Oak Ridge National Laboratory

Entanglement Capacity Estimates and Throughput Measurements of Quantum Channels

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Outline

Introduction

Network throughput: critical performance metric for network connections

- **Conventional networks:** measured as bits per second - **bps**
  - extensively studied both analytically and experimentally
  - used in practice to design and optimize network infrastructures and protocols

- **Quantum networks** - several candidates for throughput performance metrics
  - based on qubits, entangled qubits - ebits, and secret-key bits - kbits
  - **ebps**: ebits per second is particularly useful in
    - entanglement distribution rate
    - teleportation throughput

In this paper, we consider
  - **ebps** *measurements*
  - *analytical capacity estimates of* ebps "per channel use"
- over repeater-less fiber connections

Background

Throughput in conventional and quantum networks

- depends on connection length
- various other factors - not considered here
  - fiber material and quality, source quality and emission rate, performance of detectors, etc.

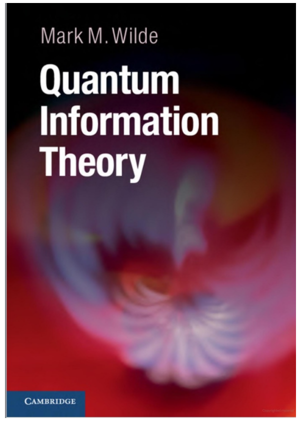
Throughput measurements:

- ebps measurements require specialized equipment
  - photonic entanglement sources and superconducting nanowire single-photon detectors – SNSPD

Capacity of repeater-less quantum connections: extensive theory developed - Wilde (2017)

quantum connections modeled as generic quantum channels

- channel capacity estimates specialized for fiber connections by using *transmissivity* η as key parameter - Pirandola *et al* 2017
  - upper bounds on achievable throughput
  - qualitative information on throughput as a function of connection length



In practice,

- ebps measurements and capacity estimates often hard to correlate
- in part due to lack of measurement platforms with precise, well-characterized analytic models

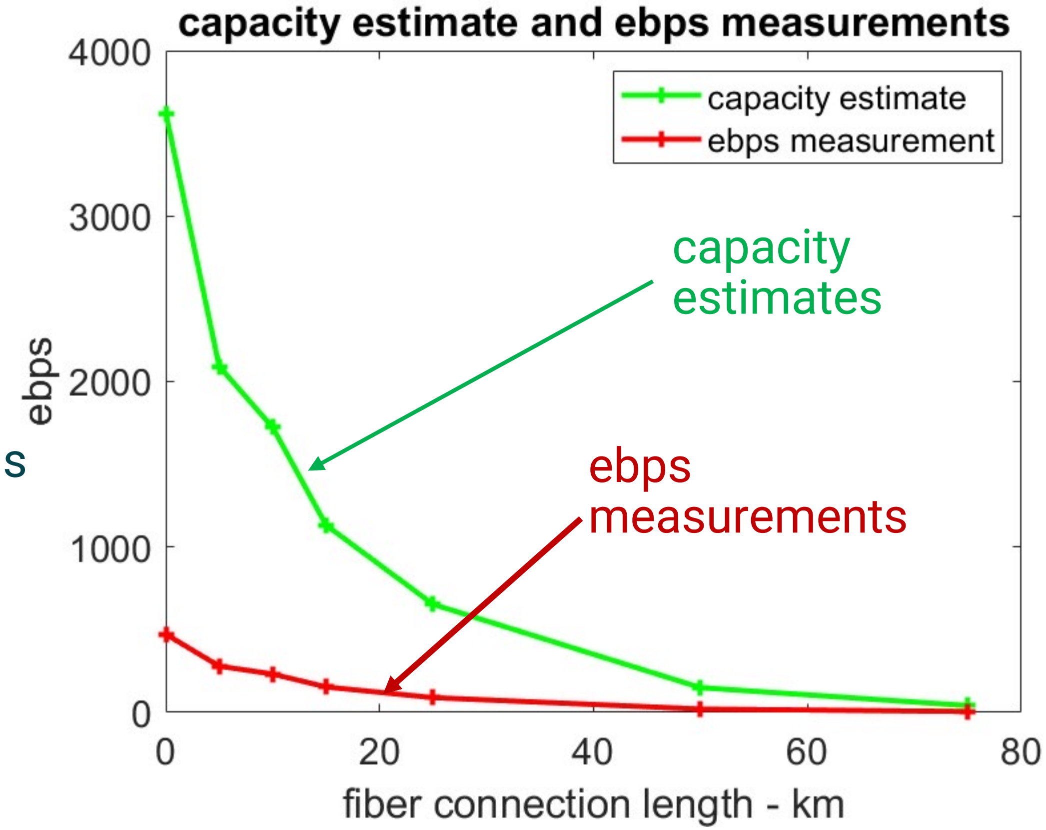
Results Summary:

Comparison of ebps measurements and capacity estimates

Quantum connections – repeater-less fiber

- ebps decays with connection length
  - sharply: faster than linear, compared to bps
- ebps throughput consistent with estimated capacity
  - resolved previous mismatch in Rao et al 2022
    - analytical capacity estimates based on light levels
    - ebps measurements based on coincidencese

    namely, ebps higher than capacity estimates



- Overall, this comparison provides insights into
  - potential approach for achieving higher ebps by using TCP-like mechanisms

In this paper

Methodology

- testbed used for measurements:
  - ebps and light intensity measurements over fiber connections of different lengths
- Analytical formulae used to estimate corresponding capacities
  - using single photon and light intensity measurements to approximate transmissivity parameter η
- ebps measurements compared with its capacity estimates

Conventional-Quantum Infrastructure ORNL quantum network (QNET)

- testbed provides measurements
  - support comparison of measurements and capacity estimates both qualitatively and quantitatively
- collection of fiber spools
  - provides a suite of single-mode fiber connections 0—90 km in length.

Measurements and estimates

- measure coincidences and light intensities over these connections
- use them in analytical formulae for ebps capacity estimates

Conventional-Quantum Network Testbed - QNET

Conventional-quantum testbed

- ebps measurements over fiber connections of different lengths
- corresponding capacity estimates using single photon and light intensity measurements used for approximate transmissivity parameter

