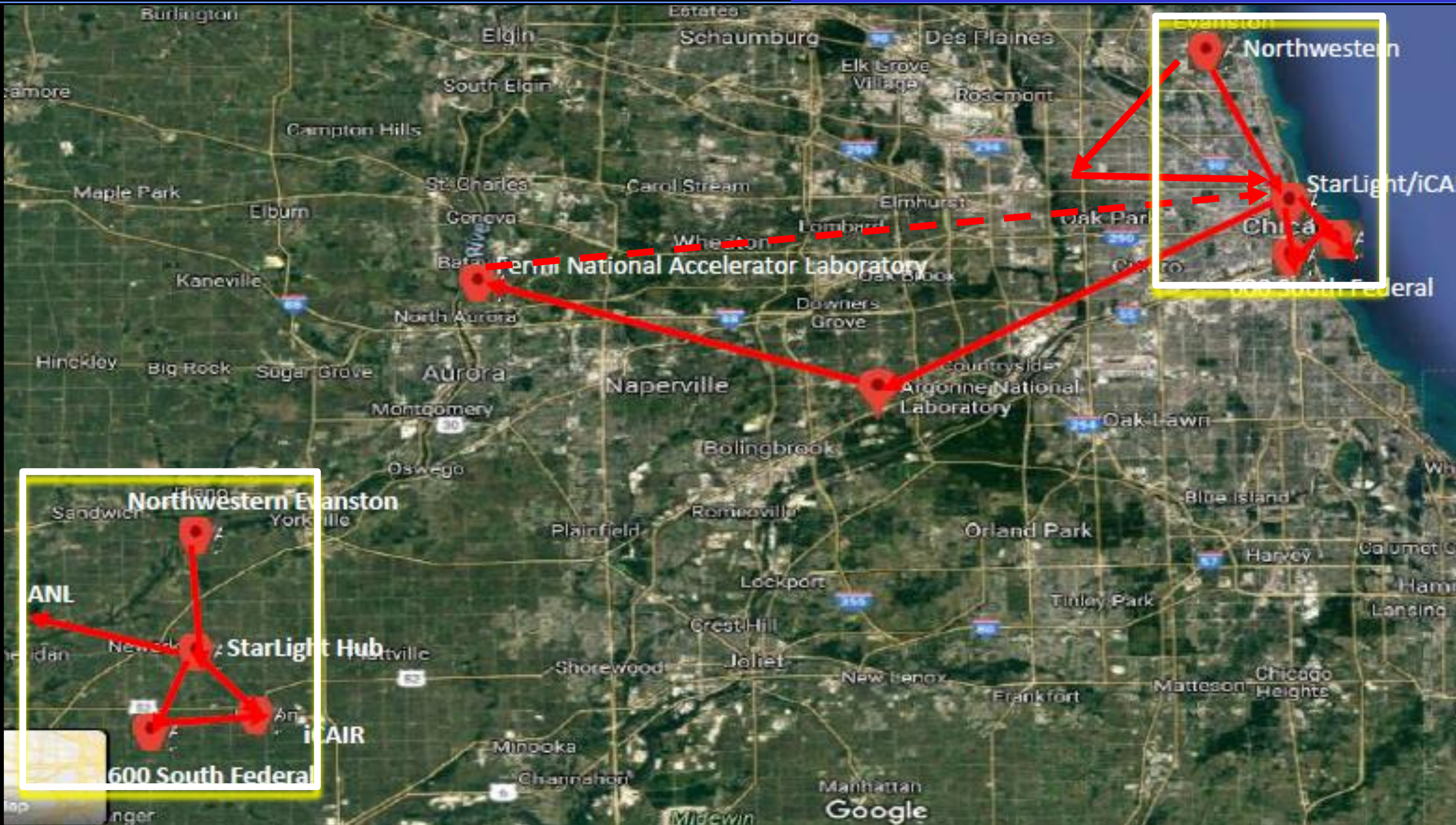
Figure 1: QILab architecture, showing an example reconfigurable testbed (top) using capabilities from the reconfigurable and adaptable service, control/management, and infrastructure planes.

