ORNL Quantum-Conventional Network Testbed

Nageswara S. V. Rao, Muneer Alshowkan, Joseph C. Chapman, Mariam Kiran, Hsuan-Hao Lu, Joseph M. Lukens, Nicholas A. Peters

Oak Ridge National Laboratory

ORNL is managed by UT-Battelle LLC for the US Department of Energy

Sponsored by Department of Energy
Advanced Scientific Computing Research office

5th Global Research Platform Workshop, September 16-17, 2024
co-located with 20th IEEE International Conference on e-Science, Osaka, Japan

Outline

1. Introduction
2. Quantum Network Testbed
   - quantum and conventional connections
   - telescoping fiber loops and spools
3. Testbed Experiments
   - entanglement distribution measurements
   - throughput and capacity estimates
4. Conclusions

Quantum and Conventional Networking

Quantum networks and **Quantum Internet**:

- promise game-changing capabilities for science discovery and facilities, quantum computing and sensing, and cyber security areas.

The Critical Connection: Practically and fundamentally, quantum networking is inextricably tied to conventional networking:

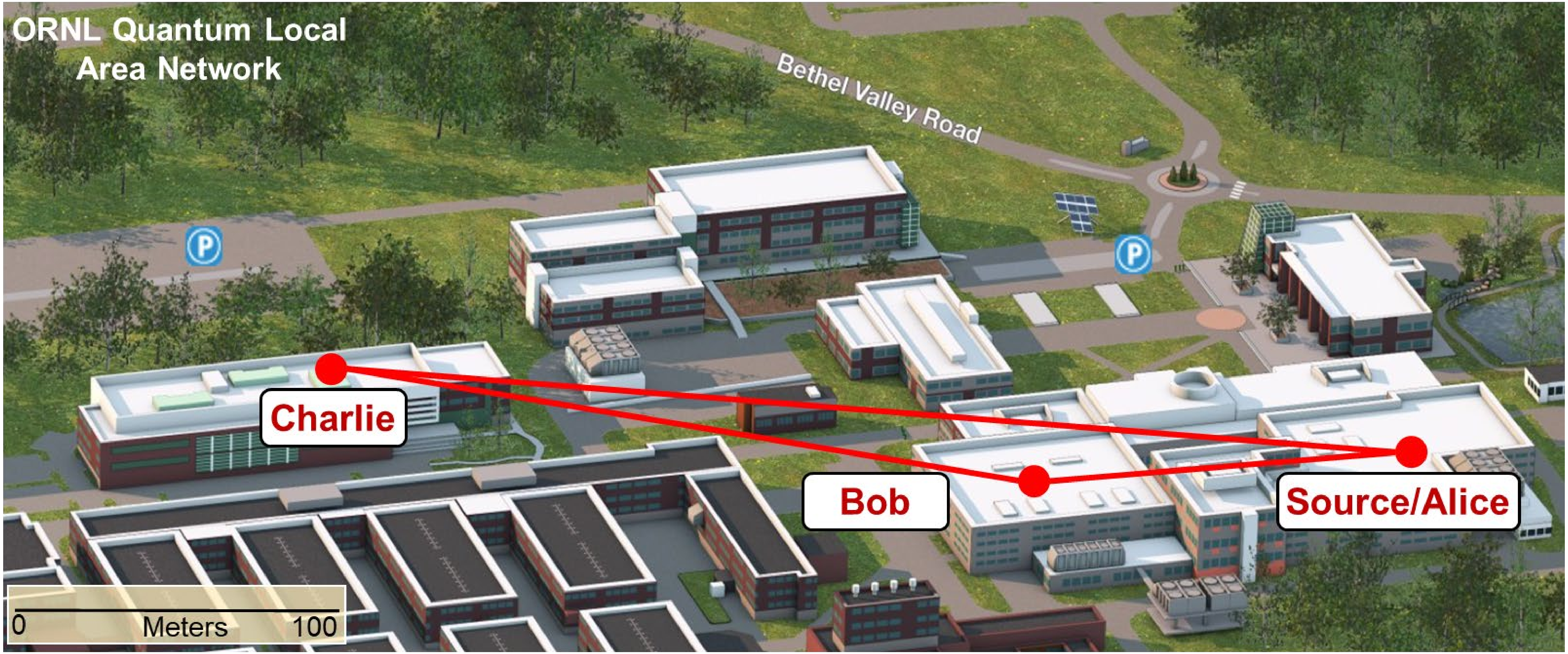
- **practical**: conventional telecom fiber infrastructure is critical to support Quantum Internet deployments
  - it is too early, expensive and unnecessary to build separate fiber infrastructure
  - control and management of quantum network devices rely on conventional
- **foundational**: critical protocols such as teleportation require both networking capabilities operating in concert

- **Example:** Need components that can send quantum signals over conventional telecom C-band fiber around 1500nm, while interacting with end systems

- **Need testbeds**: For capabilities to co-design, co-develop and co-test quantum-conventional networking technologies
  - To complement analytical and simulation approaches

ORNL Quantum Network Testbed: Quantum Nodes

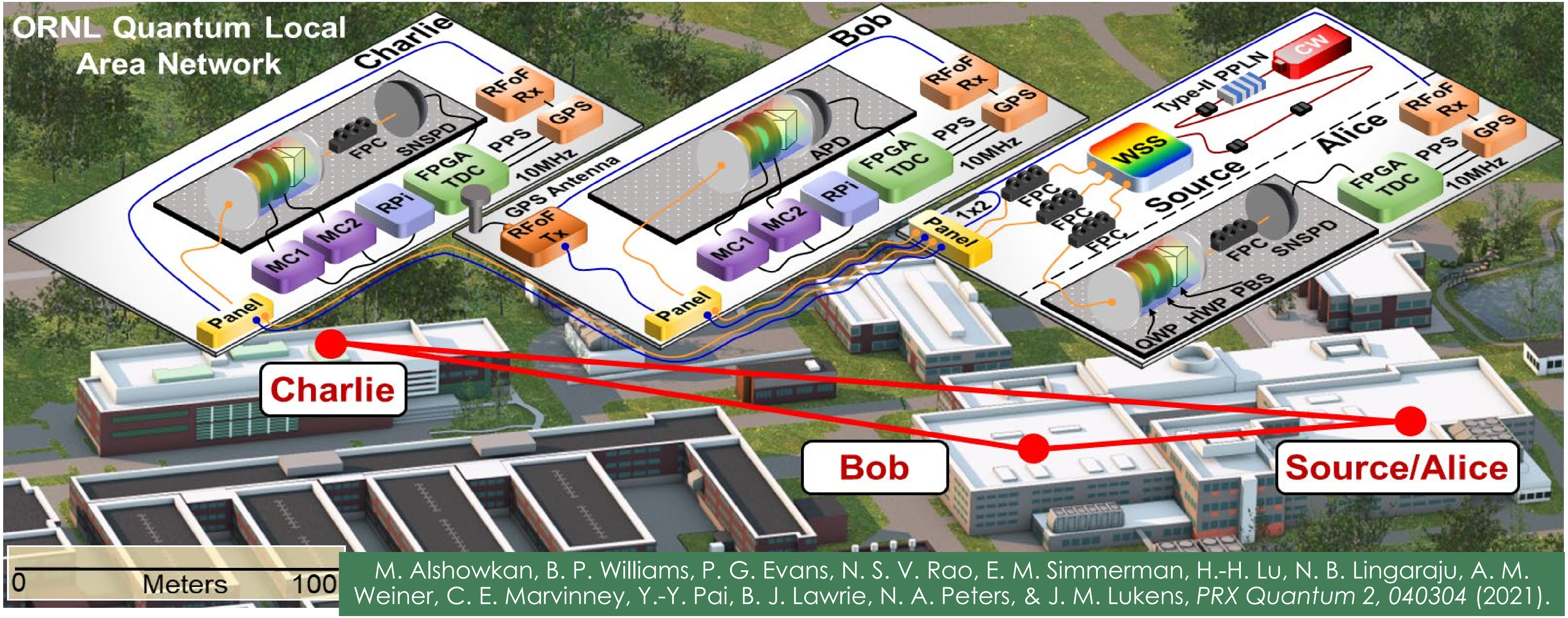
- Quantum nodes located in three buildings
- Dark fiber connections between them via optical switches – include in-ground loops and fiber spools



M. Alshowkan, B. P. Williams, P. G. Evans, N. S. V. Rao, E. M. Simmerman, H.-H. Lu, N. B. Lingaraju, A. M. Weiner, C. E. Marvinney, Y.-Y. Pai, B. J. Lawrie, N. A. Peters, & J. M. Lukens, *PRX Quantum 2, 040304* (2021).

ORNL Quantum Network Testbed Components

- Flex-grid entanglement demonstrate over deployed network
- Receivers spatially distributed, requiring tight timing synchronization



M. Alshowkan, B. P. Williams, P. G. Evans, N. S. V. Rao, E. M. Simmerman, H.-H. Lu, N. B. Lingaraju, A. M. Weiner, C. E. Marvinney, Y.-Y. Pai, B. J. Lawrie, N. A. Peters, & J. M. Lukens, *PRX Quantum 2, 040304* (2021).

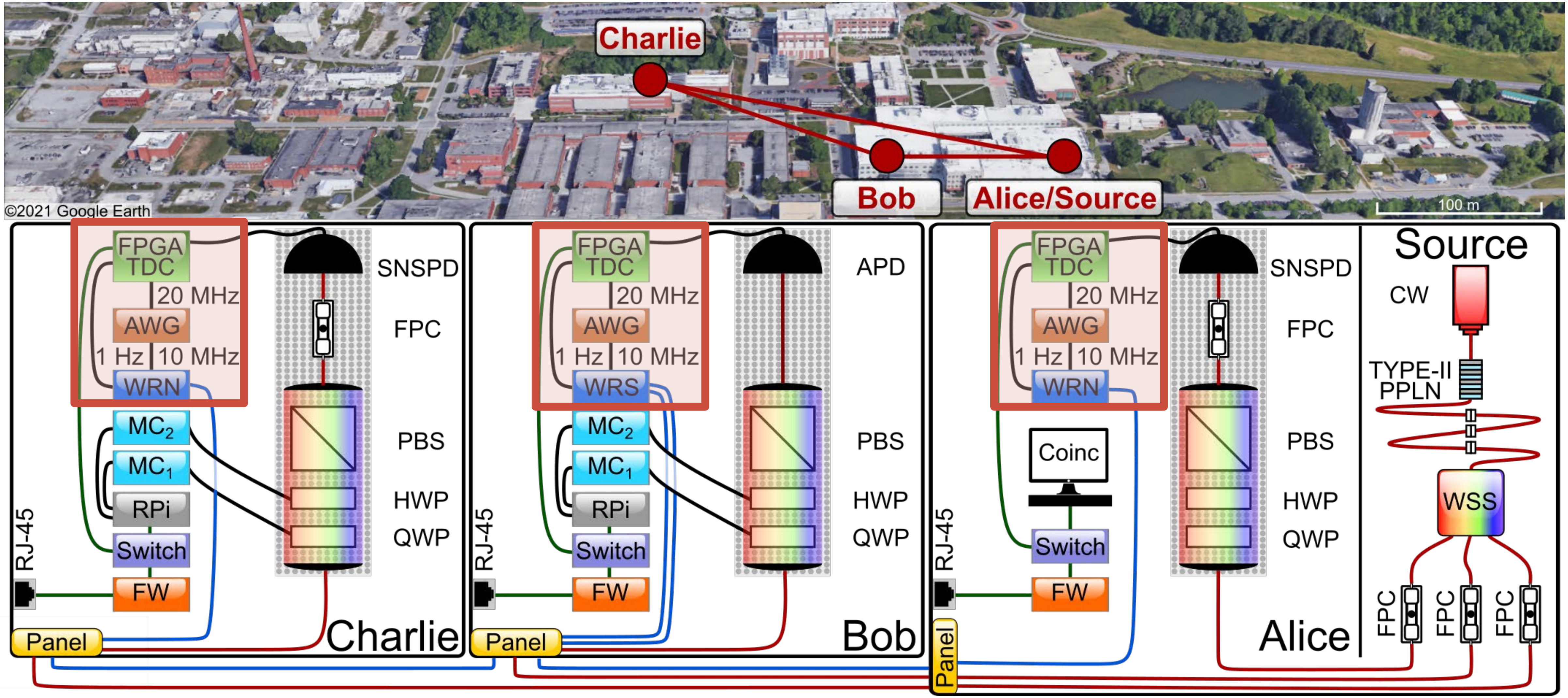
SNSPD: Superconducting Nanowire single photon detector
APD: Avalanche photon diode
PPLN: Periodically polled lithium niobate