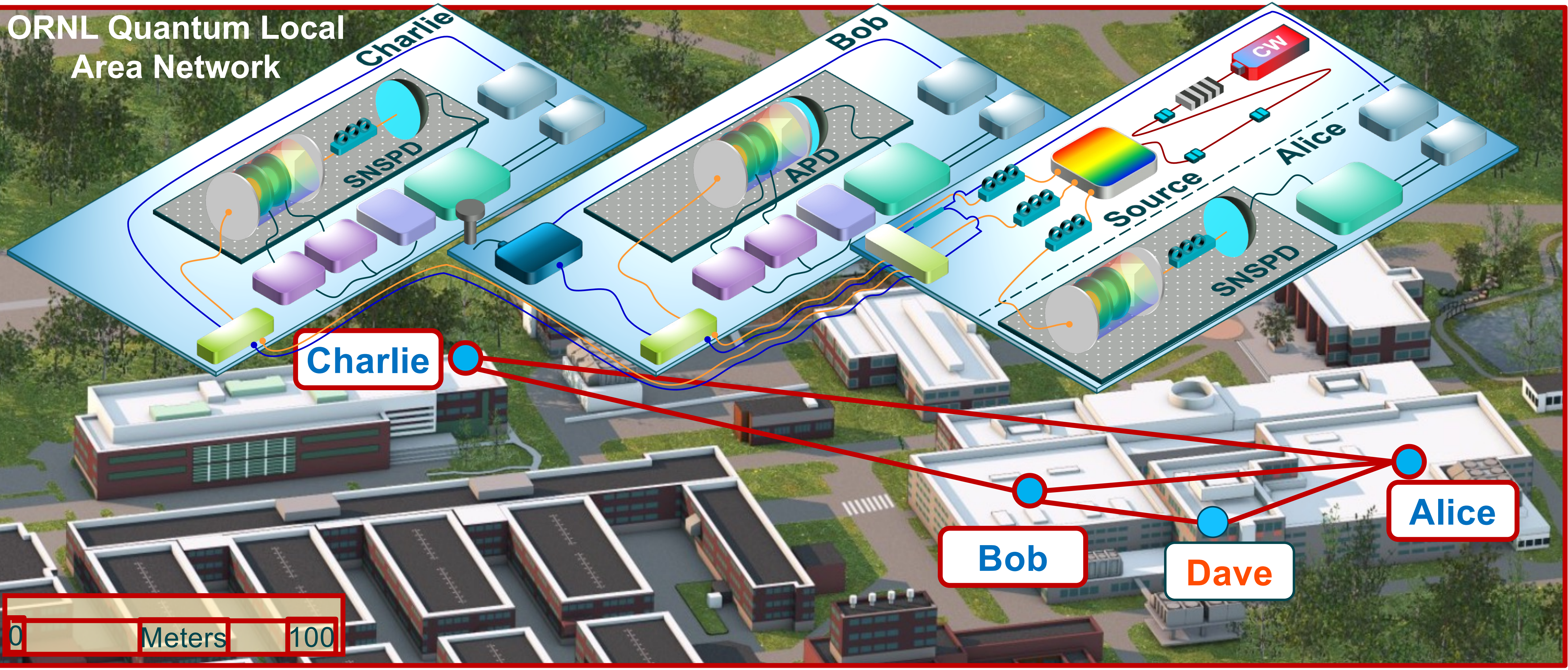
Fiber-spool Augmentation:

- fiber spools to provide a suite of single-mode fiber connections
  - 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

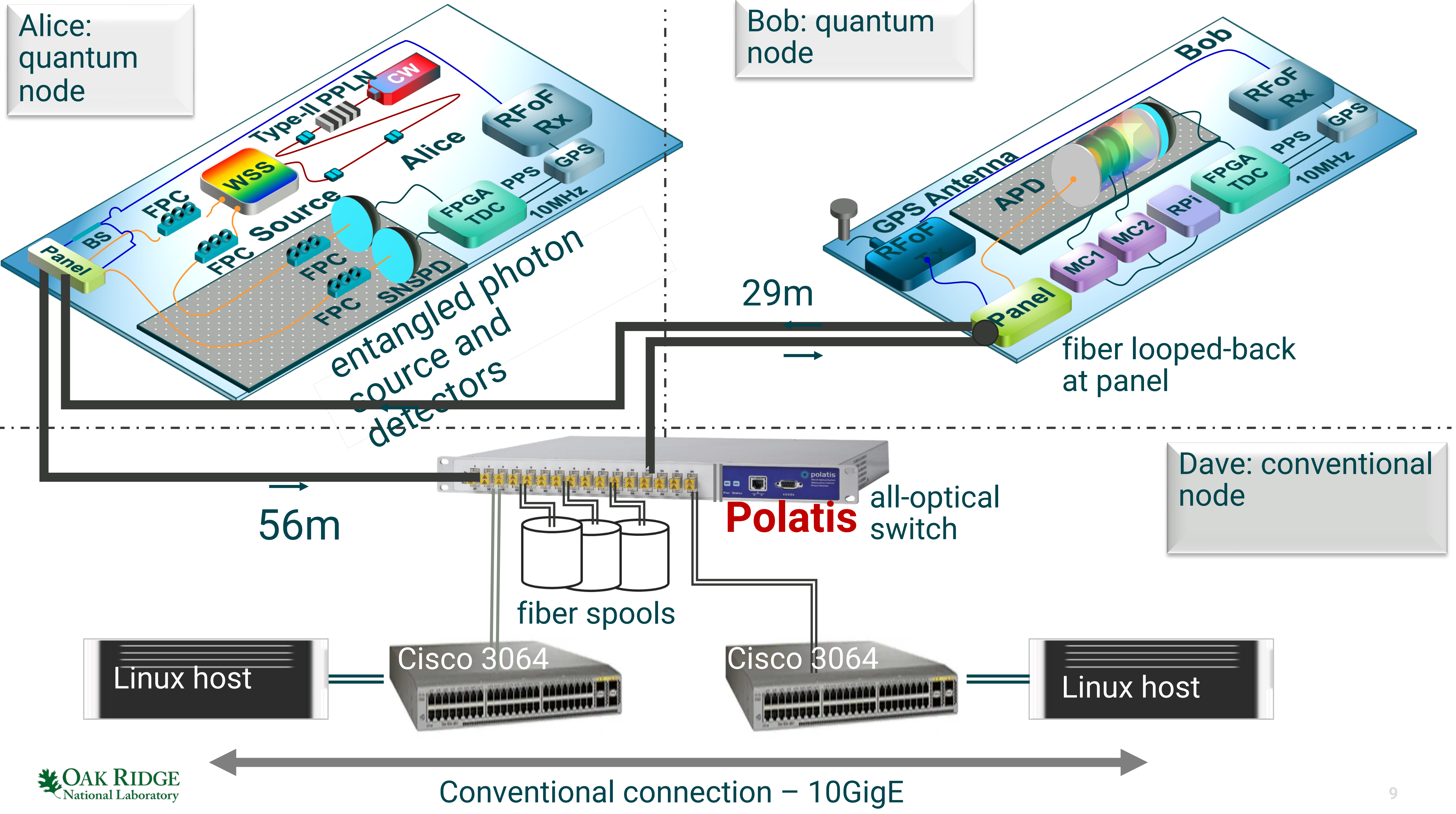
Testbed provides common platform to support