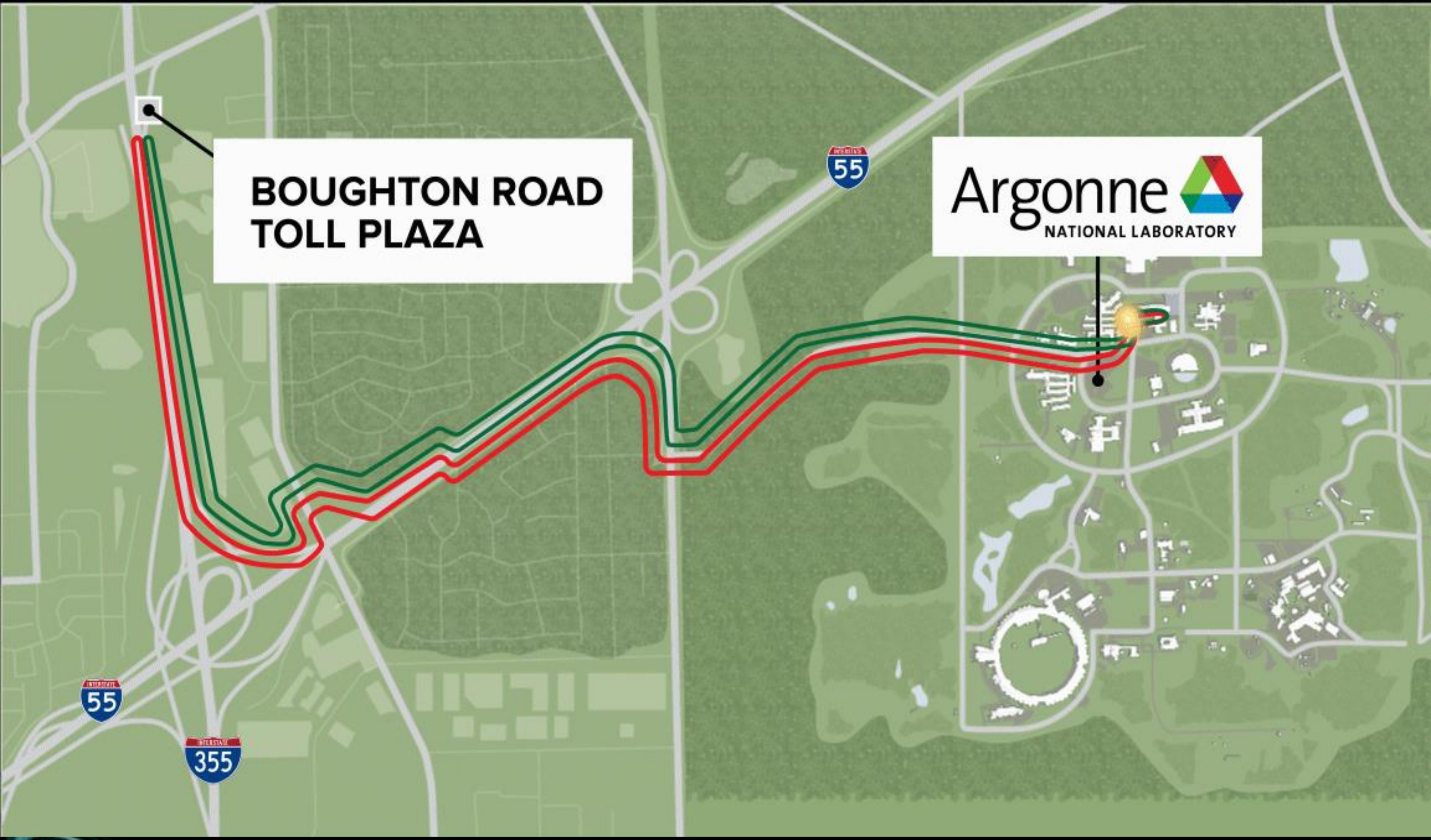
Illinois Express Quantum Network



Source: Wenji Wu, ESnet

Energing IEQnet Testbed Topology




BOUGHTON ROAD
TOLL PLAZA
Argonne
NATIONAL LABORATORY
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Polatis All-Optical Switch


Achieve More with Optical Switching™

DATA SHEET

HUBER+SUHNER Polatis

SERIES 6000i

Instrument Optical Matrix Switch

SINGLE MODE INSTRUMENT OPTICAL SWITCH FROM 4x4 TO 192x192 PORTS

Series 6000 Ultra 32x32 Optical Switch

Series 6000 192x192 Optical Switch

The Polatis Series 6000i Instrument optical switch is a high-performance, fully non-blocking all-optical matrix switch available in sizes from 4x4 up to 192x192. It is designed to meet the highest performance needs of the most demanding test and measurement applications with exceptionally low optical loss, superior connection stability and repeatability in a compact form factor. With support of Software-Defined Networks (SDNs) via embedded OpenFlow, NETCONF and RESTCONF control interfaces, the Series 6000i interfaces directly with cutting edge cloud-based network and infrastructure testing applications. The Series 6000i is based on Polatis' patented DirectLight® optical switching technology that has been proven in the most challenging defense, data center and telecom applications and is exclusively used by major network equipment manufacturers to automate testing of optical components and subsystems.