WSS: wavelength selectable switch
QWP: quarter wavelength plate
HWP: half wavelength place

FPC: fiber polarization controller
PBS: polarizing beam splitter

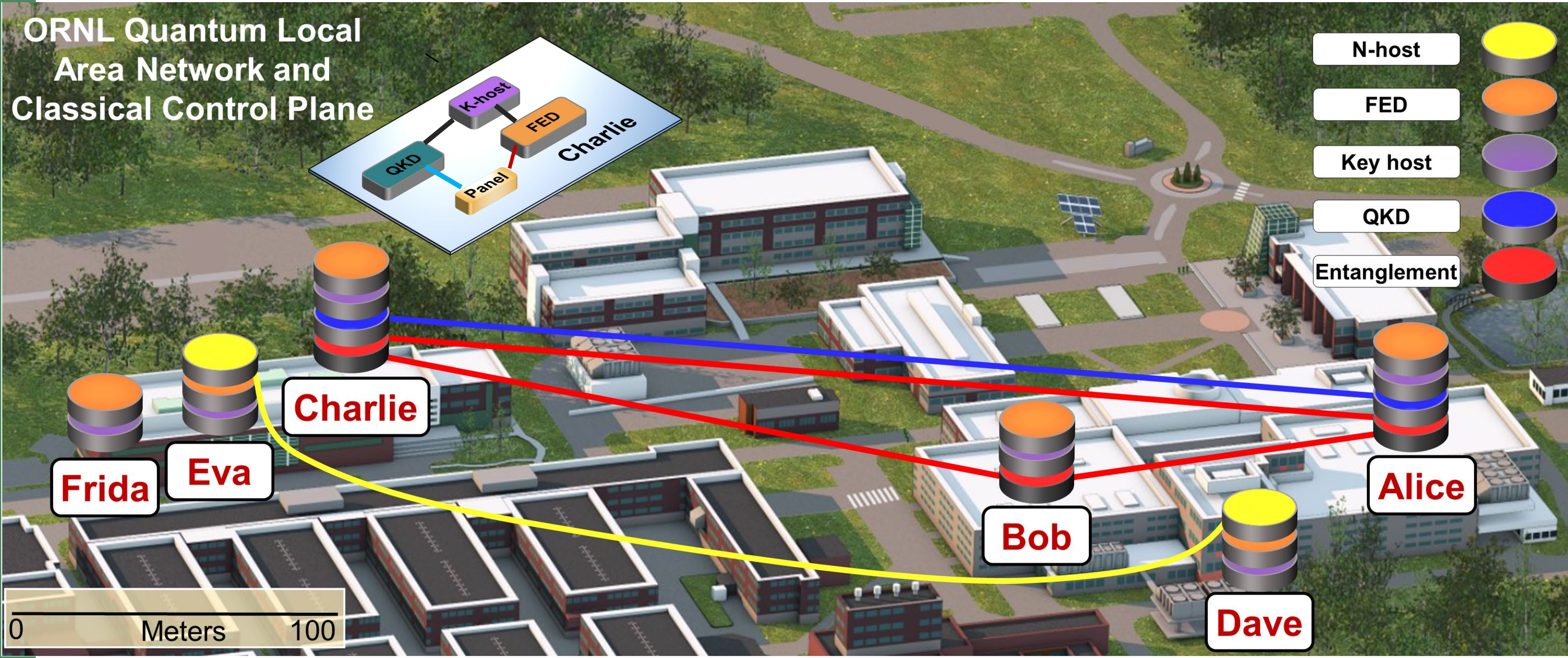
Synchronizing with White Rabbit

- Time synchronization in a **scalable** architecture
- Using commercial off the-shelf White Rabbit components and redesigned the time taggers



AWG: arbitrary waveform generator
FW: Firewall
MC: motion controller
WRN: white rabbit controller
RPi: Raspberry Pi
WRC: white rabbit controller

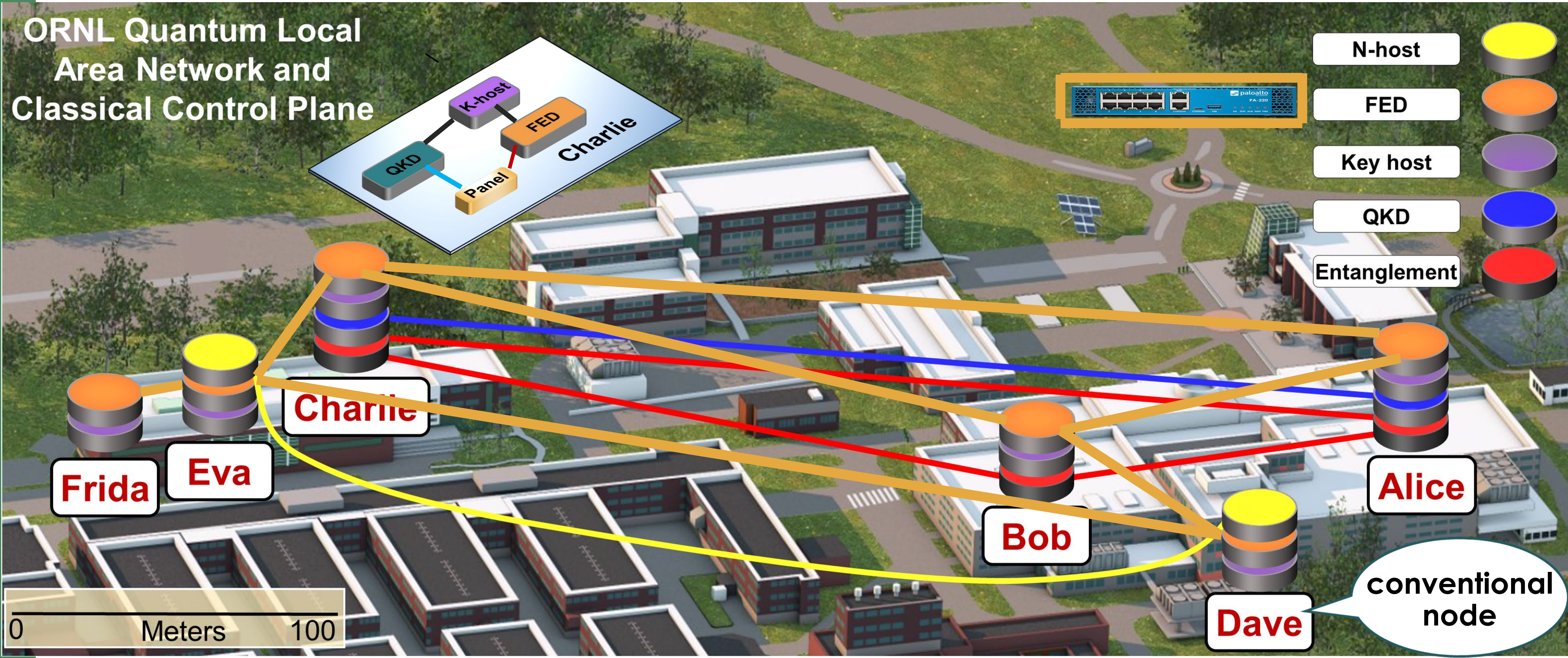
ORNL Quantum and Conventional Networking



Dave: Critical quantum-conventional node

ORNL Network Testbed: Quantum and Conventional Nodes

Control Plane Implemented using Palo Alto PA-220 devices



Oak Ridge National Laboratory

FED: Firewall and Encryption Device (FED): PA-220

Quantum-Conventional Network Testbed

Conventional-quantum testbed

- measurements to support comparison of bps (bits/sec) and ebps (entangled bits/sec)
- supports co-existence testing with quantum and conventional signals
- ebps measurements over fiber connections of different lengths
- corresponding capacity estimates using single photon detections and light intensity measurements to approximate transmissivity parameter

Fiber Augmentation: provide a suite of single-mode fiber connections

- In-ground fiber loops
  - twenty 15 km single-mode fibers
    - attached to all-optical switch
  - telescope spools combinations: provide connections suite
    - 15, 30, 45, …, 300 km
- Fiber spools
  - three 25 km, one 10 km, one 5 km, and twelve 30m single-mode fibers
    - attached to all-optical switch
  - telescope spools combinations: provide connections suite
    - 30 m; and 5, 10, 15, 25, 30, 35, 40, 50, 55, 60, 65, 75, 80 and 90 km
  - measure light intensities for these connections measured
    - used in analytical formulae to derive the corresponding ebps capacity estimates

Testbed provides common platform to support

- comparison of bps and ebps measurements and capacity estimates

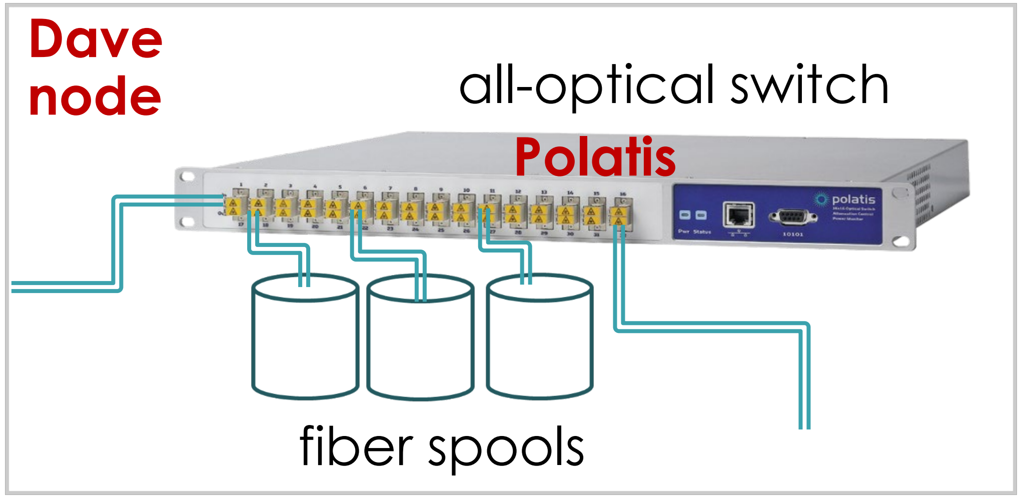
Telescoping Fiber Design: A Critical Testbed Component

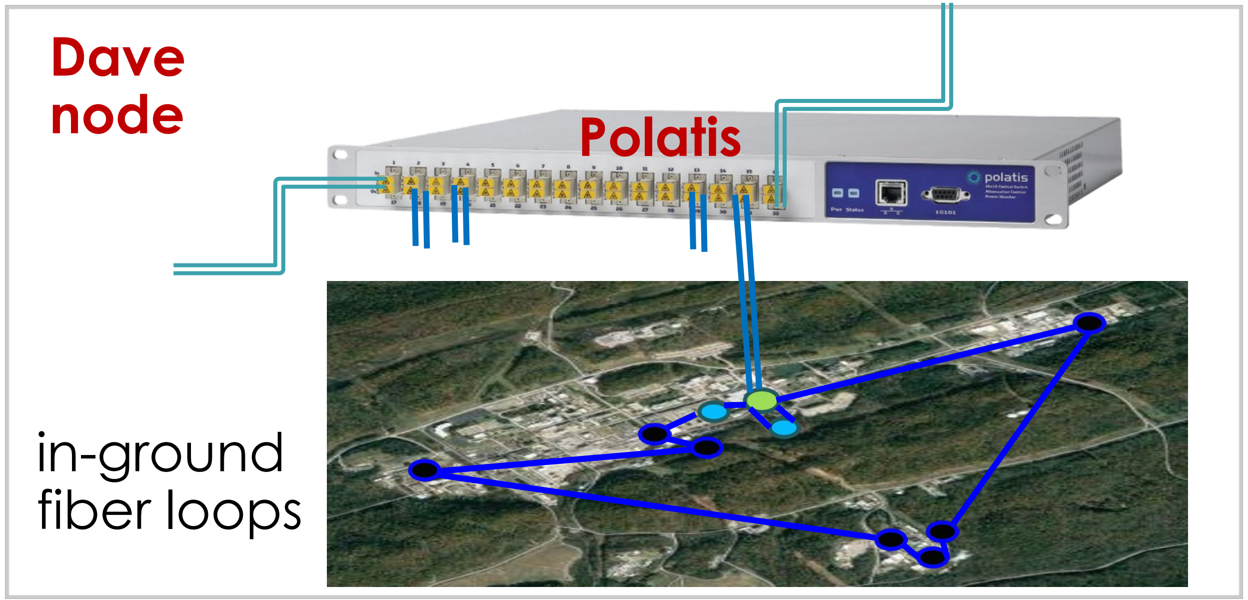
Conventional-Quantum Infrastructure

- augmented with fiber spools and in-ground loops
  - fiber spools: suite of single-mode fiber connections 0 – 90 km
    - 3*25km, 10 km, 5km
  - In-ground fiber loops: suite of single-mode fiber connections 0 - 300 km
    - 20 loops: each 15km
- **utilize spools and loops in combinations to realize a suite of connections**

