Optical transmission systems for quantum networks

Center for Quantum Networks
NSF Engineering Research Center

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CQN Winter School on Quantum Networks in partnership with CONNECT

Funded by National Science Foundation Grant #1941583

CONNECT SFI Research Centre for Future Networks

Course Outline

- Introductions and motivations
- Classical optical transmission systems
- Communication system and network engineering
- Quantum systems and coexistence
- Field trials and test bed experiments

Center for Quantum Networks NSF-ERC

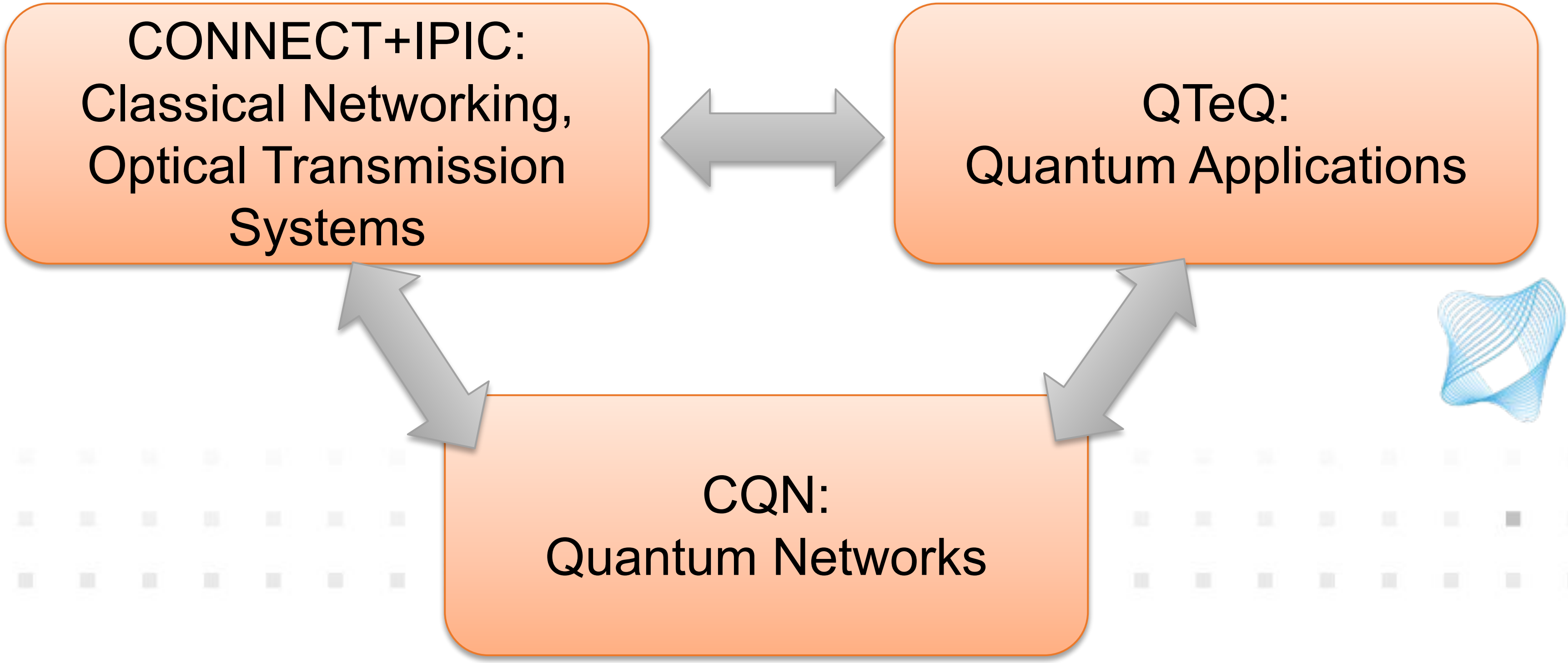
CONNECT: SFI Center of Excellence in Future Networks & Communication

- Optical, Wireless, & Data Communications in Smart Cities, IoT, ITS, Cloud
- Transformative Research on Security, Dependability, Sustainability, AI/Data Driven Intelligence, Customizability & Scalability
- Quantum Internet Technologies
- 19 PIs, 50 Funded Investigators, over 250 Researchers in Total
- €90M over 6 years, SFI+Industry+European funding