- comparison of bps and ebps measurements and capacity estimates

QNET: ORNL Conventional-Quantum Network Testbed



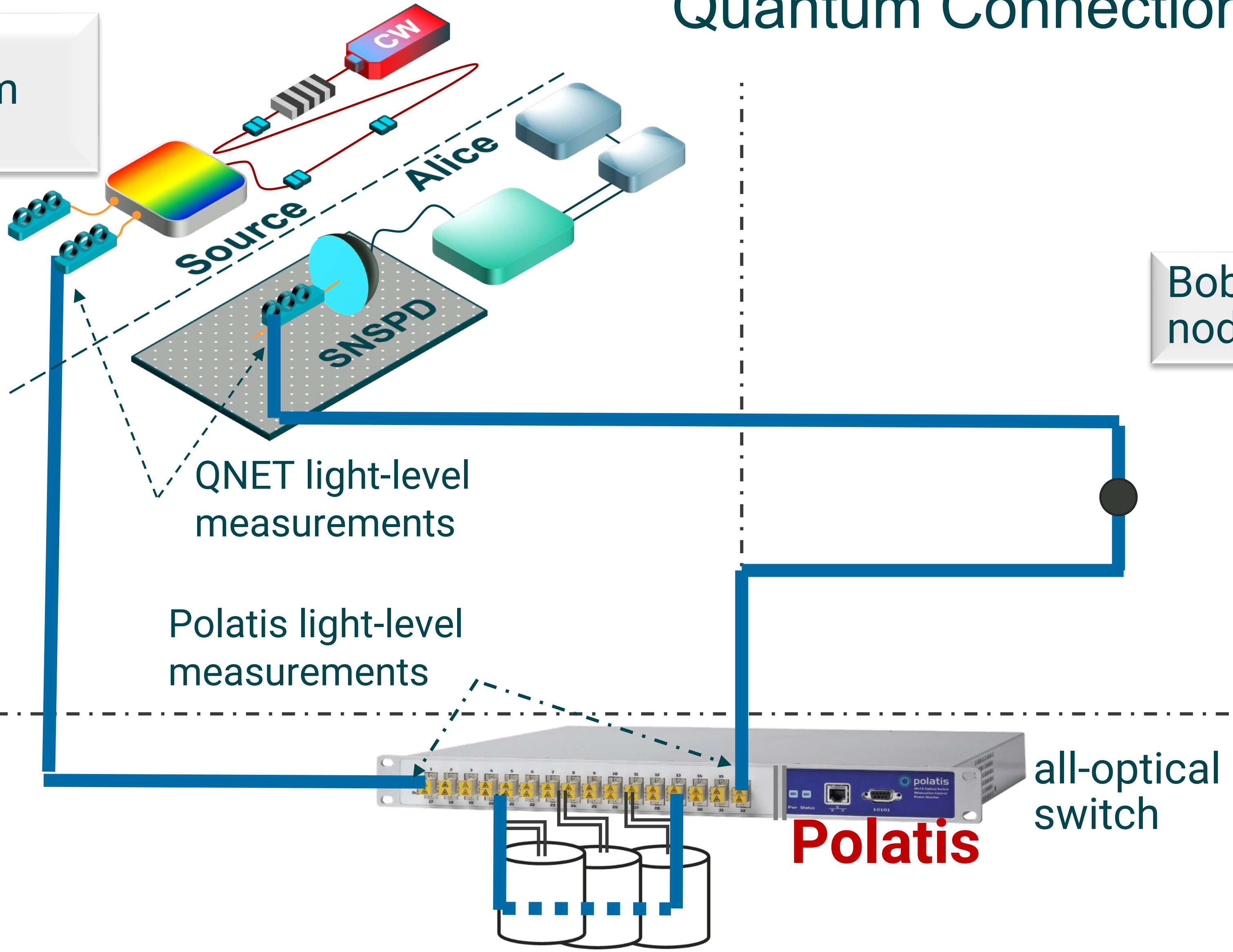
QNET augmented with fiber-spools
Nodes Alice, Bob and Dave used in this work



Alice: quantum node
Bob: quantum node
Dave: conventional node
Type-II PPLN
CW
RFoF Rx
Alice
WSS
FPC
BS
Panel
FPC Source
FPC
FPC
SNSPD
FPGA TDC
PPS
GPS
10MHz
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

Alice: quantum node



Bob: quantum node

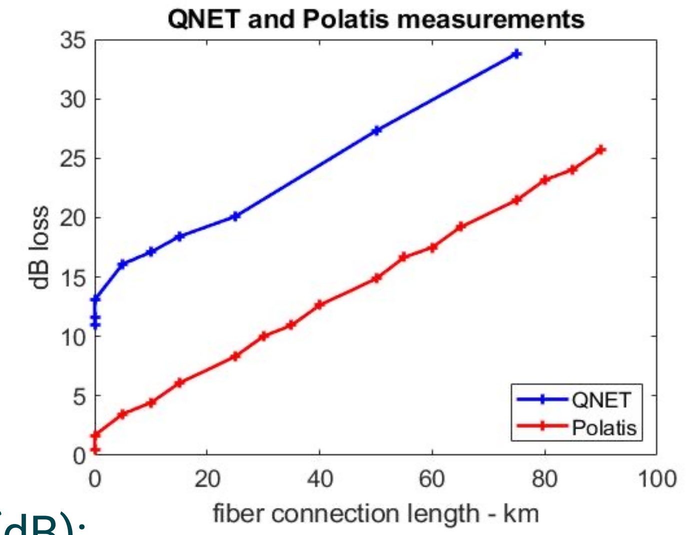
Fiber spools:
Selected for various connection lengths

Dave: conventional node

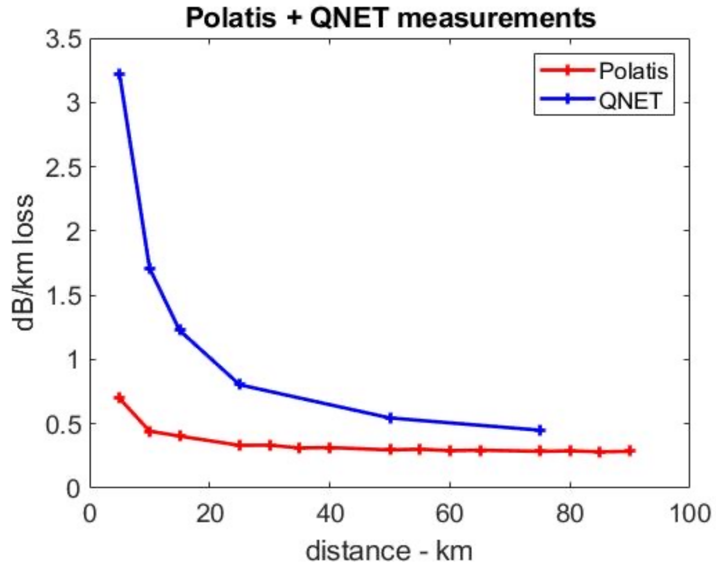
Light-Level Measurements

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



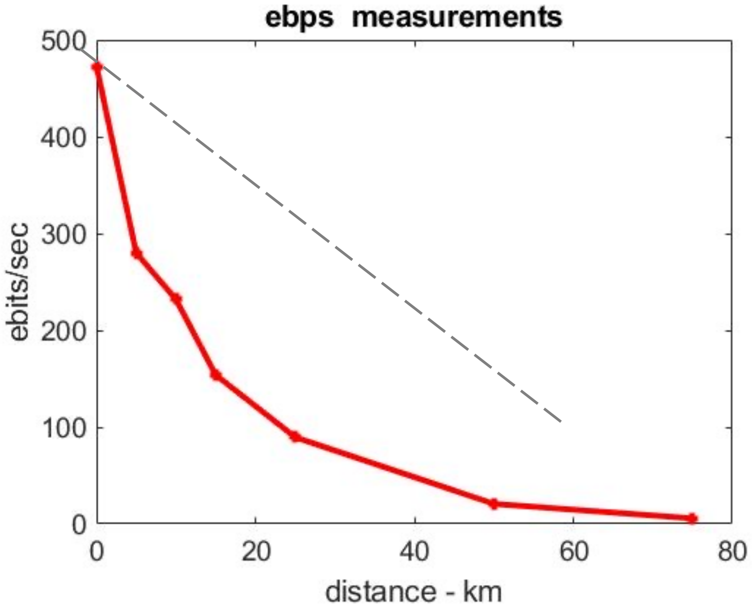
Connection loss (dB):
- subtract destination from source levels
- function of connection length in km - nearly linear
- constant additional 15 -20 dB loss for quantum connections
    - additional fiber connections to Alice and Dave - direct and via Bob and at source and detectors.