Measurements and estimates

- measure light intensities for these connections
- conventional and quantum throughput measurements





Throughput Measurements and Capacity Estimates

Methodology

conventional-quantum testbed provides measurements:

- ebps measurements over fiber connections of different lengths
- estimates of corresponding capacities
  - using light measurements to approximate transmissivity parameter η

- compare bps and ebps measurements and capacity estimates

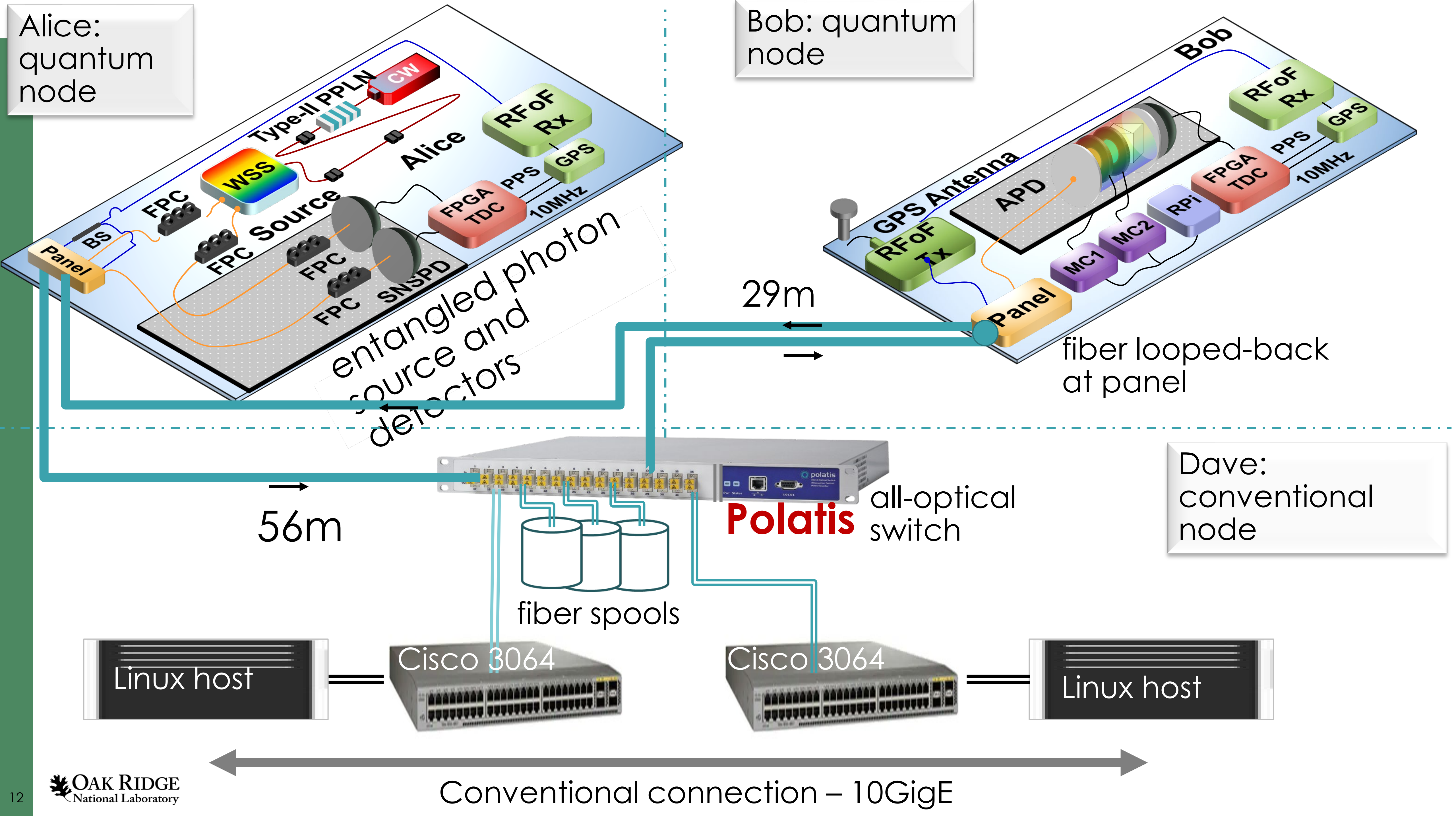
Conventional-Quantum Infrastructure

- conventional-quantum testbed that provides measurements
  - support comparison measurements and capacity estimates both qualitatively and quantitatively
- augment ORNL quantum network (QNET) with fiber spools
  - to provide a suite of single-mode fiber connections 0--90~km in length.

Measurements and estimates

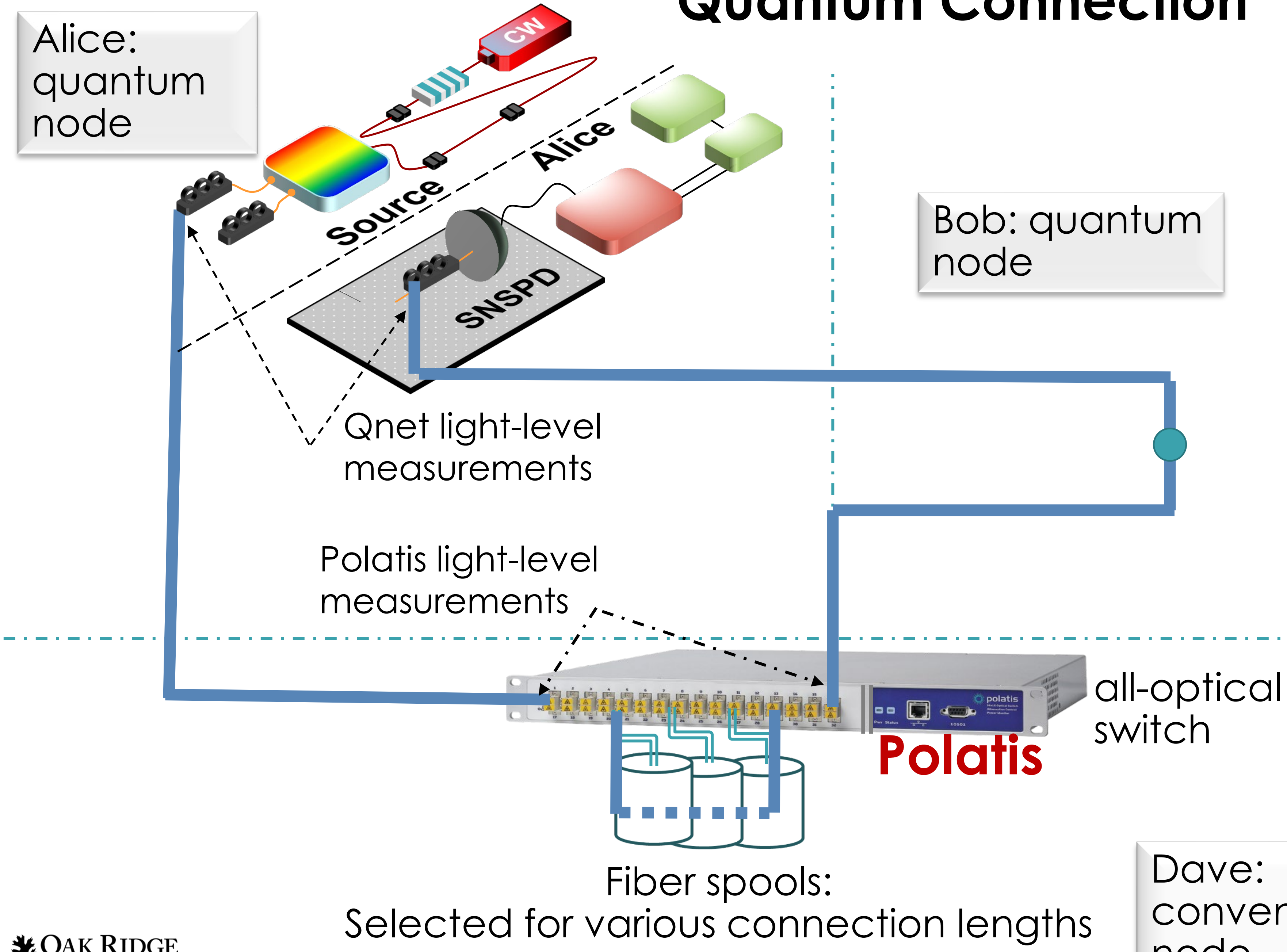
- measure single-photon detection rates and light intensities for these connections
- use them in analytical formulae for ebps capacity estimates

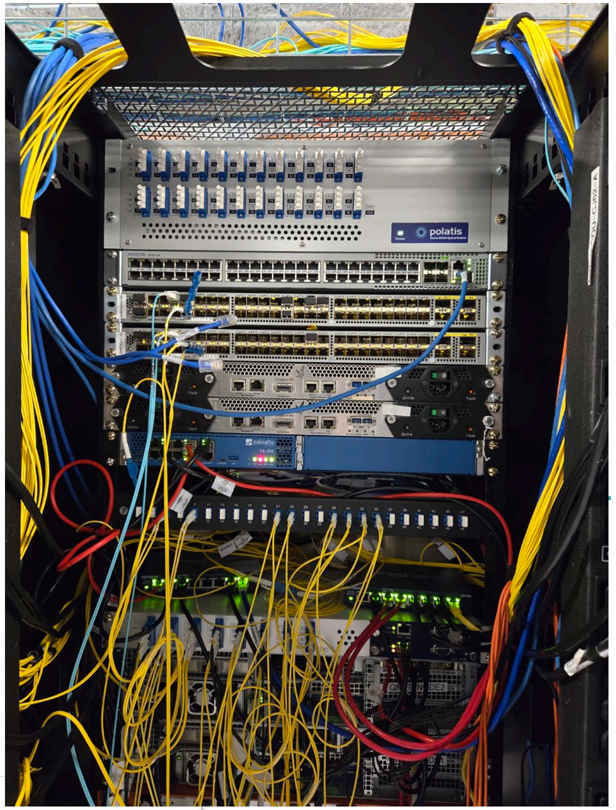
N. S. V. Rao, M. Alshowkan, J. C. Chapman, N. A. Peters and J. M. Lukens, "Throughput Measurements and Capacity Estimates for Quantum Connections," *IEEE INFOCOM 2023 - NetSciQCom 2023: IEEE INFOCOM Network Science for Quantum Communication Networks Workshop*, Hoboken, NJ, USA, 2023, pp. 1-6, [DOI: 10.1109/INFOCOMWKSHPS57453.2023]



Alice: quantum node
Bob: quantum node
Dave: conventional node
Type-II PPLN
CW
RFoF Rx
WSS
Alice
GPS
PPS
10MHz
FPGA TDC
FPC
BS
Panel
Source
FPC
FPC
SNSPD
FPC
entangled photon source and detectors
Bob
RFoF Rx
GPS
PPS
10MHz
FPGA TDC
RPi
MC2
MC1
APD
GPS Antenna
RFoF Tx
Panel
29m
fiber looped-back at panel
56m
Polatis
all-optical switch
fiber spools
Linux host
Cisco 3064
Cisco 3064
Linux host
Conventional connection – 10GigE