Convergent Quantum REsearch Alliance in Telecommunications: CoQREATE

SFI+DFE+NSF US-Ireland Centre to Centre Program

CQN: U. Arizona, MIT, Harvard, Yale, N. Arizona, U. Mass., Howard, U. Oregon, BYU, U. Chicago; QTeQ: Queens U. Belfast; CONNECT: TCD, UCD, UCC, Tyndall, DCU, Maynooth, U. Limerick, SETU, MTU, TUD



Center for Quantum Networks *NSF-ERC*

CoQREATE
Convergent Quantum Research Alliance in Telecommunications

Goals & Objectives

- Foster deep collaboration between quantum and classical networking communities
- Bring centre-scale research to critical interdisciplinary challenges for terrestrial & satcom-assisted quantum networks
  - Coexistence and transmission technologies and design
  - Network control and architectures
  - Device packaging and interfacing
  - AI/ML network control and design
  - Satellite communication assisted quantum networks

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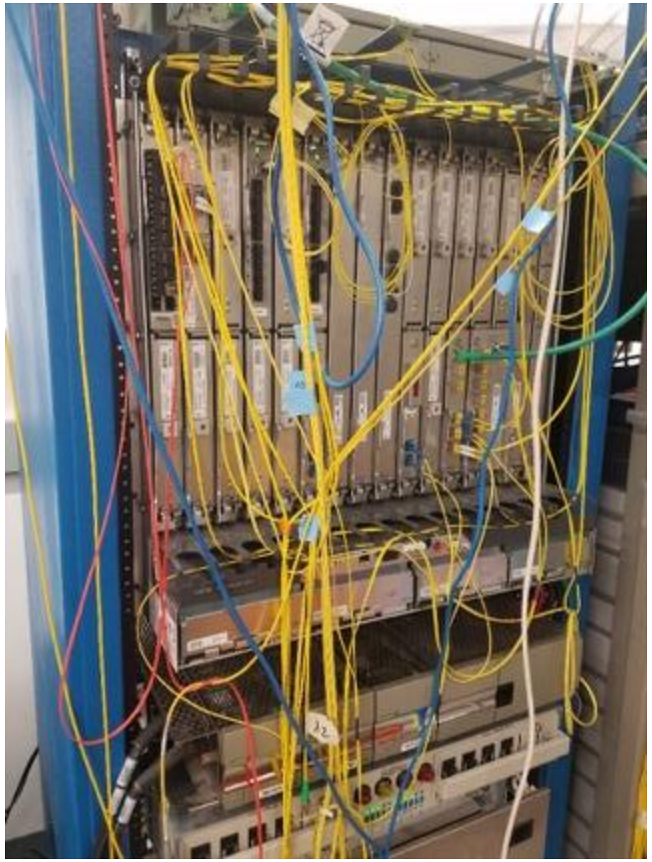
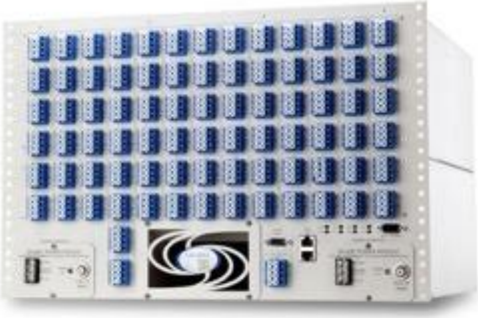
Optical Communication Systems