KEY FEATURES

- Non-blocking matrix switch sizes from 4x4 to 192x192
- Ultra-low insertion loss and superior optical specifications
- Exceptional optical stability and repeatability
- Dark fiber all-band single mode connectivity
- Fully bidirectional optics
- Available in NxN, MxN single-sided and customer configurable (NxCC) any-to-any port configurations
- Protocol and bit-rate agnostic up to 400Gbs and beyond
- Optional Optical Power Monitoring (OPMs) with user configurable optical power alarms
- Optional Variable Optical Attenuation (VOAs) on every switch connection
- Programmable port shutter for fiber break simulation
- SDN enabled with OpenFlow, NETCONF and RESTCONF command interfaces
- Configurable interface options with SNMP, TL1 and SCPI control languages
- Built-in user-friendly web GUI
- High reliability distributed architecture
- High density switching in a compact chassis
- Eco-friendly energy efficiency

DIRECTLIGHT TECHNOLOGY

The Series 6000i 4x4 to 192x192 switch leverages Polatis' patented, highly reliable piezoelectric DirectLight beam-steering technology that sets the industry standard for lowest optical loss and highest optical performance. Polatis' beam-steering technology can be switched without light being present on the fiber. This allows operators to pre-provision paths as well as switch intermittent and variable-power test signals test over lit or dark fiber. The Polatis DirectLight technology can also switch bi-directional optical test signals for PON, FTTx, and other types of transmission systems.

SDN ENABLED WITH USER FRIENDLY INTERFACES

Polatis offers a full complement of Software Defined (SDN) interfaces including OpenFlow, NETCONF and RESTCONF. Optical switching with SDN allows infrastructure vendors and system test operators to dynamically and cost effectively setup, monitor and operate cloud-based manufacturing and network test configurations. Polatis also works closely with leading SDN companies and research organizations to provide leading edge SDN solutions. Polatis also offers traditional SNMP, TL1, GPIB and SCPI command languages that allow for seamless integration with test equipment controller systems. Each switch also has a user-friendly secure web browser GUI interface that can be used to provision, monitor and control the switch and the switch software can be easily upgraded in the field without affecting in-service switch operations.

FLEXIBLE SWITCH MATRIX SIZE OPTIONS

The Series 6000i switch is available in symmetric (NxN), asymmetric (MxN) and a single-sided (NxCC) customer configurable switch with any-to-any port connectivity. Matrix sizes from 4x4 to 192x192 are available allowing designers to select the optimum size for each application. Polatis offers three different size versions of the Series 6000i. The 4x4 to 32x32 high-performance 6000i-Ultra, with under 1.0dB max loss and superior stability and repeatability, is designed for the most demanding applications and fits in a compact 1RU size. The 36x36 to 48x48 6000i-Lite, with under 1.9dB max loss, is designed for applications that need larger matrix sizes that still fit into a compact 1RU form factor. The larger 60x60 to 192x192 6000i, also with under 1.9dB loss, is designed for applications that a need larger matrix sizes while still maintaining instrument grade specifications.

OPTIONAL POWER MONITORS AND OPTICAL TAPS

Polatis switches can be customized to incorporate a wide variety of passive and active components to suit individual customer testing needs. Polatis Series 6000i switches include options for integrated Optical Power Monitors (OPMs) and optical taps on every connection. The power monitoring can also be used to provide Variable Optical Attenuation (VOA) on every connection. The power monitors and VOA can be used together to adjust signal test levels to test dynamic range, protect sensitive test equipment along with many other testing applications.