Quantum Connection



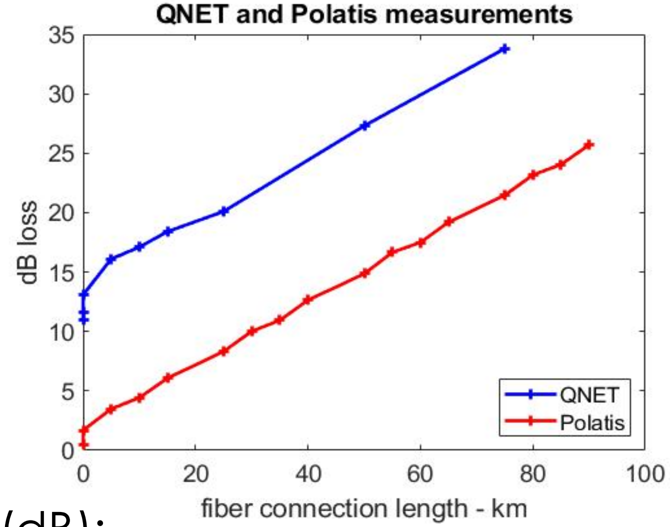


Dave: conventional node

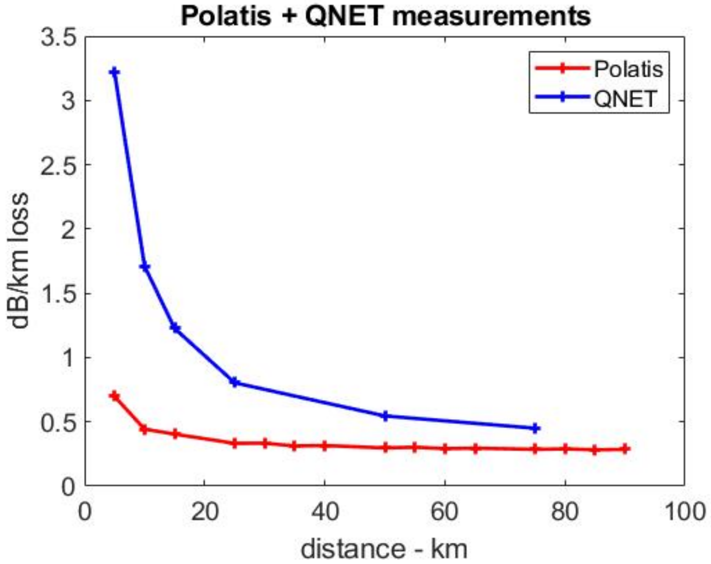
Light-level Measurements

For conventional and quantum connection
- light levels (dBm) measured on all-optical switch - Polatis measurements.

For quantum connections,
- additional light level measurements at source and detectors in node Alice - QNET measurements



Connection loss (dB):
- subtract destination from source levels
- function of connection length in km - nearly linear
- constant additional 15 -20 dB loss for quantum connections
  - additional fiber connections to Alice and Dave - direct and via Bob and at source and detectors.



Loss rate per distance estimate - divide connection losses by length,
- decreasing trend with connection length
- higher values at shorter connections
  - higher fraction of losses due to
  - fiber patches at nodes, cross-connects optical switch, and at source and detectors

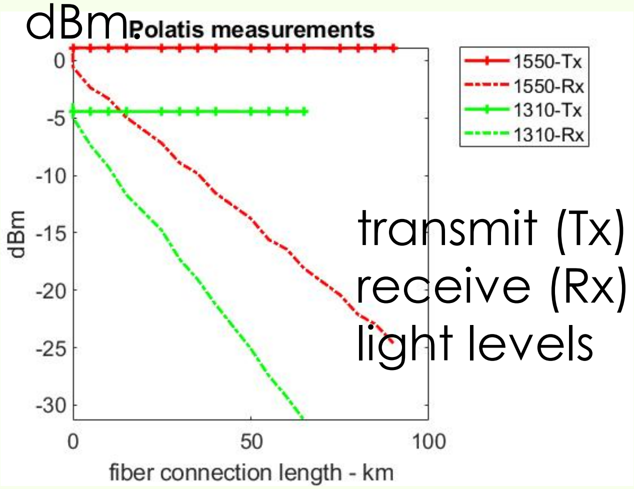
OAK RIDGE National Laboratory

Conventional throughput measurements

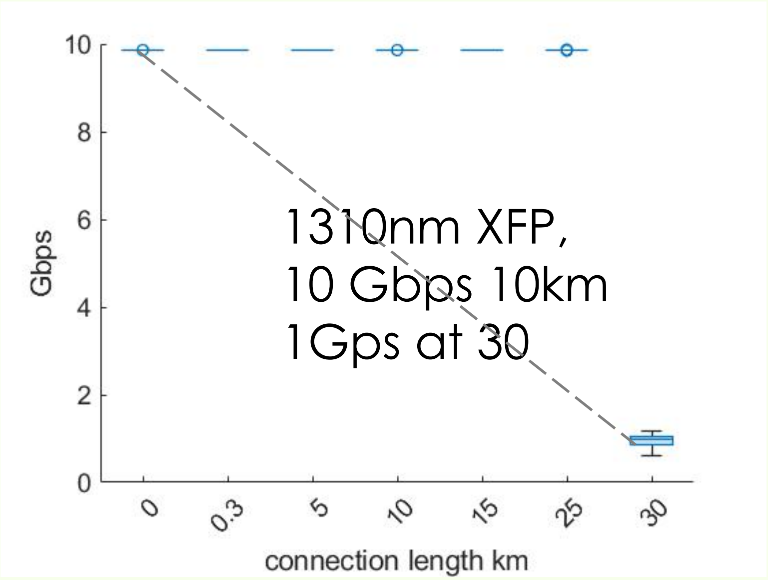
The bps using iperf3 between two Linux hosts at Dave connected through all-optical switch.

1310 nm XFP 10~km target distance
1550 nm XFP 80 km target distance

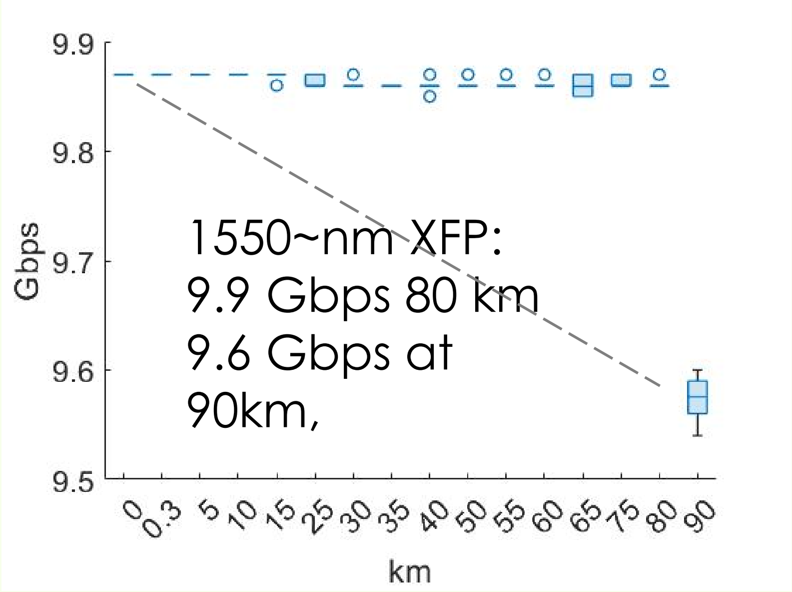
1550nm XFP higher source power ~2.5 dBm.



transmit (Tx)
receive (Rx)
light levels



1310nm XFP,
10 Gbps 10km
1Gps at 30



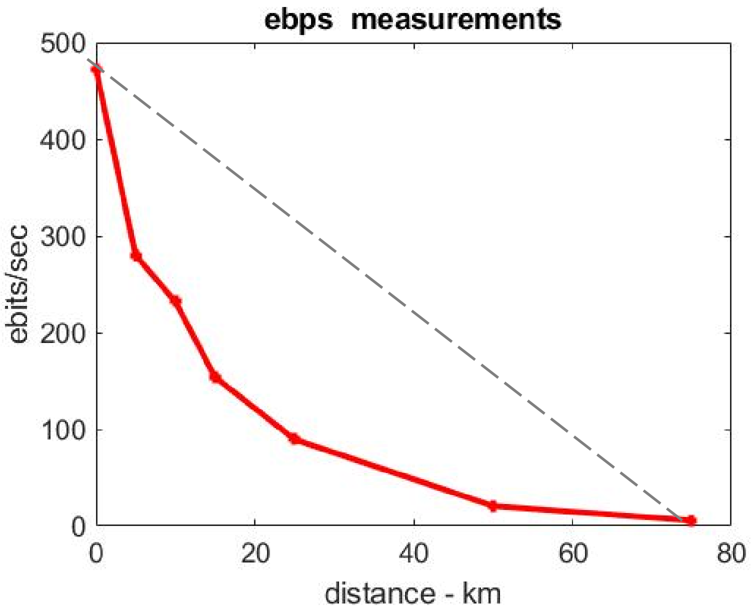
1550~nm XFP:
9.9 Gbps 80 km
9.6 Gbps at
90km,

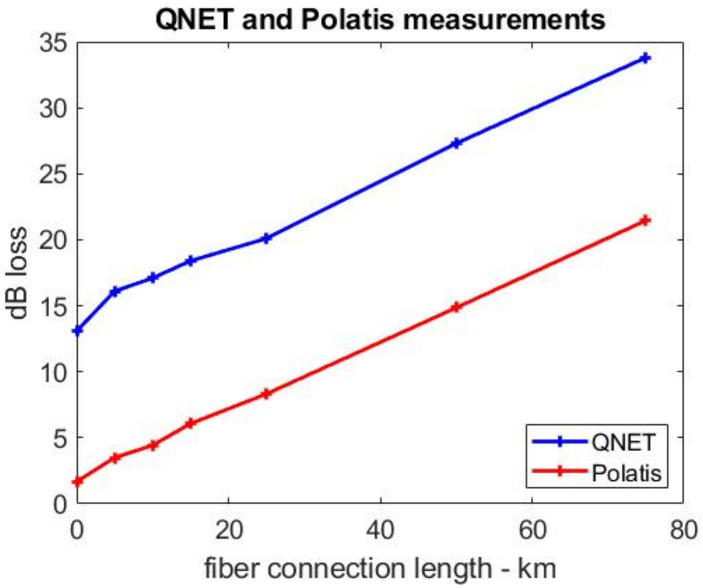
Shape of the throughput profile
- **concave** – typical in optimized conventional networks.
- **convex** – indication of bottlenecks (insufficient TCP or other buffers) Rao et al 2018

- convex shape observed both for ebps measurements capacity estimates
- Shannon capacity bps based on signal-to-noise ratio
  - qualitatively convex shape - do not include effects of buffers and loss of TCP

ebps measurements over quantum connections

- Coincidence rate measurements of entangled photon source at various distances
  - calculate entanglement throughput approximated by two detections within1nano second window
- in practice, measured fidelities >90% on QNET





ebps measurements
- decrease with connection length
- profile is convex

sharp contrast with TCP bps measurements.