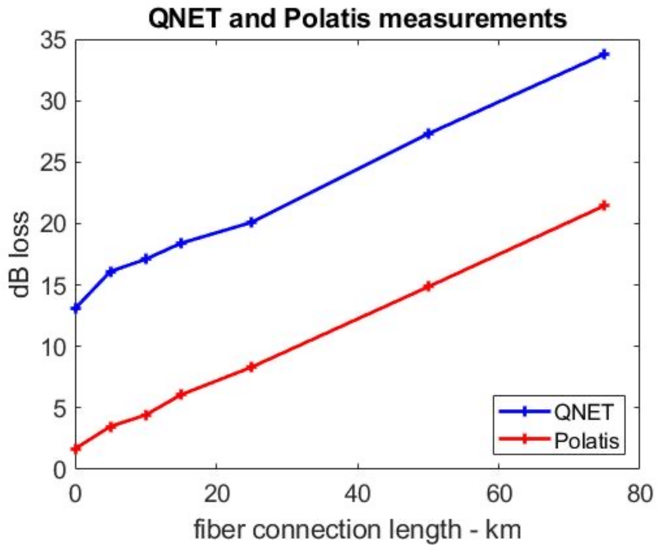


Loss rate per distance estimate - divide connection losses by length,
- decreasing trend with connection length
- higher values at shorter connections
    - higher fraction of losses due to
    - fiber patches at nodes, cross-connects optical switch, and at source and detectors

ebps Measurements over Quantum Connections

- Coincidence rate measurements of entangled photon source at various distances
  - estimate entanglement throughput
- 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

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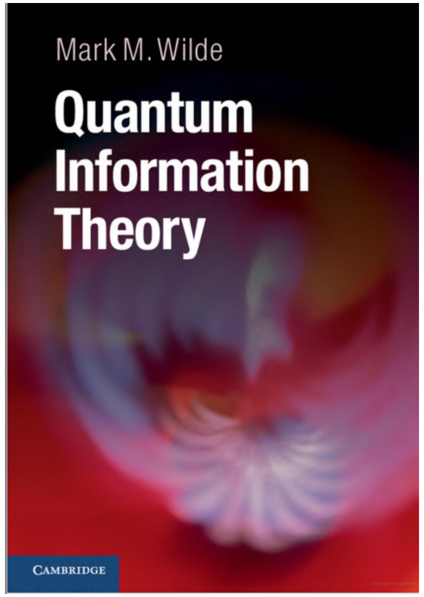
Quantum Channel Models: Capacity Estimates

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 η process tomography using QNET measurements - Chapman etal2023



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

- uses transmissivity parameter 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:

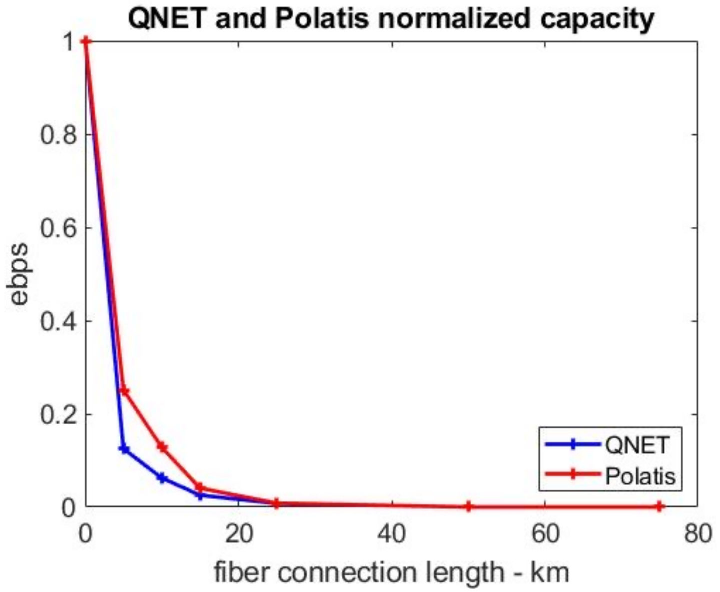
$$D_2(\eta) = -\log_2(1-\eta).$$

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 in this case: fraction of entangled photons successfully transmitted over channel

- our 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



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

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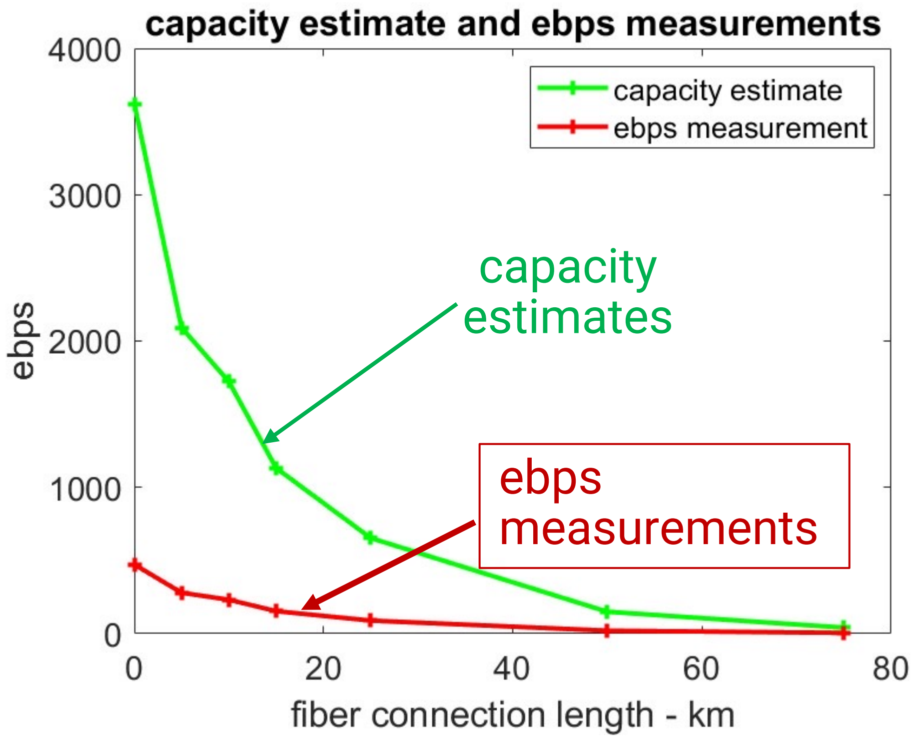
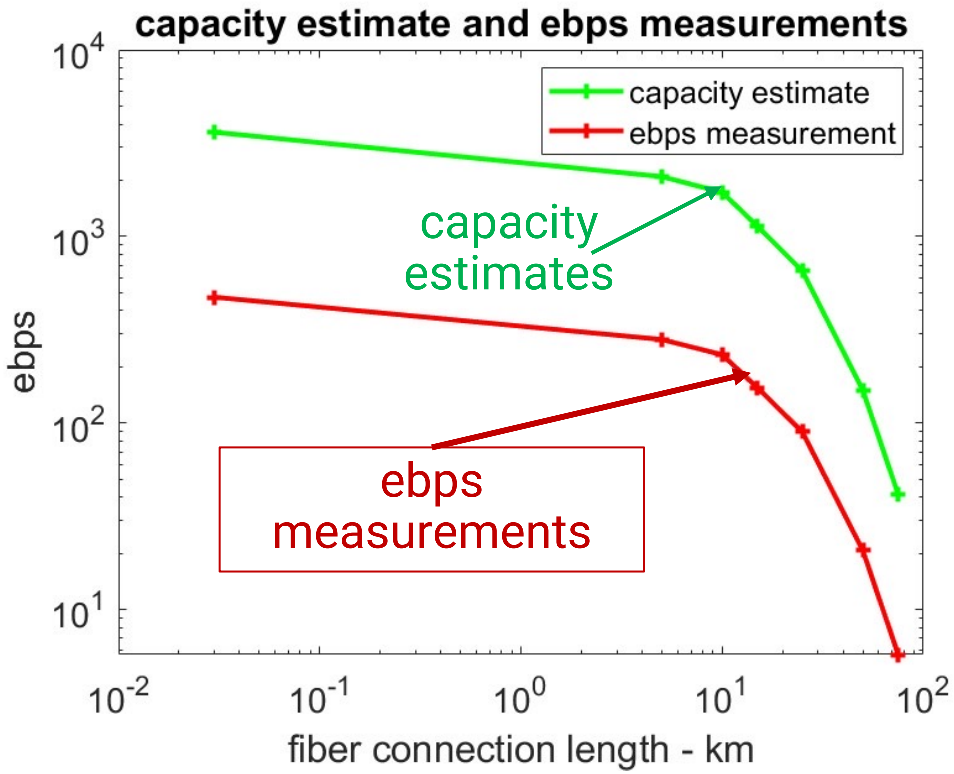
Comparison: Measurements and Estimates