Rev. 6000i 052017.001

Polatis:

- SDN Enabled
- Minimum Insertion dB Loss
- Single Mode

STARLIGHT℠

Polatis Optical Switch Specifications

Performance Parameters	Polatis 6000i-Ultra Up to 32x32[1] and 64xCC	6000i-Lite and 6000i Up to 192x192[1] and 192xCC
Typical Insertion Loss[2]	0.5dB	0.9dB
Maximum Insertion Loss[2]	1.0dB	1.9dB
Maximum Insertion Loss with single OPM[2]	1.3dB	2.2dB
Loss Repeatability[3]	+/-0.05dB	+/-0.1dB
Connection Stability[3]	+/-0.05dB	+/-0.1dB
	For All Switch Sizes	
Operating Wavelength Range	1260-1675nm	
Return Loss (with APC connectors)	>50dB	
Max Switching Time	25ms	
Crosstalk	<-55dB	
Polarization Dependent Loss (PDL)	<0.1dB (C+L Bands) <0.3dB with optional OPM (1510-1610nm)	
Dark Fiber Switching	Yes	
Bi-Direction Optics	Yes	
Wavelength Dependent Loss (WDL)	<0.3 dB (C+L Band)	
Optional Optical Power Monitoring (OPM)	Calibrated wavelength range 1290-1330nm and 1450-1640nm Dynamic range -40dBm to +24dBm Accuracy +/-0.5dBm	
Maximum Optical Input Power	+27dBm	
Switch Lifetime	>10^9 Cycles	
Operating Temperature	+10ºC to +40ºC <85% RH non-condensing	
Storage Temperature	-40ºC to +70ºC <40% RH non-condensing	

OFC 2022 Paper

Entanglement Distribution in Installed Fiber with Coexisting Classical Light for Quantum Network Applications

Jordan M. Thomas, Gregory S. Kanter, Ely M. Eastman1, Kim F. Lee, Prem Kumar

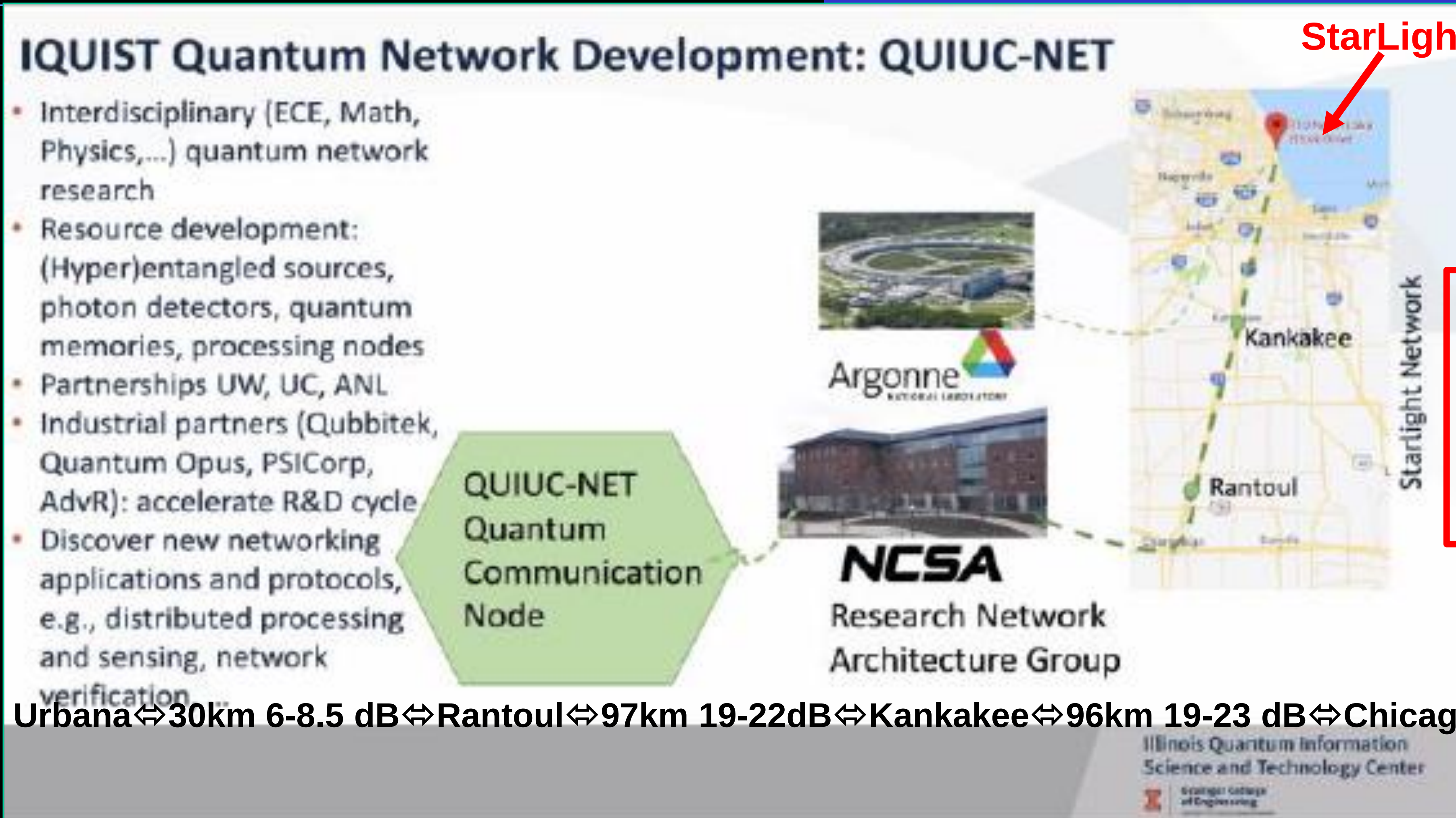
Center for Photonic Communication and Computing, Department of Electrical and Computer Engineering, Northwestern University, Evanston, IL 60208, USA