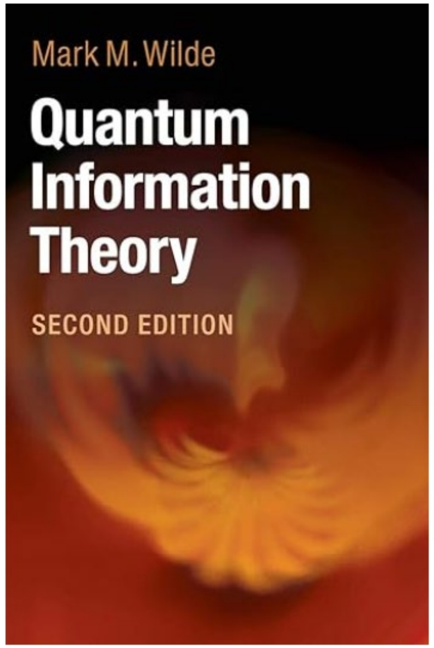
Connection losses between source and detectors
- corresponding Polatis values

Losses nearly linear with connection length
- mean offset of 12.22 dB between QNET and Polatis losses

Used in capacity estimates – but limited accuracy

OAK RIDGE National Laboratory

Quantum Channel Models: Capacity Estimates



Capacity estimates for fiber connections

- derived under various conditions using variety of parameters
- specializing general quantum channels specified by mathematical descriptions - Wilde 2017

Generic quantum communications channel

- defined as linear, completely positive, trace preserving map
  - corresponds to quantum physical evolution
- Takes particular form according to Choi–Kraus decomposition in terms of Kraus operators
- Several versions of quantum capacity are defined and estimated under parametrizations
  - for example, dephasing and loss channels
  - channel models inferred by process tomography using QNET measurements - Chapman etal2023

Our Model: specific characterization of simplified optical fiber channels without repeaters

- uses transmissivity parameter η for pure loss channel – Pirandola et al 2017

Capacity Estimates: Transmissivity of Fiber

For fiber connections, ebps capacity estimate per channel use – Pirandola et al 2017 based on transmissivity η of optical fiber:

$$D_2(\eta) = -\log_2(1-\eta).$$

Bound on ebits for channel use - channel rate under fixed source rate

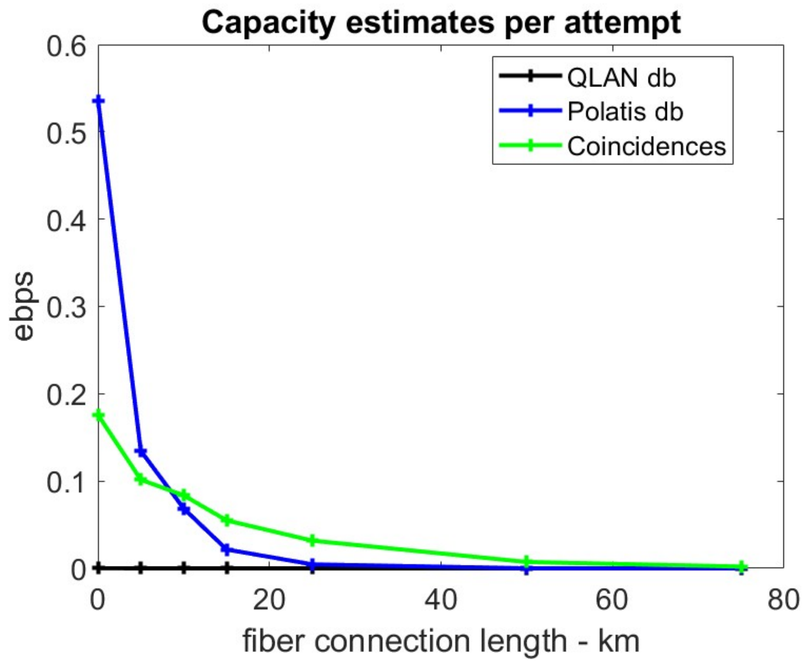
Here, η is typically linear in connection length – implies capacity profile is typically convex

Transmissivity: fraction of entangled photons successfully transmitted over channel

- first approximation: fraction of power that passed through
  - convert loss in dB into fraction and subtract from 1
  - connections treated as fiber – not patching and switching
- Second approximation: single photon and coincidence counts

Using QLAN and Polatis measurements, we approximate η and compute $D_2(\eta)$

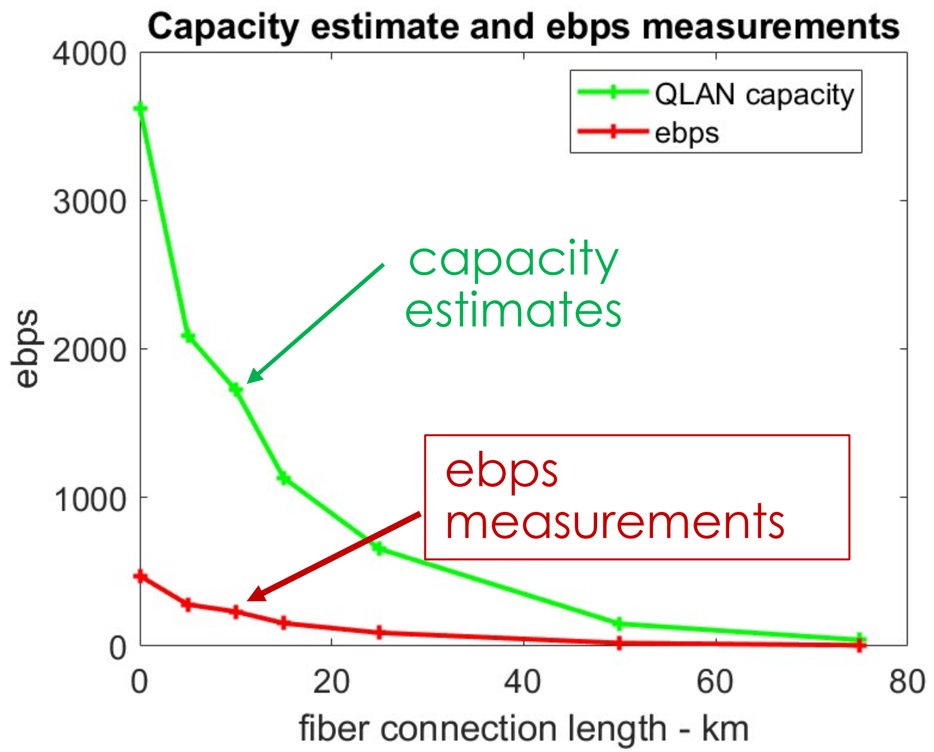
- P-capacity: Polatis measurements- shorter connection of only fiber spools
- Q-capacity: includes connection between quantum and conventional nodes
- Coincidences: two SNSPD detections within time window

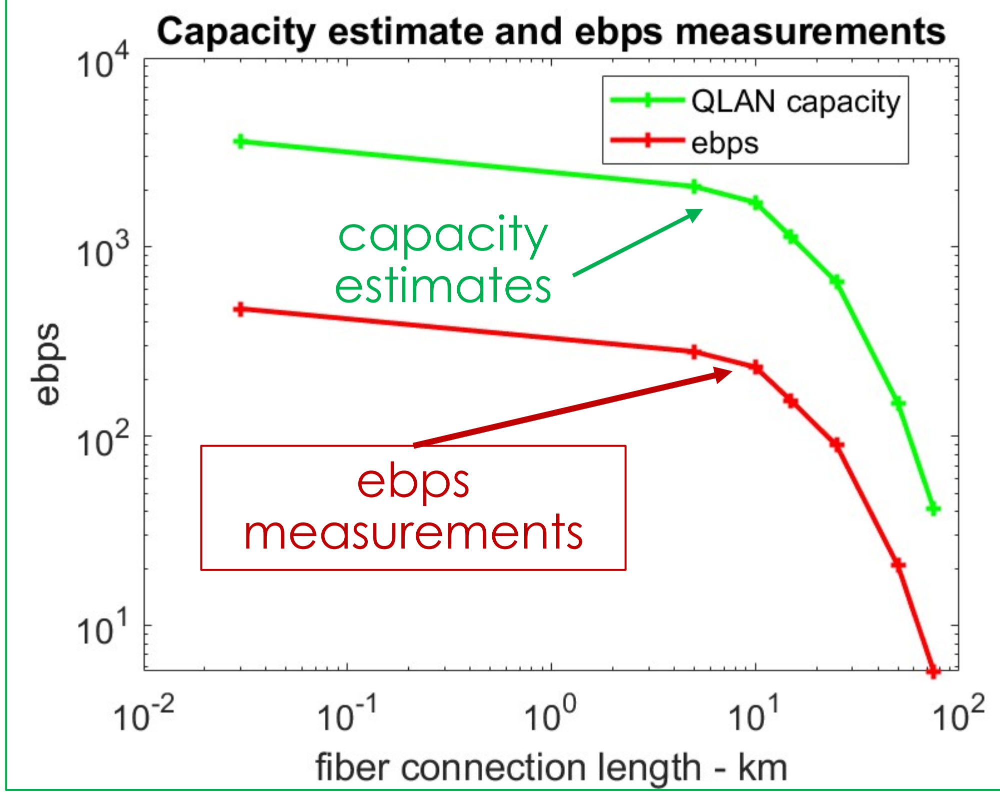


Comparison: Measurements and Estimates

ebps measurements and capacity estimates based on QNET baseline coincidences measurements

- normalized with local coincidence measurements





Both ebps measurements and corresponding capacity estimates

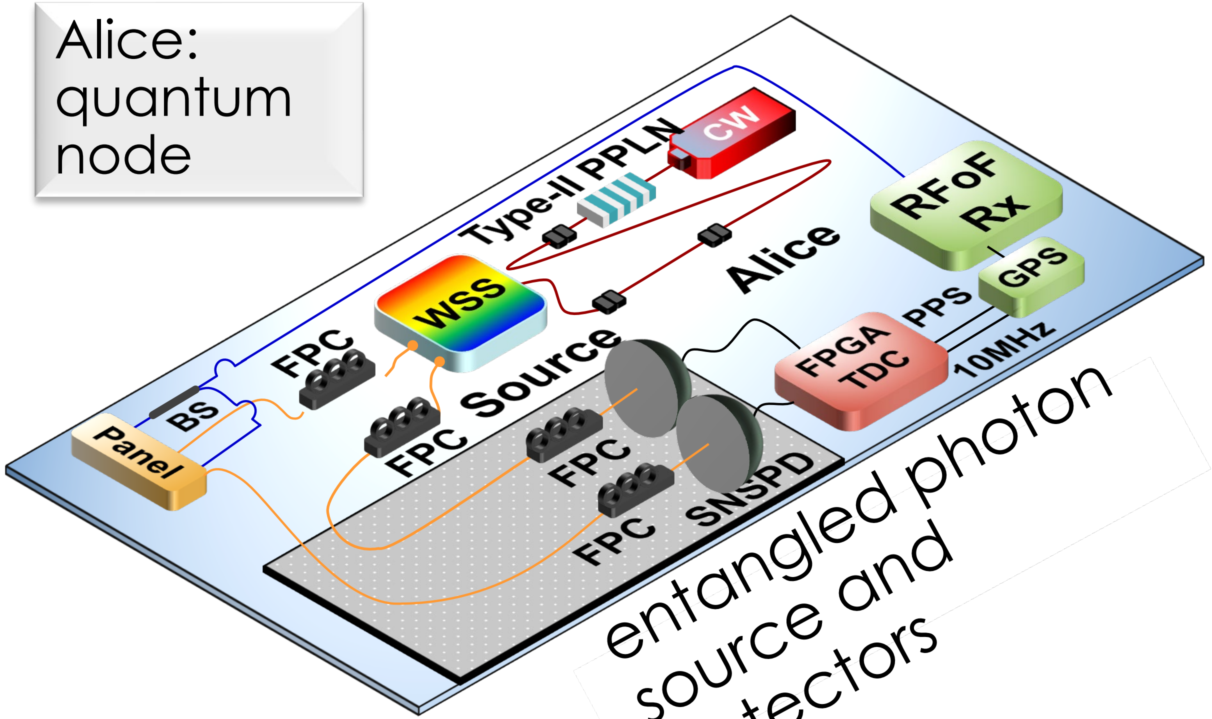
- decrease rapidly with distance as expected
- shape is **convex** - similar to TCP profile under severe bottlenecks

N. S. V. Rao, M. Alshowkan, J. .C. Chapman, N. A. Peters, H. Lu, J. M. Lukens, S. Guha, Entanglement capacity estimates and throughput measurements of quantum Channels, 11th workshop on Innovating the Network for Data Intensive Science (INDIS 2024), Atlanta, GA, USA, 2024.