ebps measurements and capacity estimates based on QNET baseline coincidences measurements

- normalized with local coincidence measurements





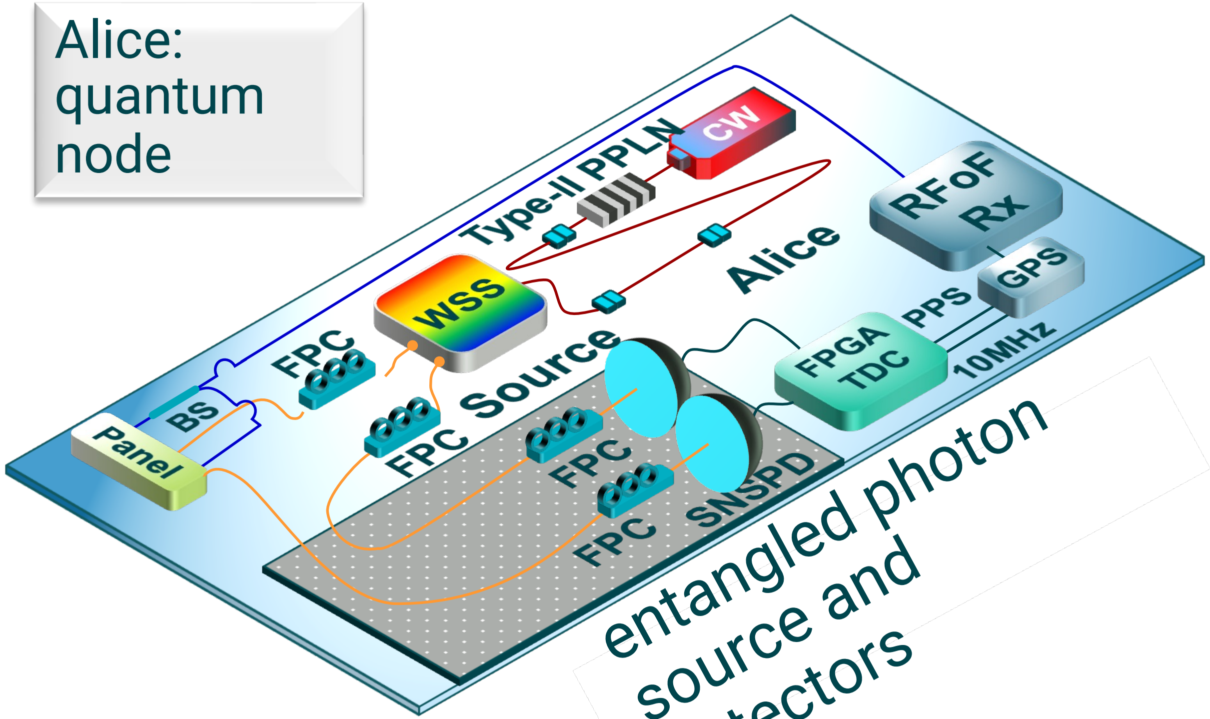
Both ebps measurements and corresponding capacity estimates

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

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
  - used to derive multiplier of $D_2(\eta)$ to derive capacity upper-bound of ebps

Alice:
quantum
node



entangled photon
source and
detectors

Capacity estimates: Previous Approximations

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
  - 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