Abstract: We show polarization entangled photons coexisting with milliwatt power classical light over 45.6 km of installed optical fiber. The entanglement source has a built-in alignment signal for quantum transmitter-receiver polarization basis alignment.

OFC 2022 Paper

- Demonstration Of O-band/C-band Quantum/Classical Wavelength Allocation With Temporal and Spectral Filtering in Coincidence Detection As Useful Noise Mitigation Methods For Coexistence scenarios in fiber-optic Quantum Networking.
- High visibility two photon interference fringes Demonstrated over 45.6 km of installed underground SMF-28 fiber with Copropagating ~7 dBm classical launch power.
- An O-band classical alignment signal is built into the entanglement source to align each node in a polarization entanglement network to the same polarization reference frame.
- The combination of these two methods allows for robust WDM based polarization entanglement networks to be integrated into real world installed fiber networks.

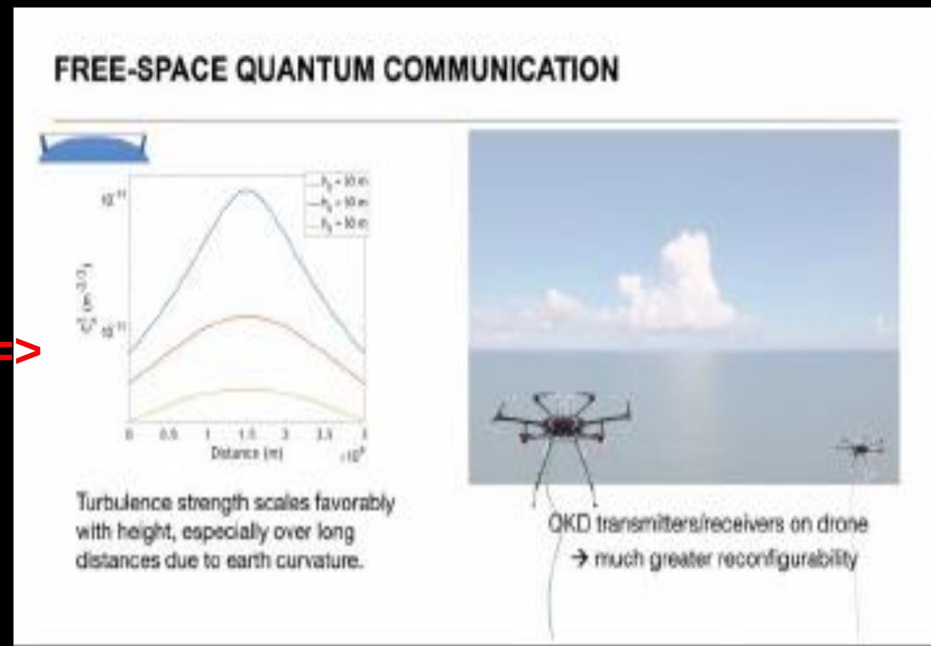
IQUIST Quantum Network Testbed: QUIUC-NET



Urbana⇔30km 6-8.5 dB⇔Rantoul⇔97km 19-22dB⇔Kankakee⇔96km 19-23 dB⇔Chicago

IQUIST Quantum Network Testbed: QUIUC-NET

(Hyper)Entangled Sources
Photon Detectors
Quantum Memories
Processing Nodes
Net Aps
Protocols
Distributed Processing
Sensing Net Verification
Repeater Enhanced Quantum Links
Free Space Quantum Communications=>