Capacity estimates: Baseline Measurements

- Coincidence Measurements – approximation to number of attempts in capacity formulae no network fiber connection – assumed no losses between source and detector
  - Required for capacity estimate formulae

Alice: quantum node



entangled photon source and detectors

Capacity estimates: First Approximations – light levels

Derived treating connections as fiber no explicit accounting for patching and switching

Estimation is approximate:

- measured power level includes other components

Connection power level transmission to approximate transmissivity approximations:

- **Non-selective losses**: QNET measurements utilize spectral filtering and calibration for 1560-nm entangled photons, and
  - represent that includes singles and entangled photons
  - **Assumption**: losses are not selective and represent entangled ones
- **Broader spectrum**:
  Polatis measurements:
  - broader spectrum than QNET measurements and have a
  - coarser resolution with no spectral filtering and calibration.
  - **Assumption:** losses are somewhat uniform around entangled photon bandwidth
- **Not pure fiber**: connections consist of
  - multiple cross-connects at patch panels
  - connections to and within Polatis switch

Overall, capacity estimates derived using ``pure'' fiber models

- additional losses effect both throughput measurements and light levels,
- **Assumption**: play secondary role particularly at longer connection lengths

not accurate – underestimate capacity

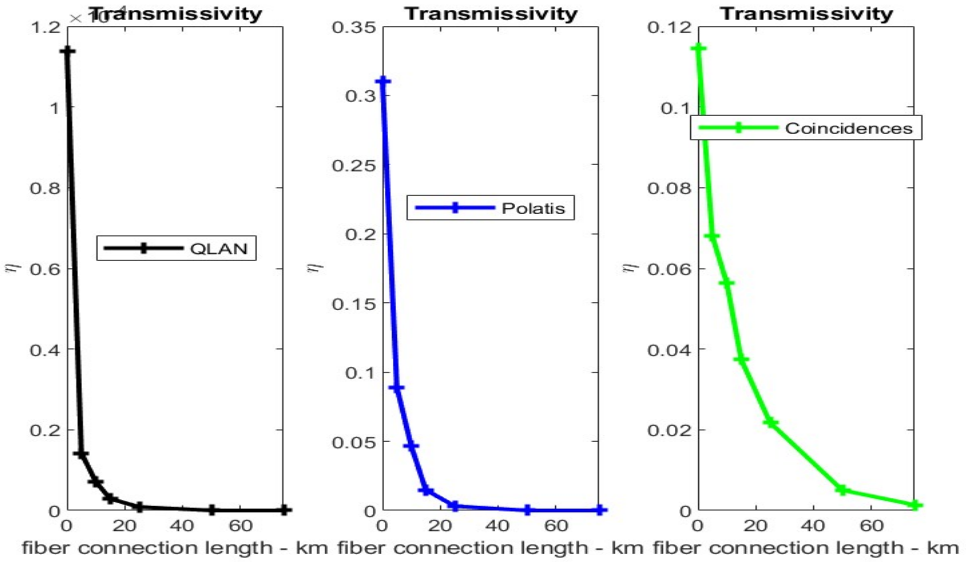
N. S. V. Rao, M. Alshowkan, J. C. Chapman, N. A. Peters and J. M. Lukens, "Throughput Measurements and Capacity Estimates for Quantum Connections," *NetSciQCom 2023: IEEE INFOCOM Network Science for Quantum Communication Networks Workshop*, 2023, pp. 1-6.

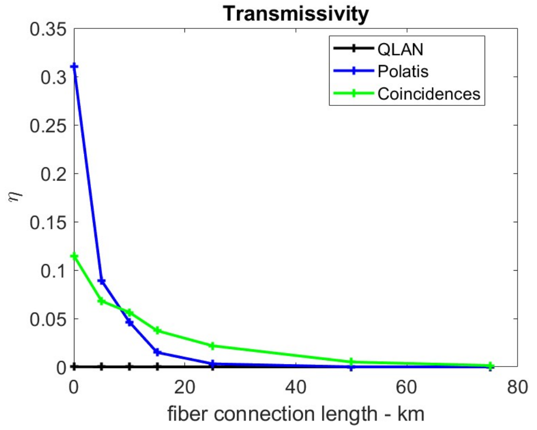
Transmissivity estimates: Light Measurements

Derived treating connections as fiber no explicit accounting for patching and switching

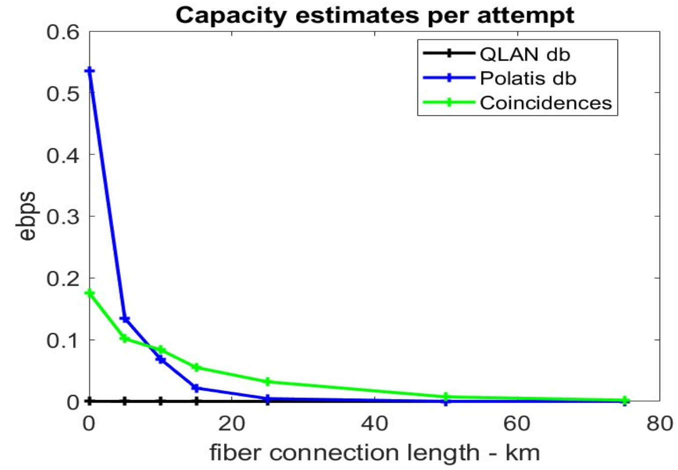
Estimation is approximate:

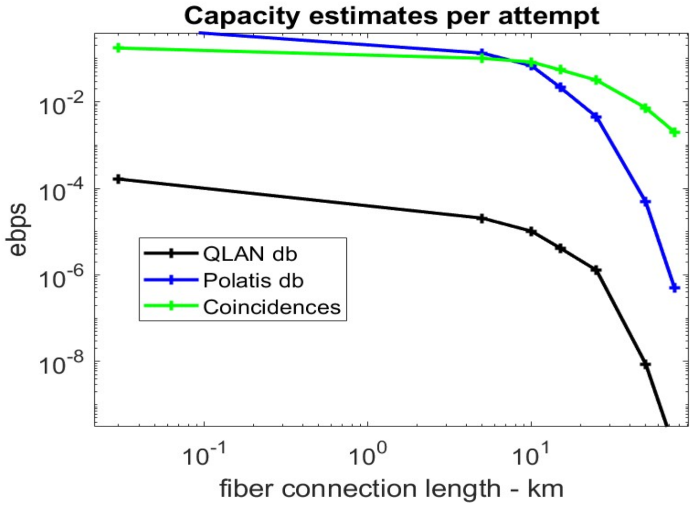
- measured power level includes other components





$$D_2(\eta) = -\log_2(1-\eta).$$

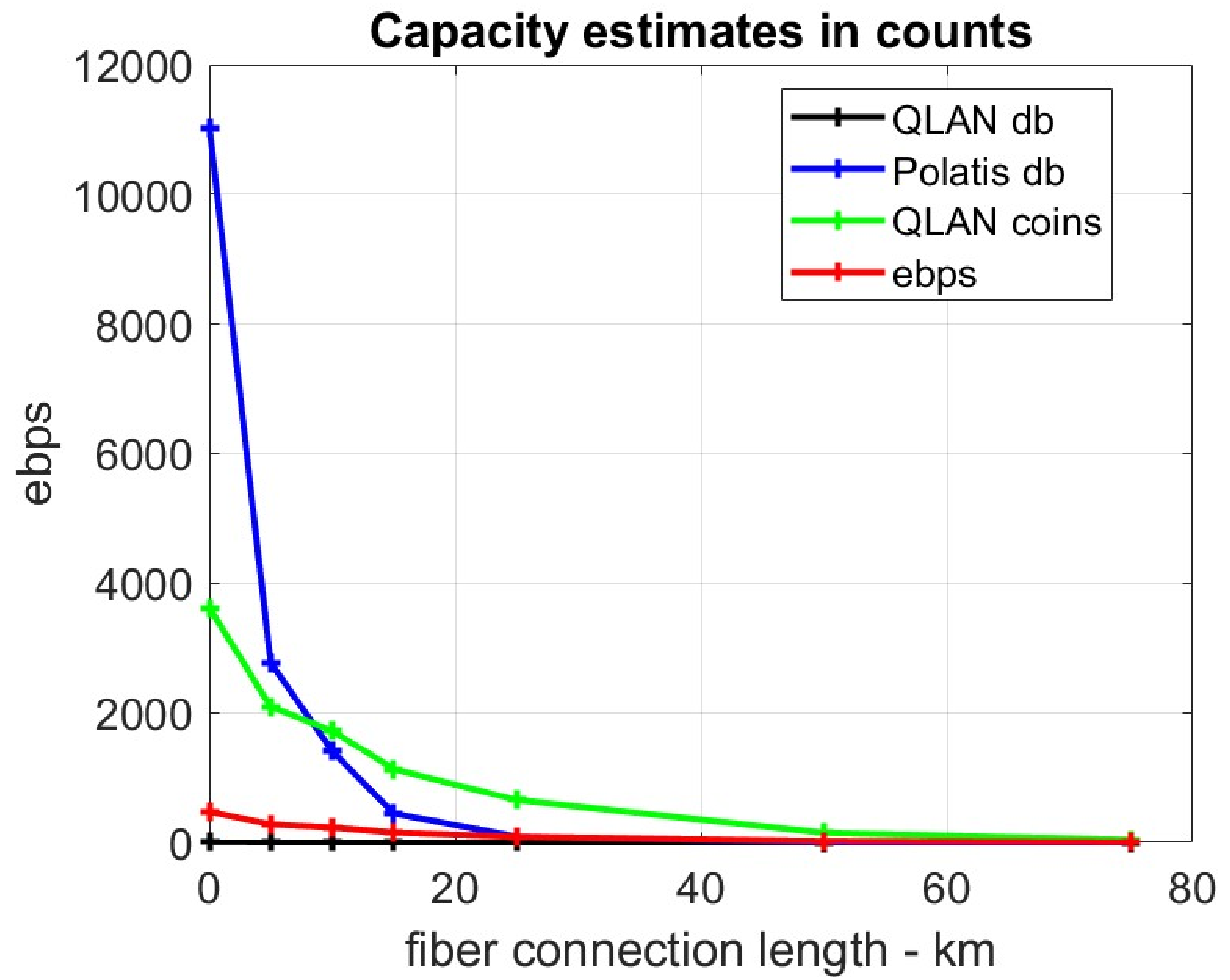




Capacity estimates: Light Measurements

Derived treating connections as fiber no explicit accounting for patching and switching
Estimation is approximate:

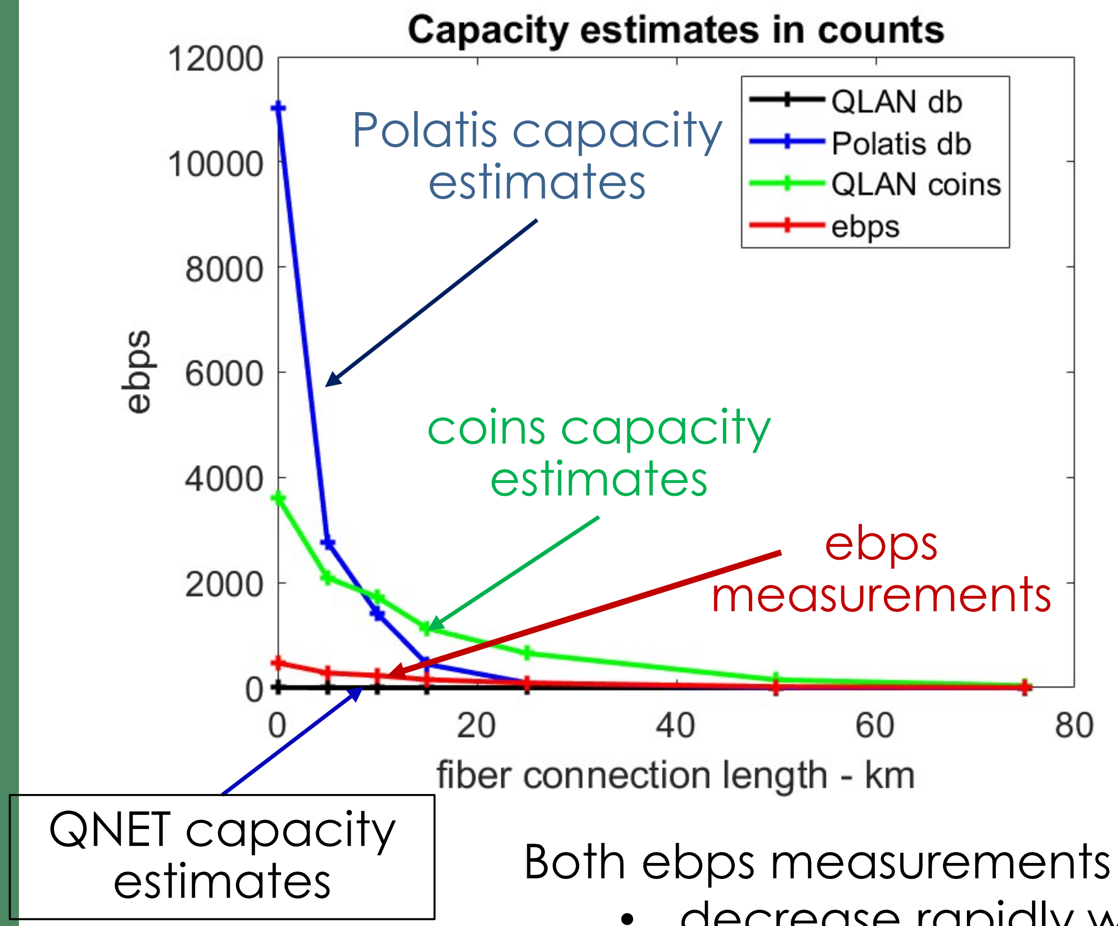
- measured power level includes other components