Metro System

Long Haul System

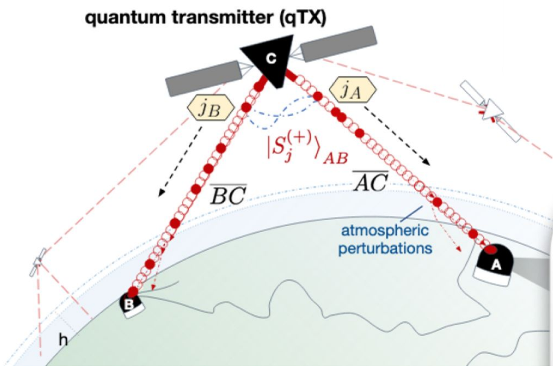


Optical Switch

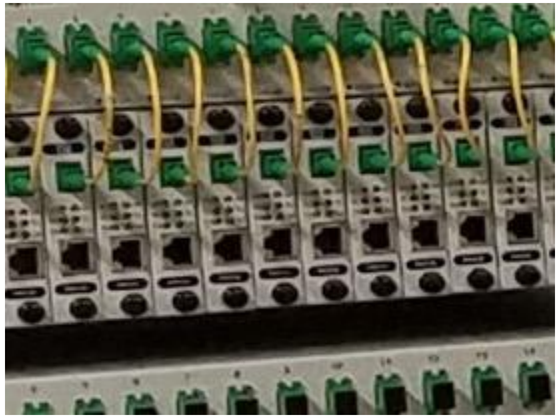


Data Center Network

Satellite communication system



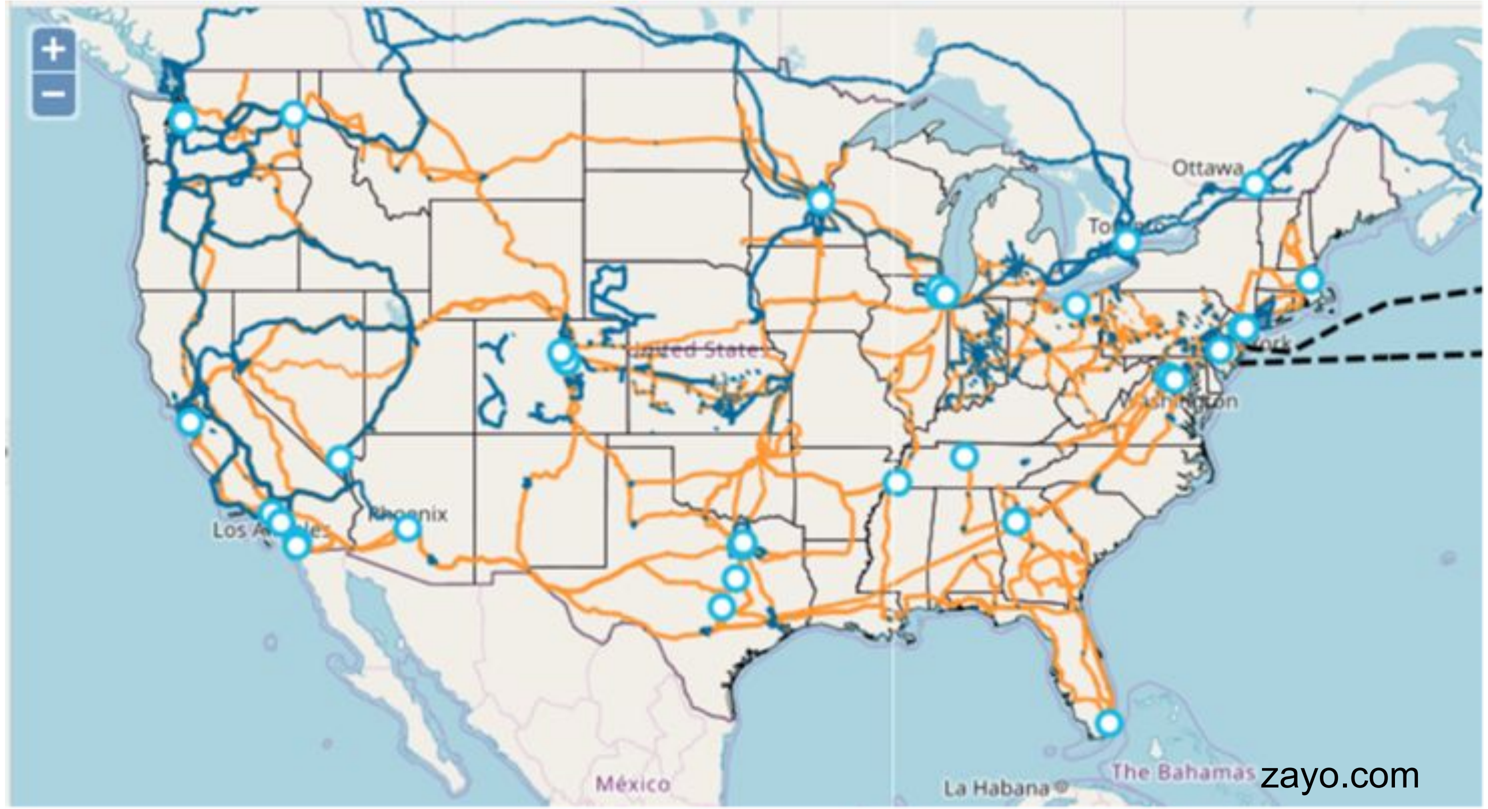
PON Access System



Submarine Fiber Cable Ship

The network today

- No point-to-point trans-continental links
- Carriers continue to build out large mesh network
- Connecting in regional and metro networks