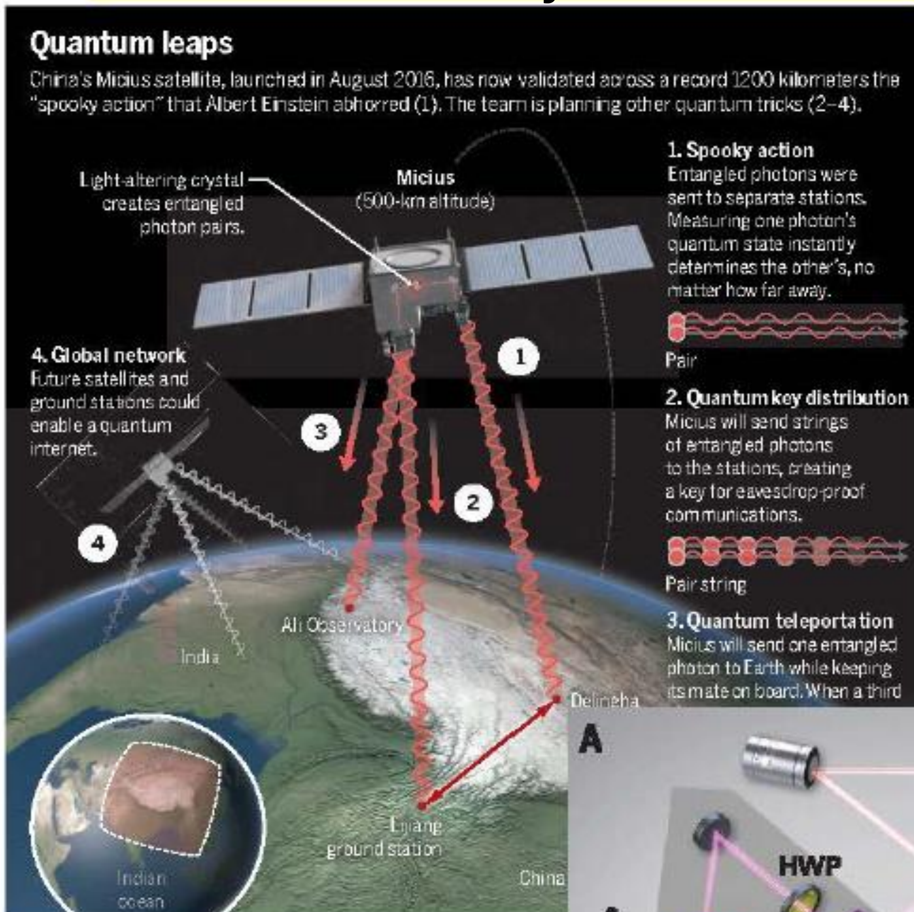
Source: Paul Kwiat, Director, IQUIST

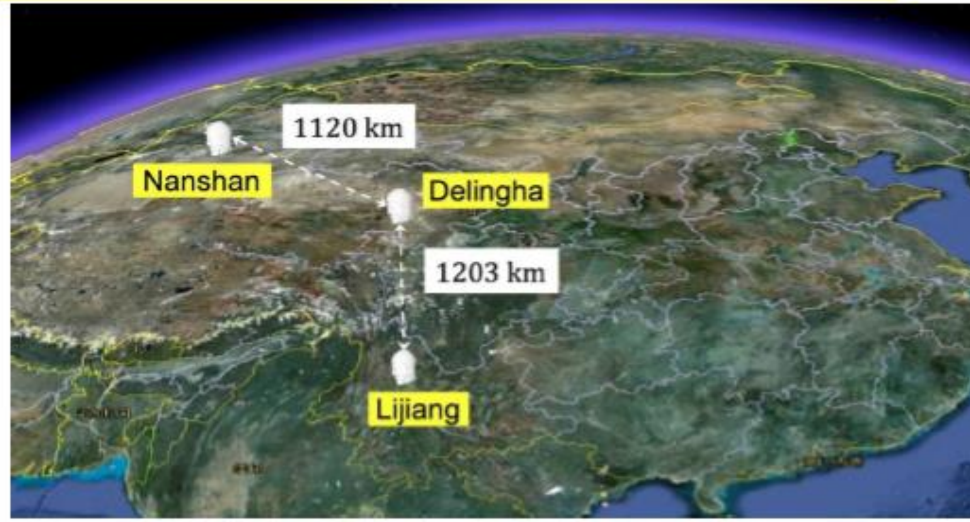
UIUC

Source:
Prem Kumar
Northwestern University

Source Aboard Satellite Micius
Entanglement Distribution over 1200 km