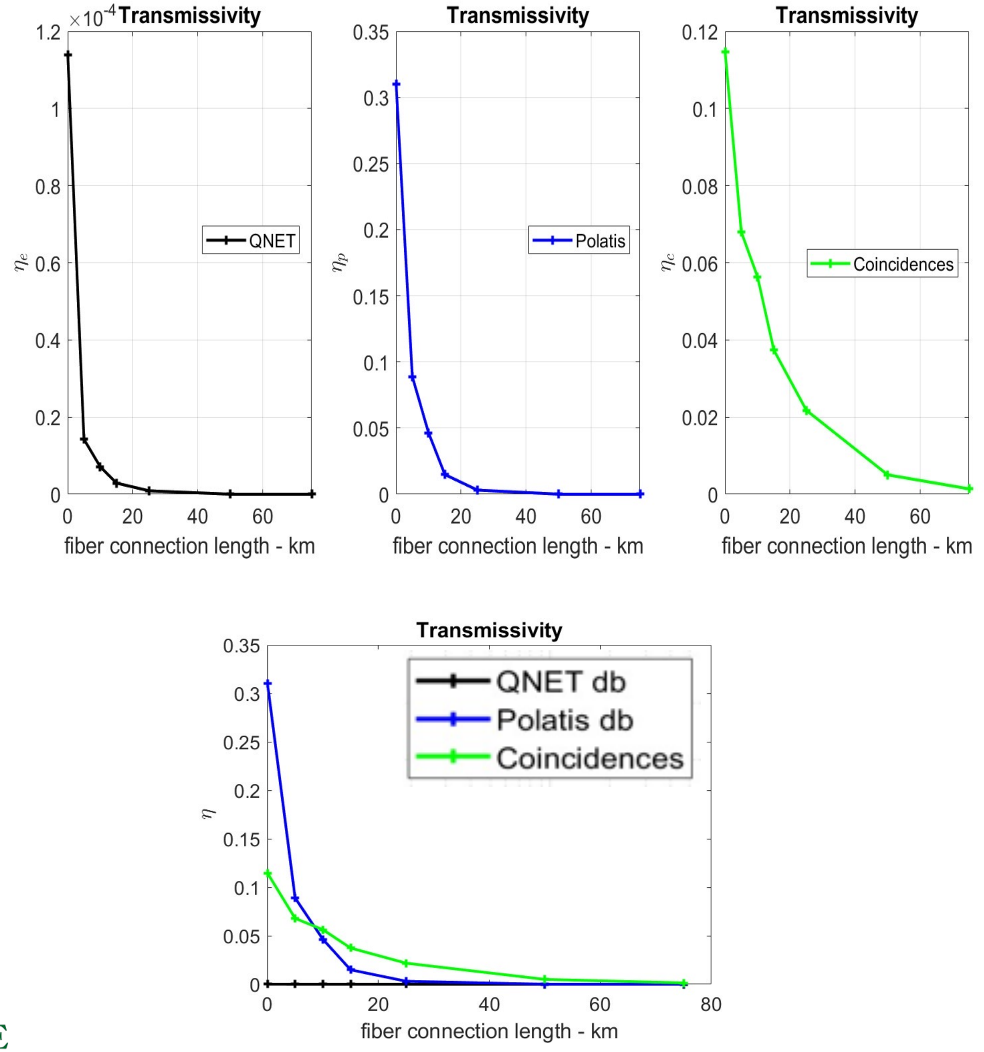
not accurate – underestimate capacity

Transmissivity Estimates: Light Measurements

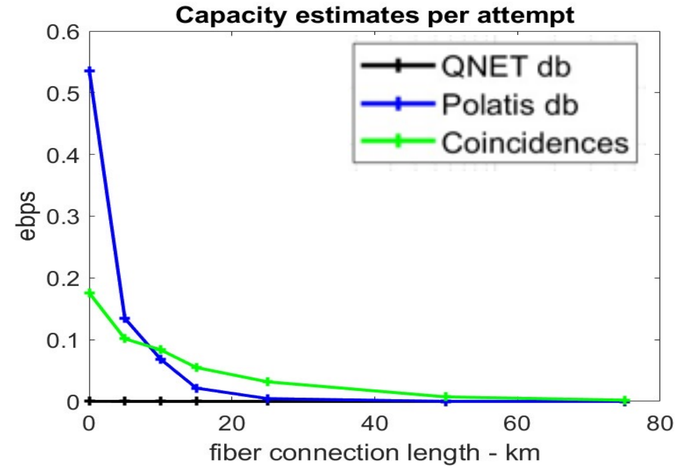
Derived treating connections as fiber no explicit accounting for patching and switching

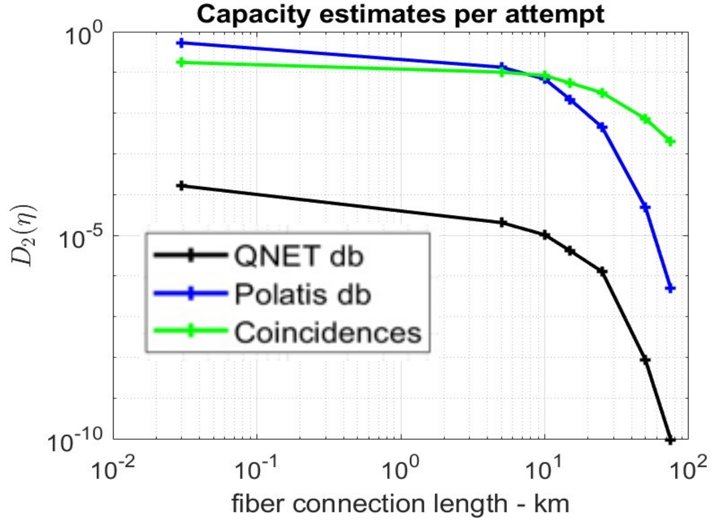
Estimation is approximate:

- measured power level includes other components



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





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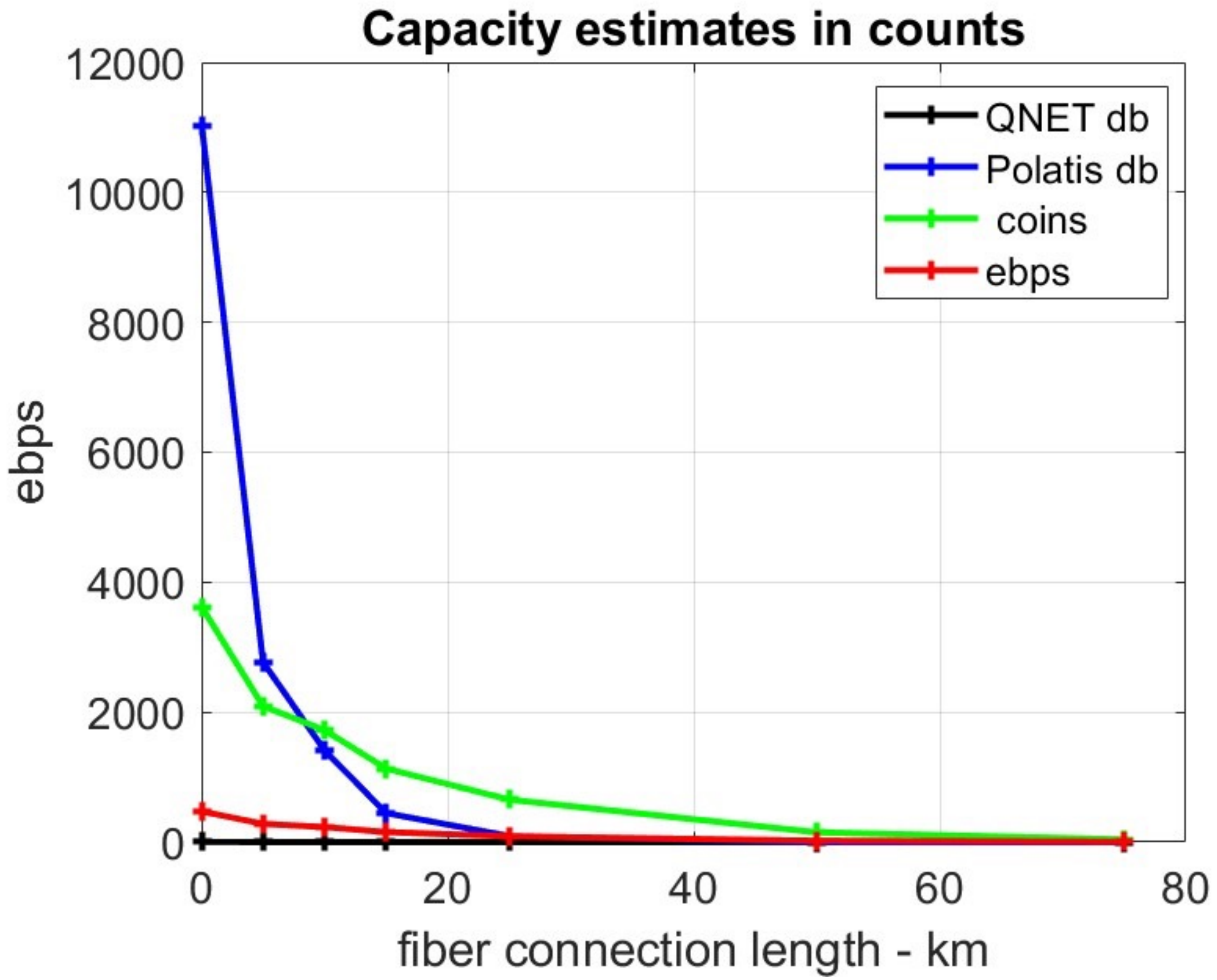
Capacity estimates: Light Measurements