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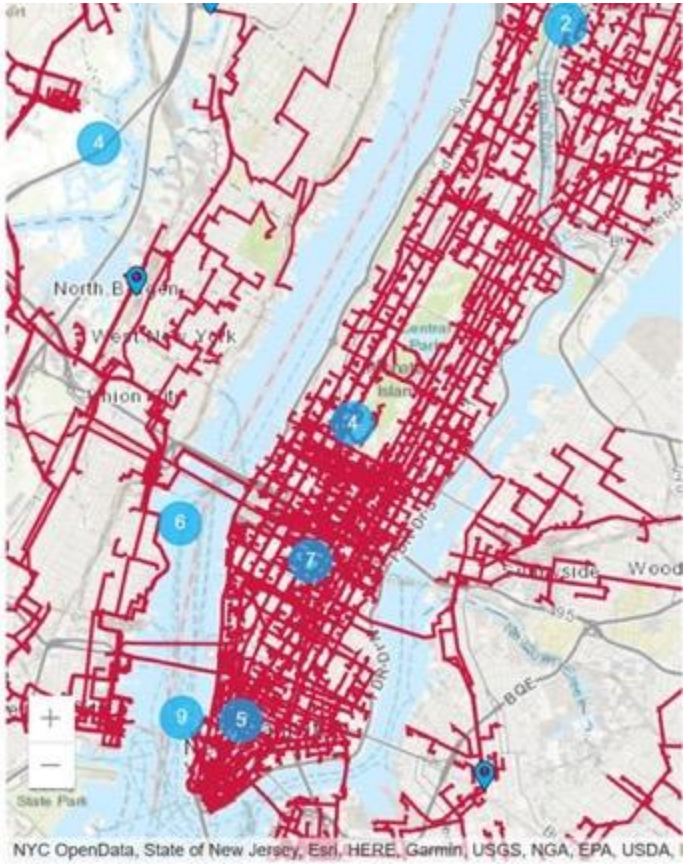
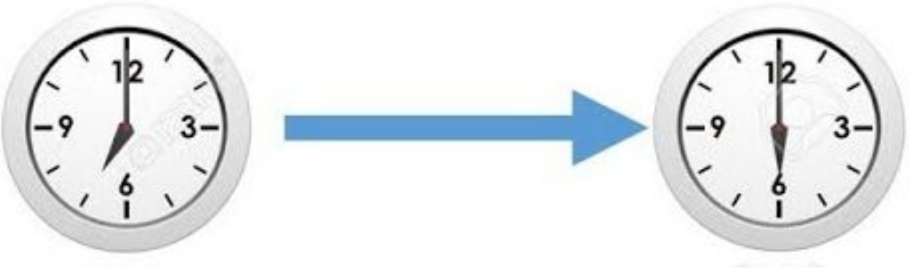
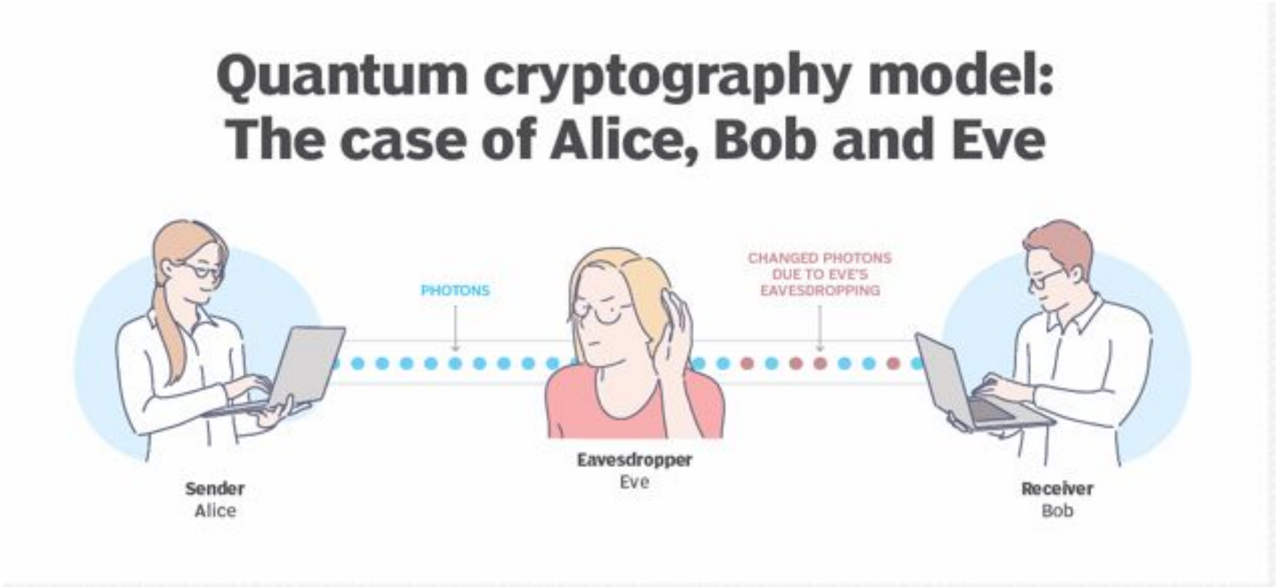
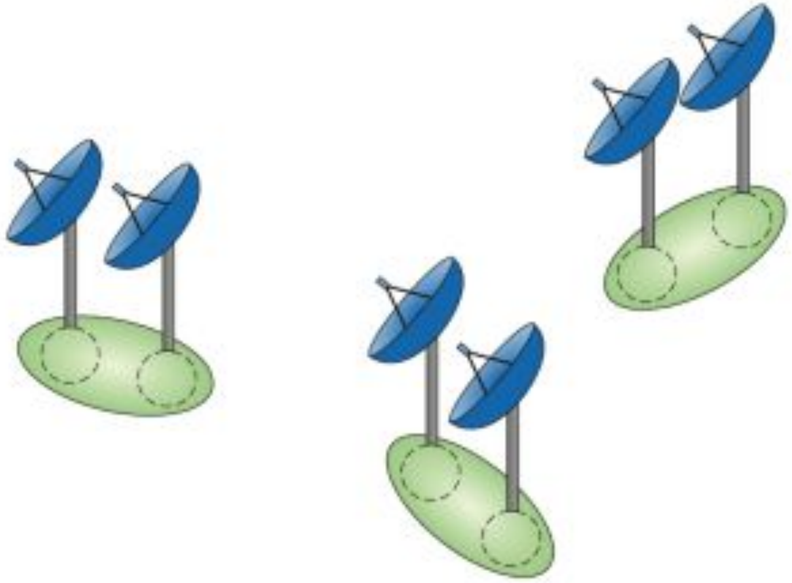