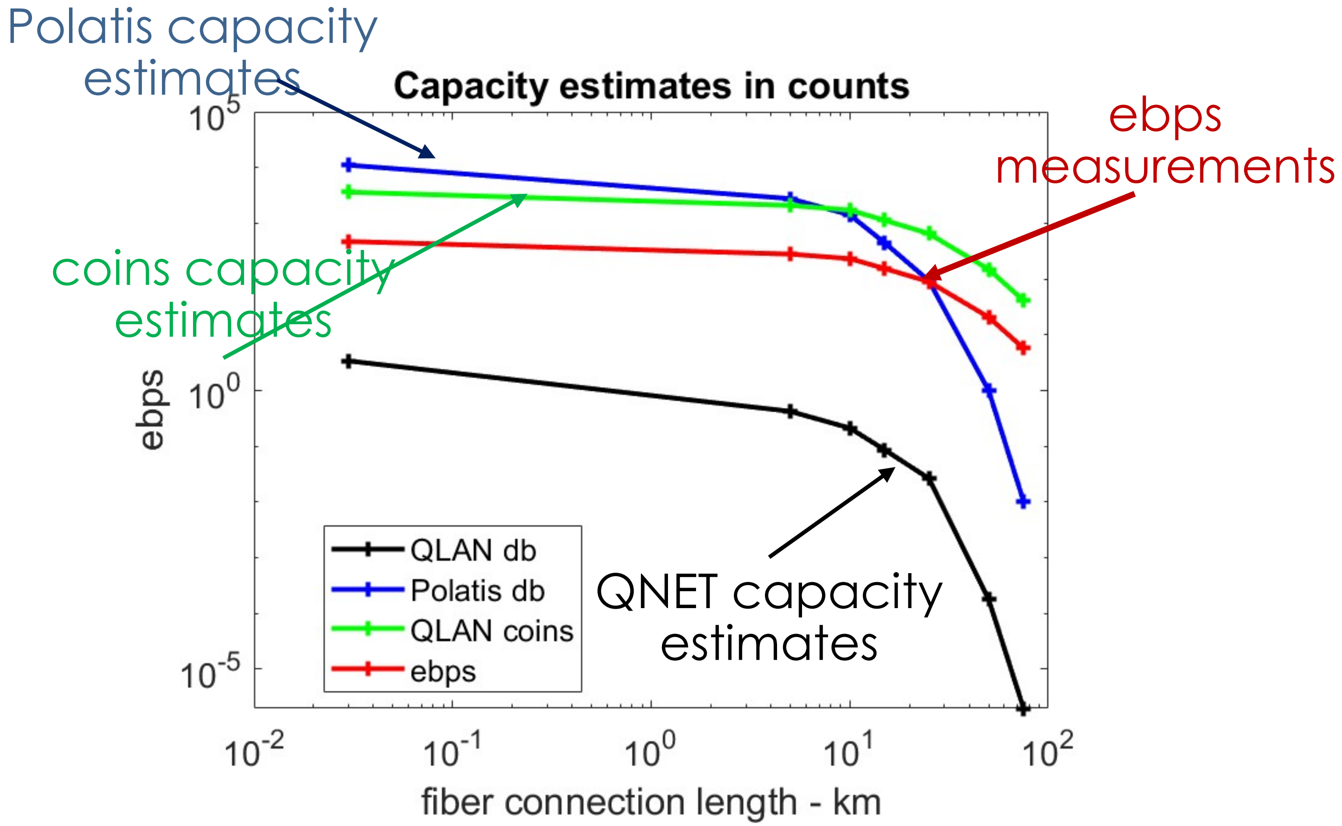


Comparison: Measurements and Estimates

ebps measurements and capacity estimates based on QNET measurements

- normalized with highest values over 30-m fiber spool connection for illustration
- estimates based on Polatis measurements - smaller connection losses by about 12.22dB

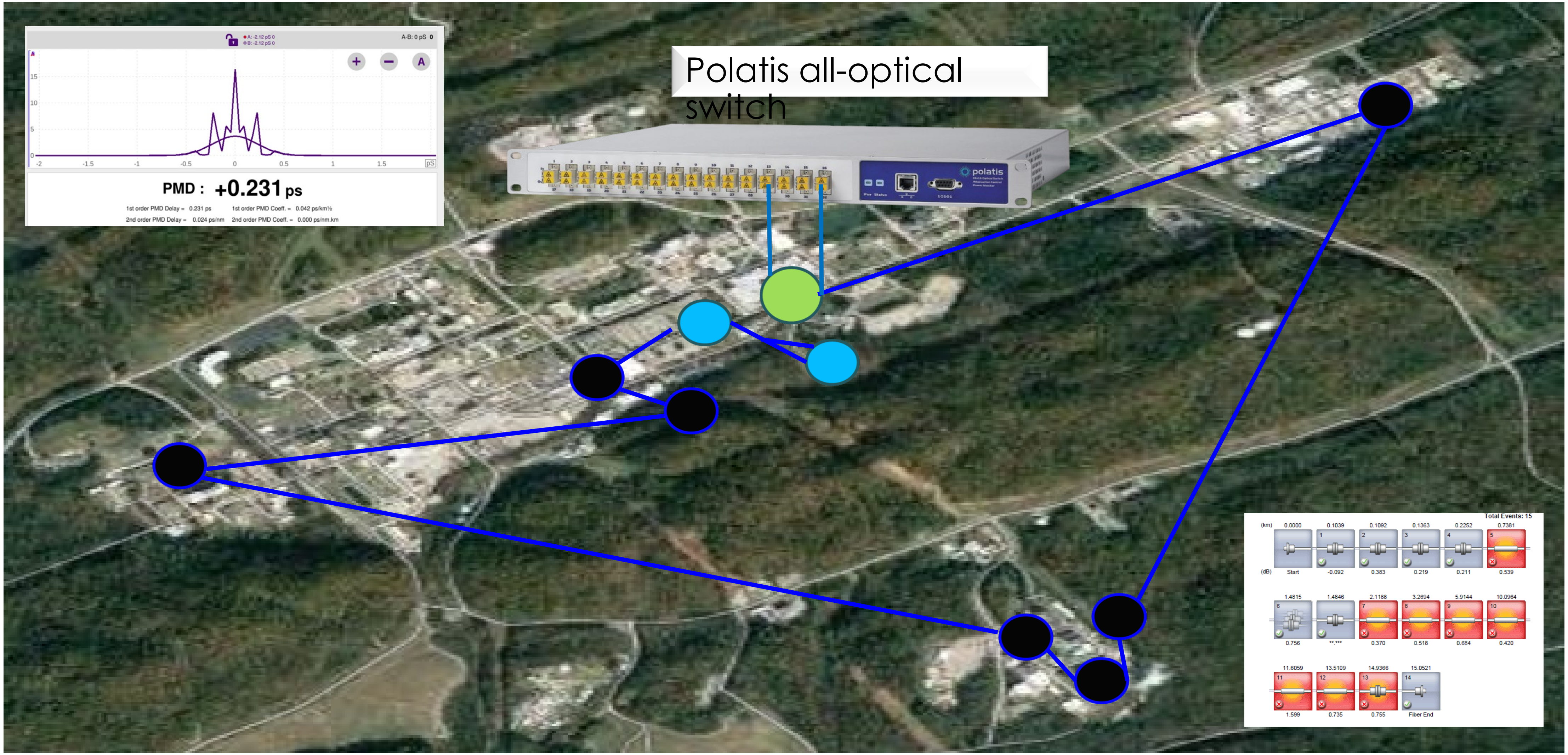




Both ebps measurements and corresponding capacity estimates

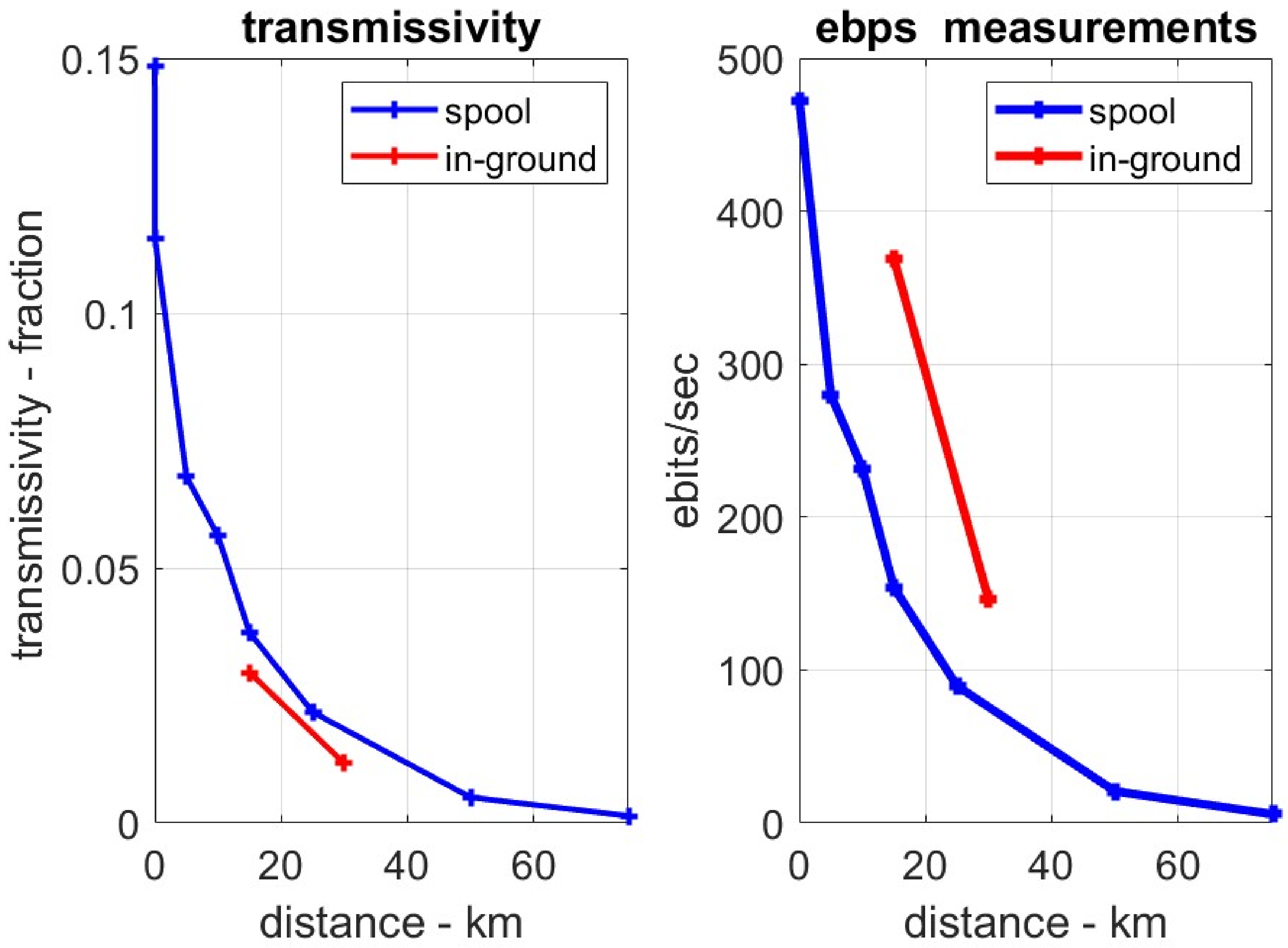
- decrease rapidly with distance as expected
- shape is **convex** - similar to TCP profile under severe bottlenecks
- capacity estimates based on Polatis measurement higher