CPCC



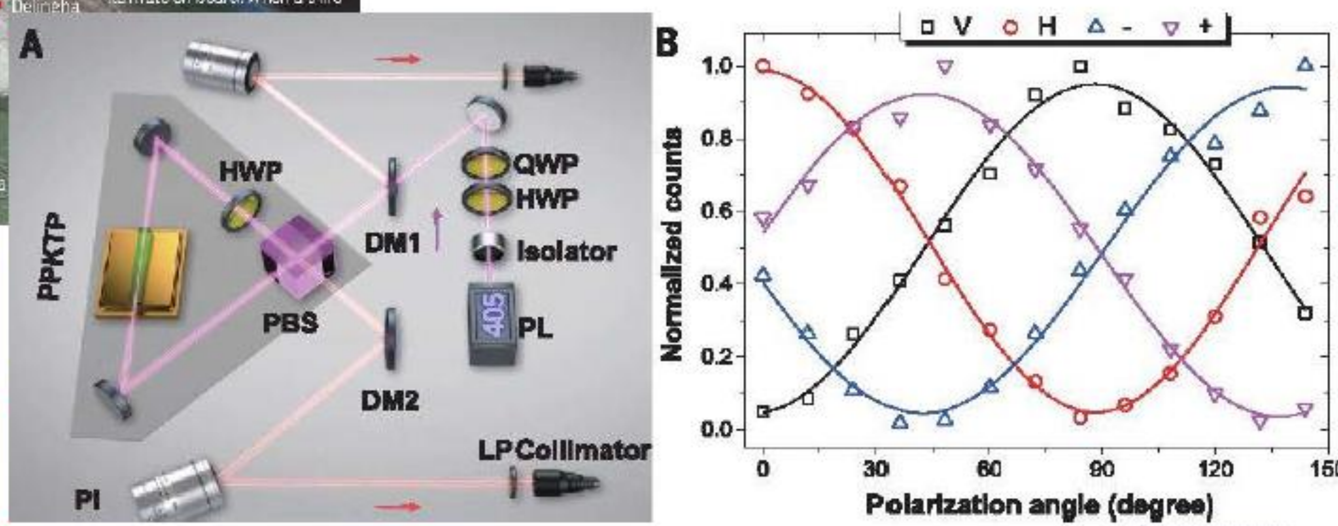


F. N. C. Wong *et al.*, Phys. Rev. A 73, 012316 (2006)

Phase stable Type-II SPDC in a pol. Sagnac loop

Yin *et al.*, Science **356**, 1140–1144, June 2017.