Why quantum networks?

- Secure communications and identification
- distributed quantum computing
- clock synchronization
- quantum sensor networks
- extended baseline for telescopes



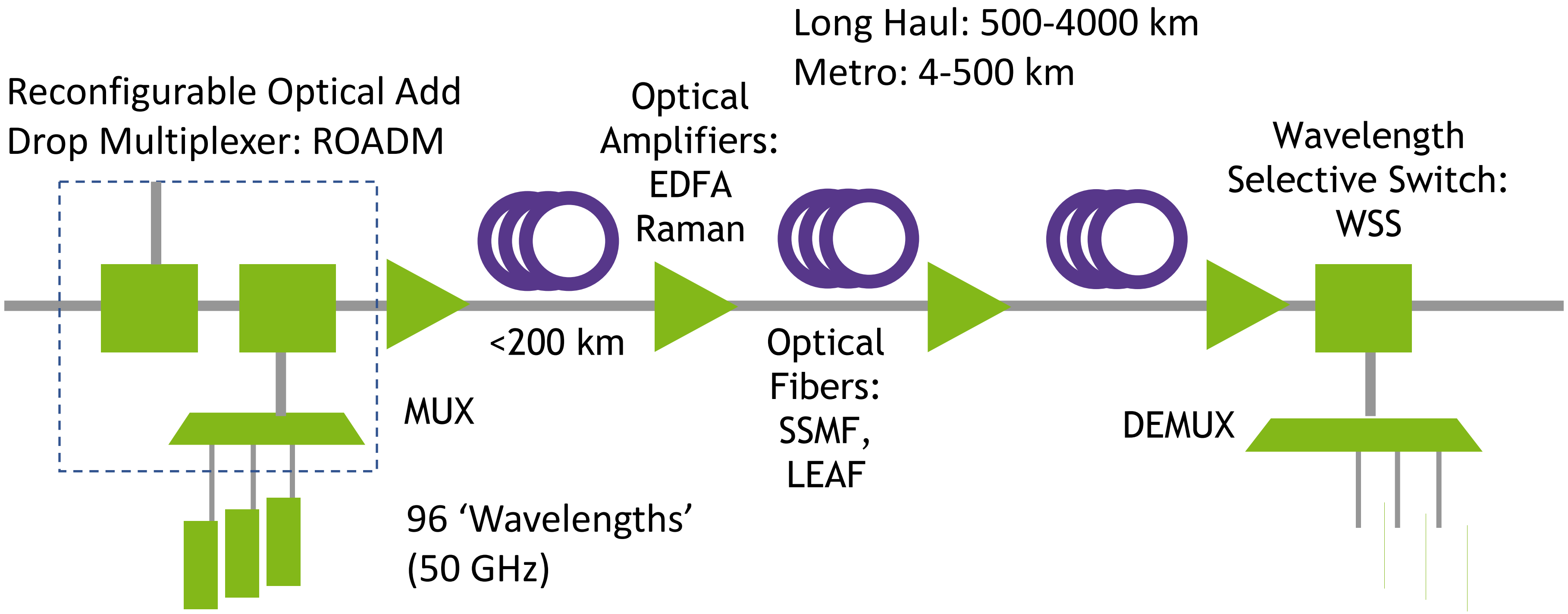




Classical optical transmission systems

Classical network components

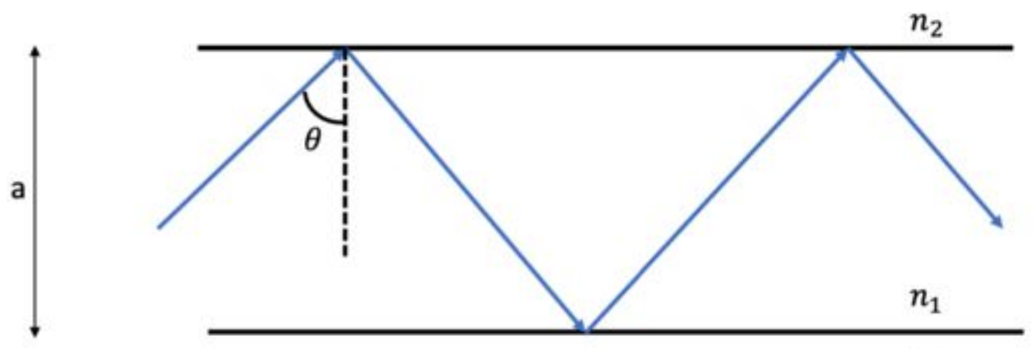