20 single-mode fiber loops: each 15km



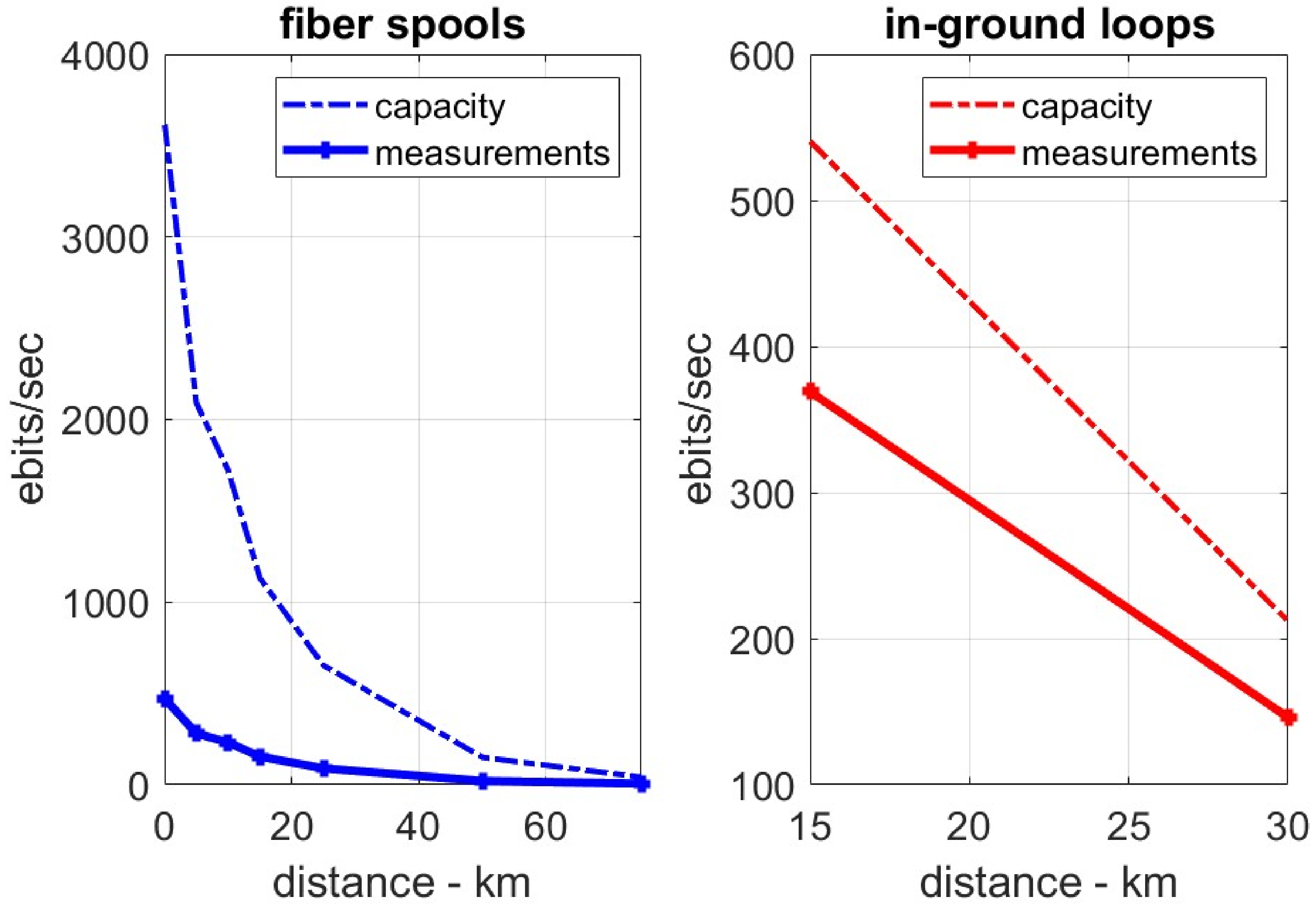
Measurements collected: PMD - Polarization mode dispersion; CD - chromatic dispersion
OTDR – Optical Time Domain Reflectometer

Fiber Spools and In-Ground: transmissivity and ebps



OAK RIDGE
National Laboratory

Fiber Spools and In-Ground: ebps and capacity

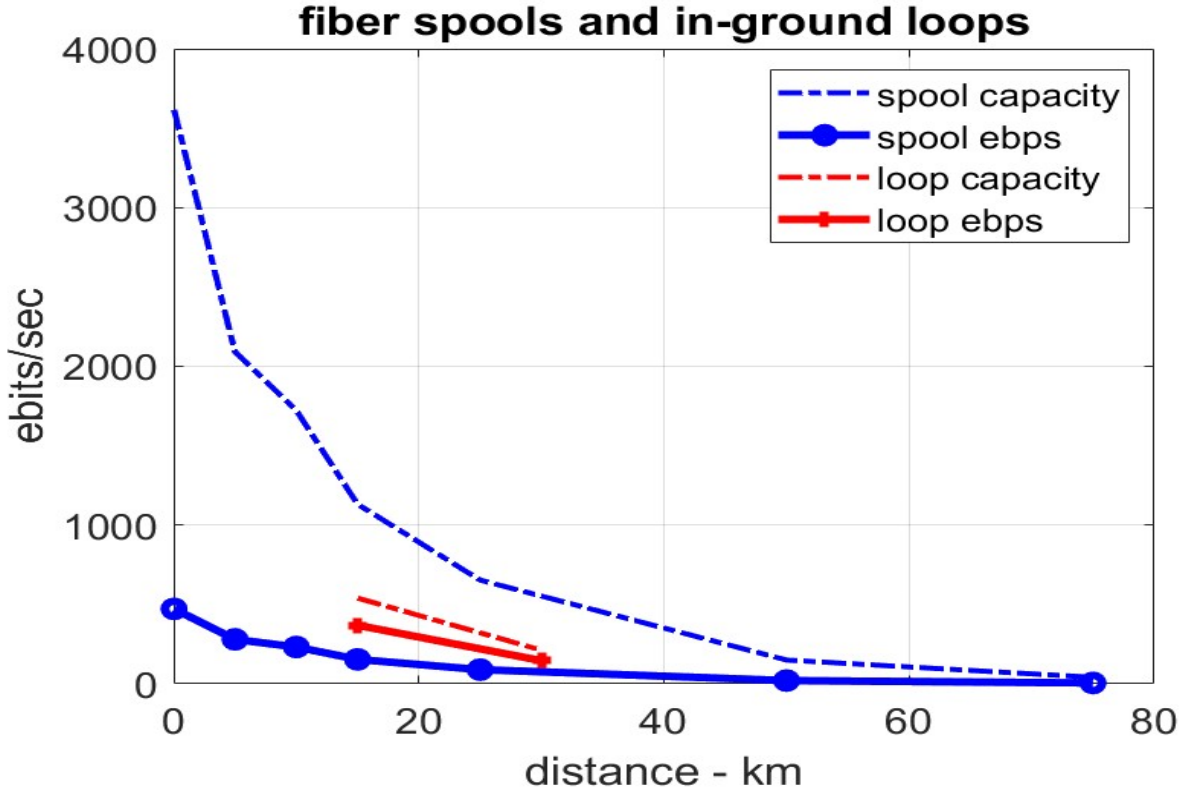


OAK RIDGE National Laboratory

Fiber Spools and In-Ground Loop Measurements: Early Results

ebps measurements collected on 1 and 2 inground loops – 15 and 30km

- In-ground loops have
  - lower transmissivity (hence, lower capacity)
  - higher ebps measurements



Possible Explanation: Fiber quality

OAK RIDGE National Laboratory

Conclusions

Summary:

- Described quantum conventional network testbed:
  - supports variety of network R&D projects – co-existence tests (not covered here)
- Testbed with telescoping suites of fiber connections
  - In-ground fiber loops and in-house fiber spools provision suite of optical connections
  - bps and ebps throughput and power levels during measurements - used for ebps capacity estimates
- Briefly described experiments:
  - Entanglement distribution
  - Throughput and capacity estimation

Future Work:

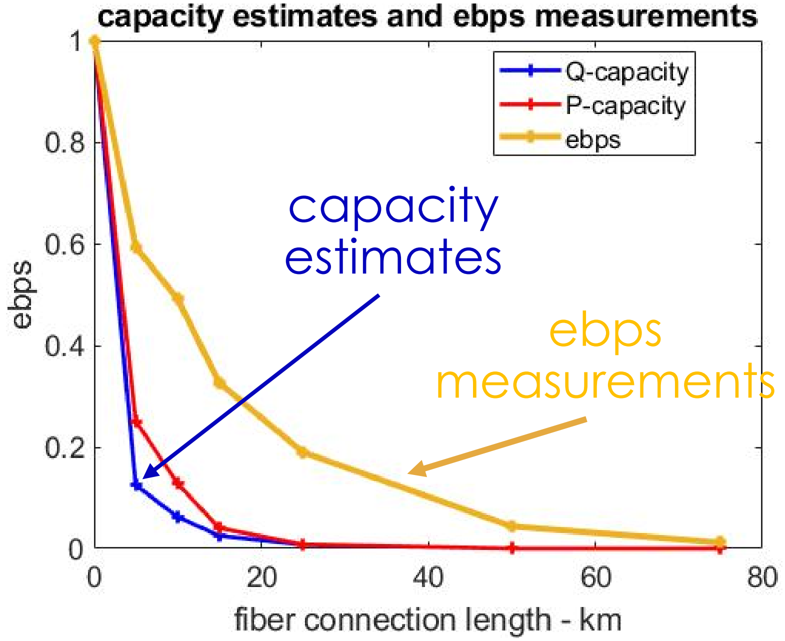
- Several testbed capabilities needed
  - wide-area fiber connections
  - repeaters and routers – infrastructure to test them
  - software for operations, provisioning and orchestration
- Particular capability: test potential role of buffers and loss recovery for flow control of entanglement distribution
  - similar to TCP mechanisms in conventional networks

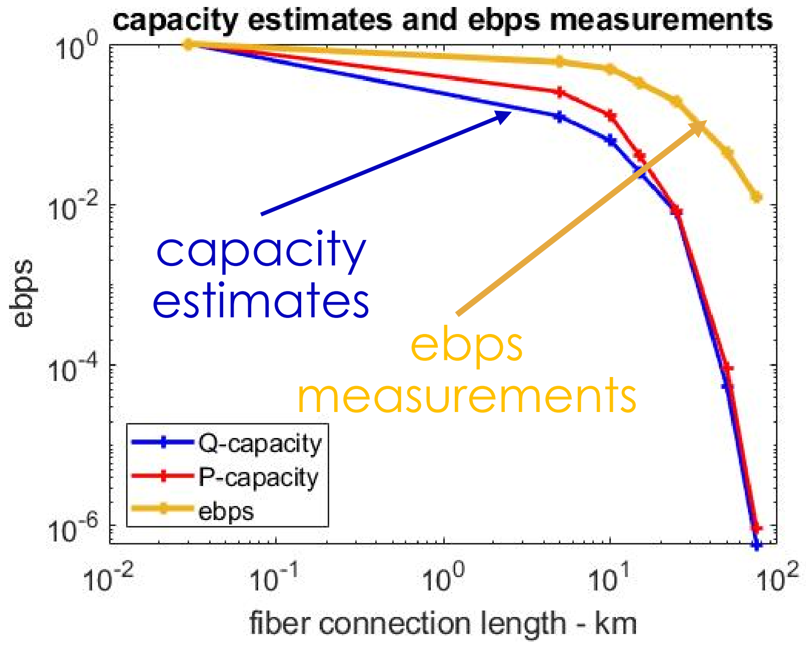
Thank you

Comparison: Models and Physical Connections

Both ebps measurements and corresponding capacity estimates

- while both decrease rapidly, **ebps measurements are higher than capacity estimates**





Postulation: degree of misalignment between

- assumptions used for the capacity estimation and
- QNET conditions under which the light intensity measurements are collected

Further refinements needed to correlate measurements with theoretical estimates

Comparison: somewhat similar to Shannon limit estimation (conventional optical connections) several refinements needed to correlate measurements with theoretical estimates

N. S. V. Rao, M. Alshowkan, J. C. Chapman, N. A. Peters and J. M. Lukens, "Throughput Measurements and Capacity Estimates for Quantum Connections," *NetSciQCom 2023: IEEE INFOCOM Network Science for Quantum Communication Networks Workshop*, Hoboken, NJ, USA, 2023, pp. 1-6.