Bell inequality violation over 1200 km

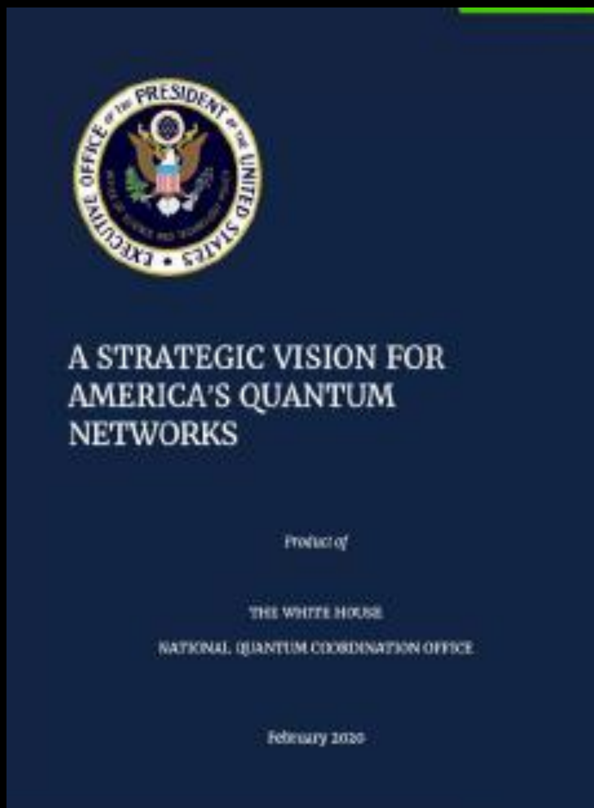


Potential Quantum Repeater

- ***Multiplexed Quantum Repeaters Based On Dual-Species Trapped-ion Systems***
- ***Prajit Dhara, Norbert M. Linke, Edo Waks, Saikat Guha, and Kaushik P. Seshadreesan***
- ***Phys. Rev. A 105, 022623 – Published 25 February 2022***
- **“Trapped ions form an advanced technology platform for quantum information processing with long qubit coherence times, high-fidelity quantum logic gates, optically active qubits, and a potential to scale up in size while preserving a high level of connectivity between qubits.**
- **These traits make them attractive not only for quantum computing, but also for quantum networking.**
- **Dedicated, special-purpose trapped-ion processors in conjunction with suitable interconnecting hardware can be used to form quantum repeaters that enable high-rate quantum communications between distant trapped-ion quantum computers in a network.**
- **In this regard, hybrid traps with two distinct species of ions, where one ion species can generate ion-photon entanglement that is useful for optically interfacing with the network and the other has long memory lifetimes, useful for qubit storage, have been proposed for entanglement distribution.**
- **We consider an architecture for a repeater based on such dual-species trapped-ion systems.**
- **…**
- **Our results bolster the case for near-term trapped-ion systems as quantum repeaters for long distance quantum communications.”**

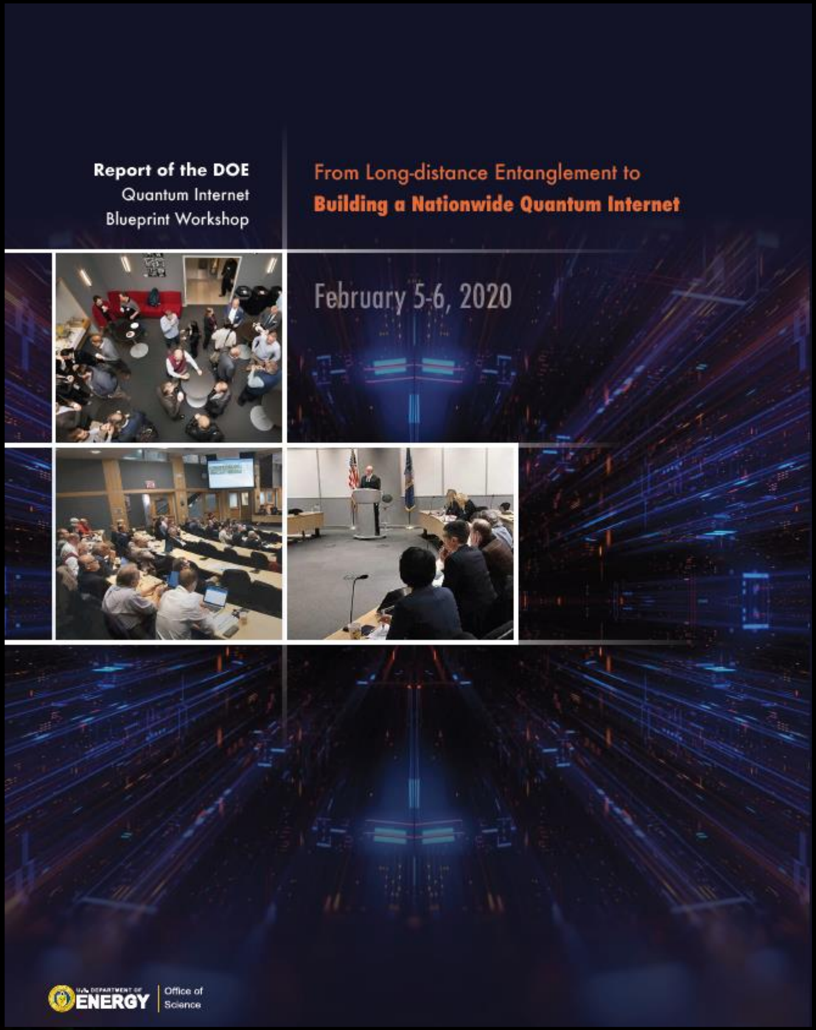
Future Directions

- Additional Testbeds, Experiments, and Prototypes Are Being Planned To Support Multiple Quantum Scenarios
- These Projects Are Developing And Validating Viable Platforms for Quantum Network Testbeds For Rapid Prototyping, System Characterization And Optimization
- New Comprehensive System Designs Are Being Created For Quantum Communications And Networking, Including Advanced Programming Paradigms For Service Creation And Implementation
- Specific Customized Properties Will Enable Information To Be Exchange Among And Across Quantum-Classical Boundaries



National Policy Report On Quantum Networks

ESnet Quantum Internet Initiative



Report of the DOE Quantum Internet Blueprint Workshop: From Long-Distance Entanglement To Building a Quantum Internet

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Thanks to the NSF, DOE, NASA, NIH, DARPA
Universities, National Labs, International & Industrial Partners,
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