Derived using measured power level to derive approximation to η

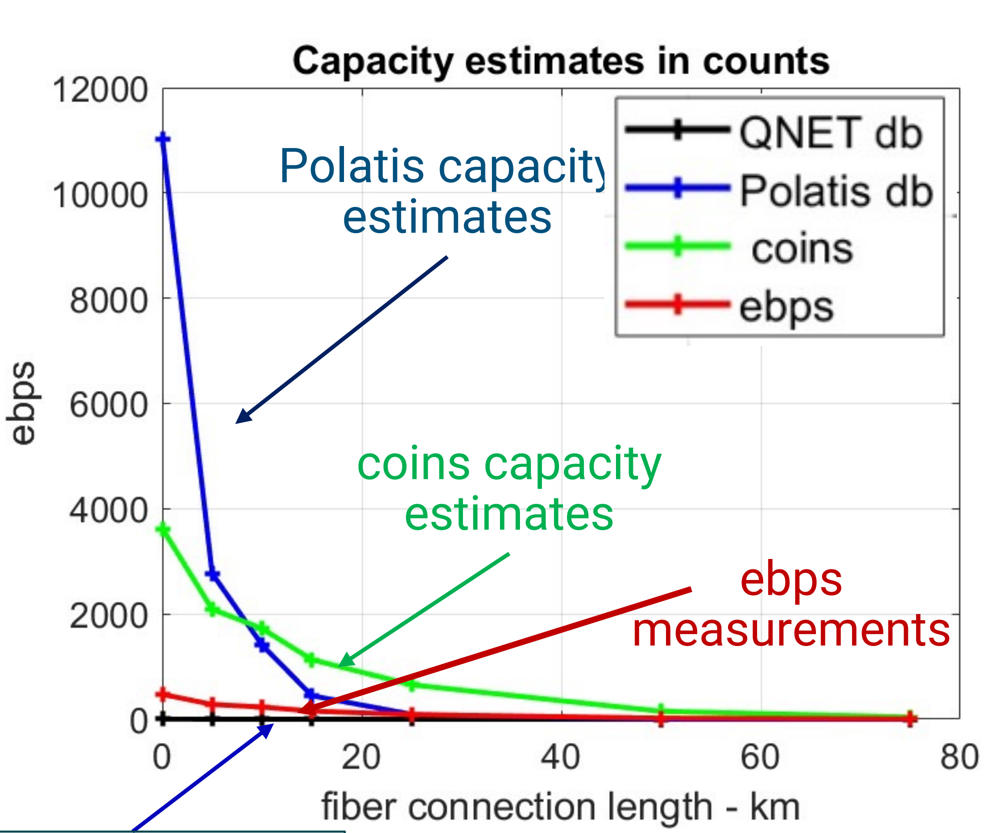
- includes other components



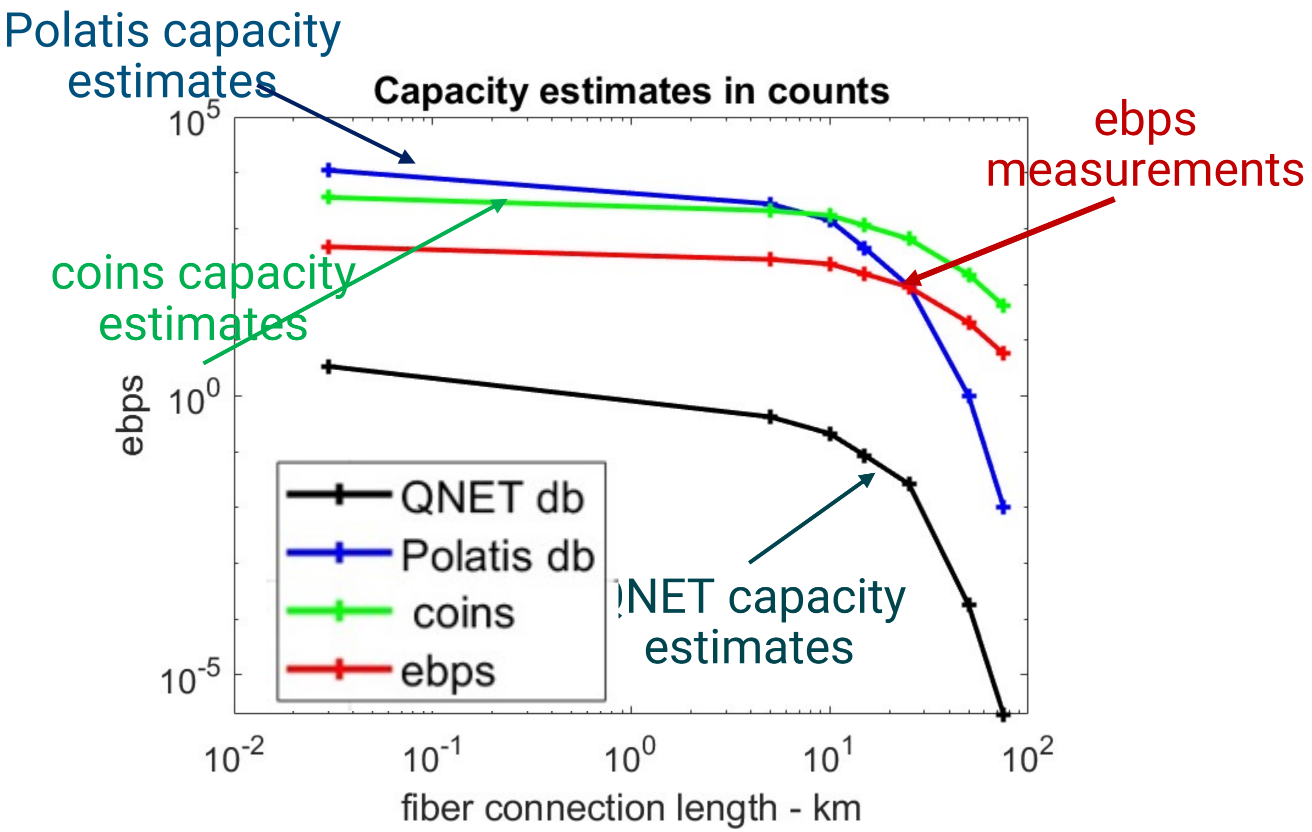
Comparison: Measurements and Estimates

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



QNET capacity estimates



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

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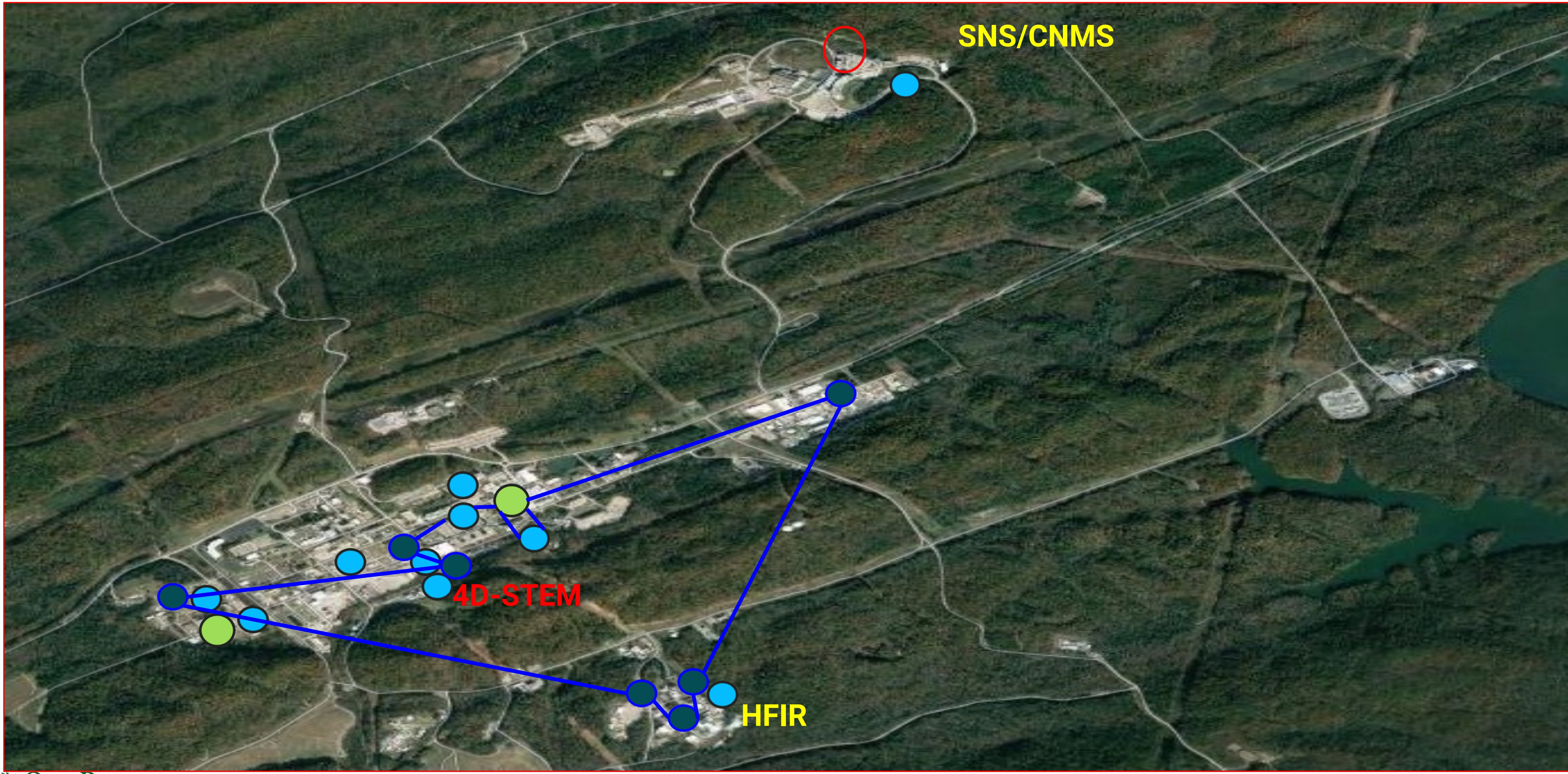
Quantum fiber loop – 15km 20 loops



core

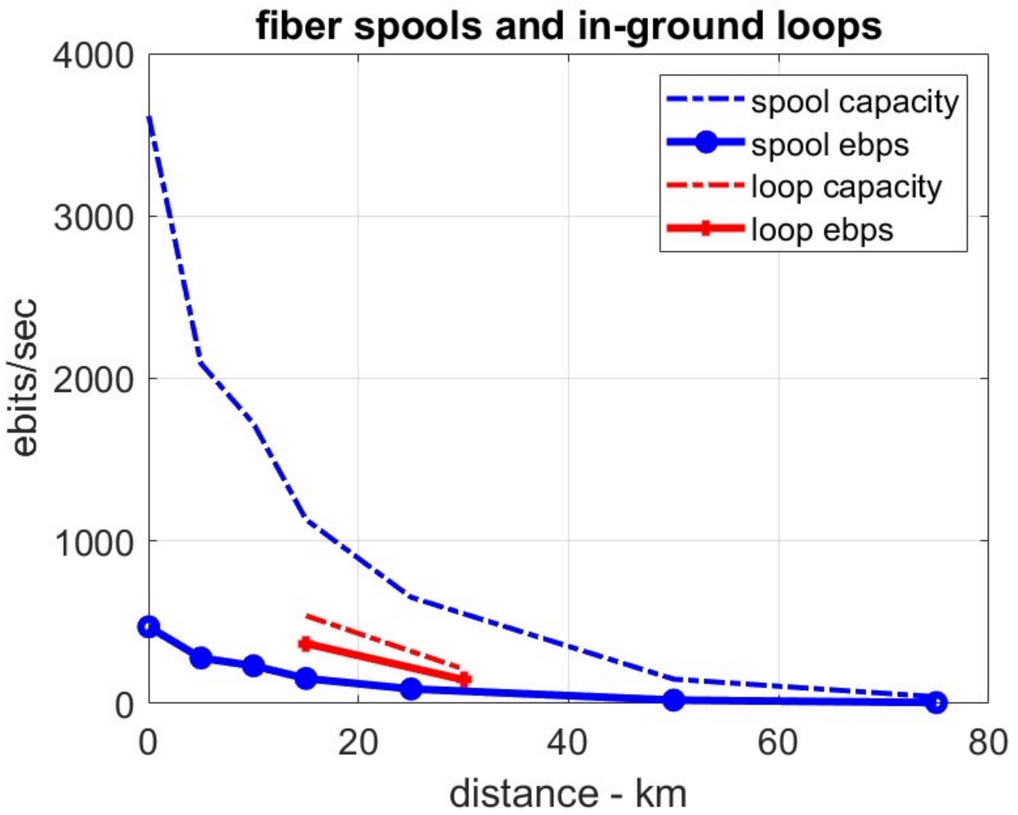
distribution

Fiber Spools and Inground-Arial Loop Measurements

Very early results – need deeper study

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

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



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Conclusions

Summary:

- Initial attempt to relate ebps measurements and analytical capacity estimates for quantum connections
  - conventional network throughput extensively studied both analytically and experimentally
- QNET testbed
  - fiber spools and loops - suite of optical connections: ebps throughput and power levels

- Our results provide useful insights:
  - ebps throughput measurements below capacity estimates
    - multiplier to capacity estimates require specific measurements
    - resolved previous mismatch between experimental and analytic conditions using power levels
      - direct use of light intensity measurements lead to inaccurate (lower) capacity
  - throughput profiles of ebps and capacity estimates decay faster than linear
    - sharp contrast: concave profiles of TCP bps measurements - decrease slower than linear

Future Work:

- Investigation in several directions
  - refinements in both measurements and analytical estimates
- **Open question**: potential role of buffers and loss recovery for ebps throughput
  - similar to TCP mechanisms in conventional networks

Thank you