Long-haul and Metro networks

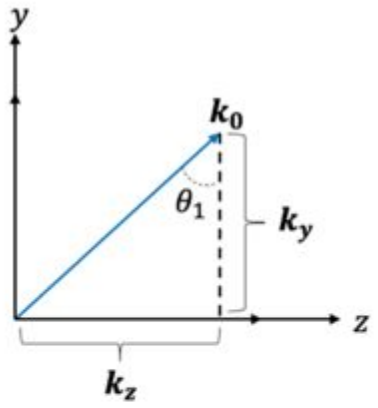


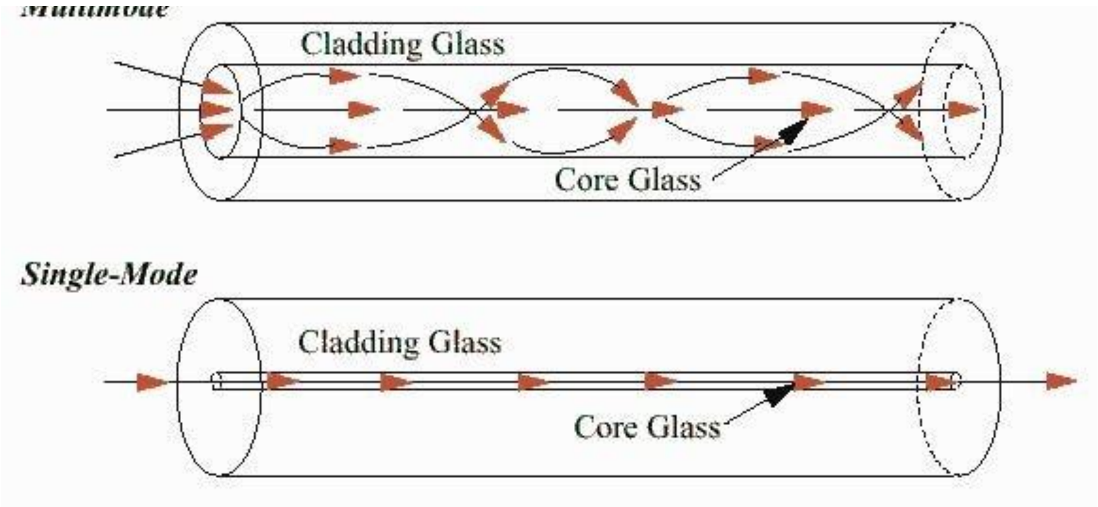
Optical fiber characteristics

Optical fibers

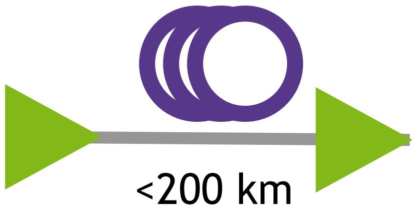
- Single mode
- Multimode
- Step index
- Graded index
- Material selection
  - Glass
  - Plastic
  - Doped fibers





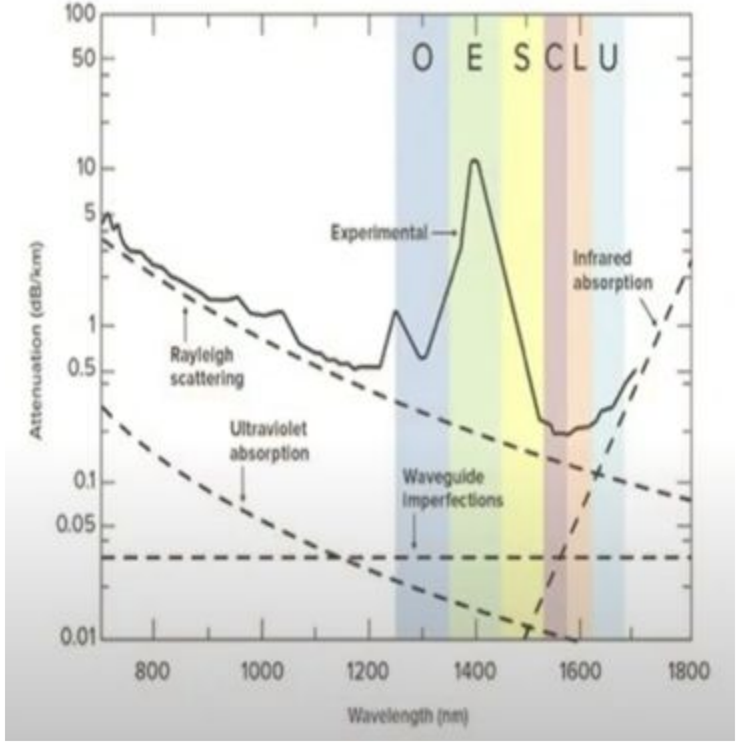


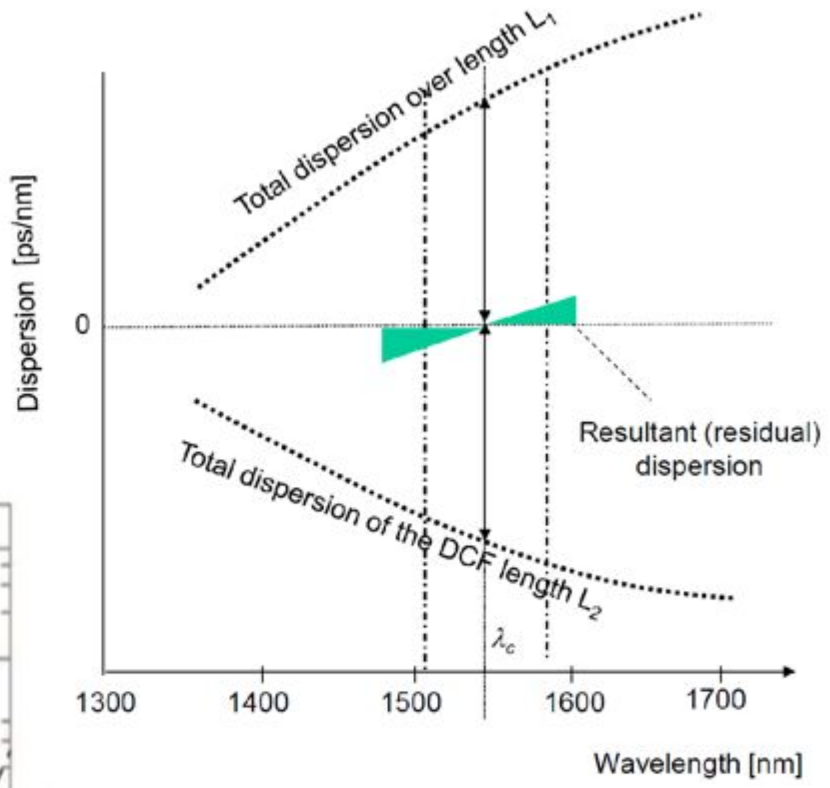
Optical fiber characteristics

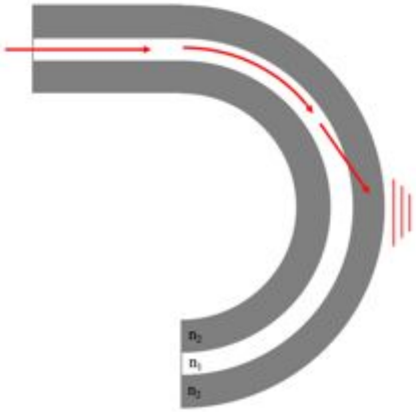


Loss mechanisms in fiber

- Absorption
- Scattering
  - Rayleigh scattering
  - MIE scattering
- Dispersion
  - Spatial (modal)
  - Chromatic
  - Polarization
- Bending loss







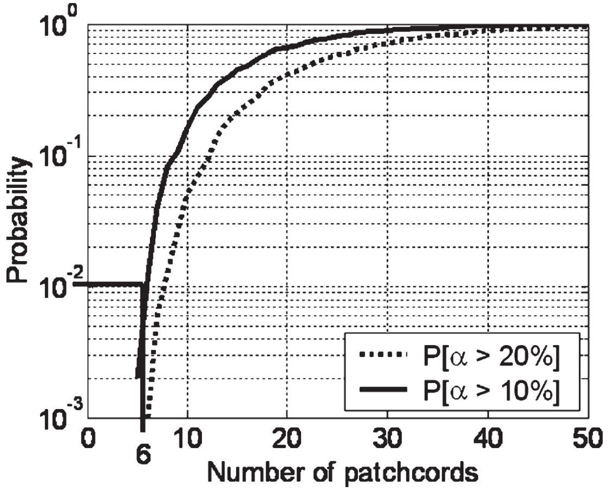
Managing Fiber Loss for Quantum Signals

Practical considerations, standard fiber types

- Loss coefficient varies slightly with wavelength and along the fiber length
  - No two spools are the same
  - Deployed fibers are spliced together every few miles–results in slightly higher loss per distance
    - Metro fibers can be very high loss: 0.3-0.4 dB/km (almost double!)
- Patch panels will kill you: some buildings have multiple patch panels with 0.5-1 dB/panel

Novel fiber types

- Bend insensitive fibers: important in buildings where bends can accumulate
- Avoid polarization maintaining fibers outside the lab due to noise from imperfect connectors
- Hollow core fibers promise lower loss!

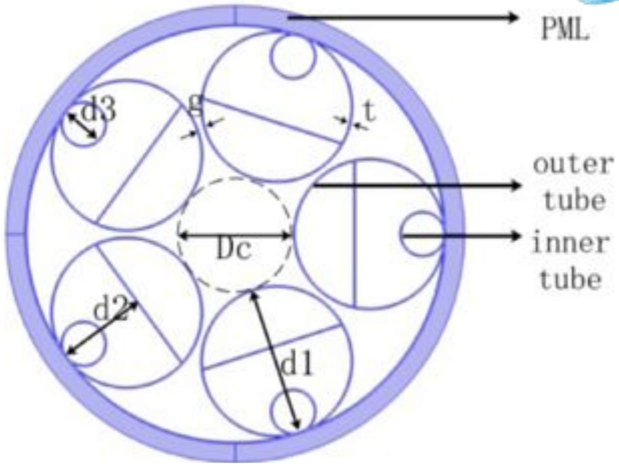


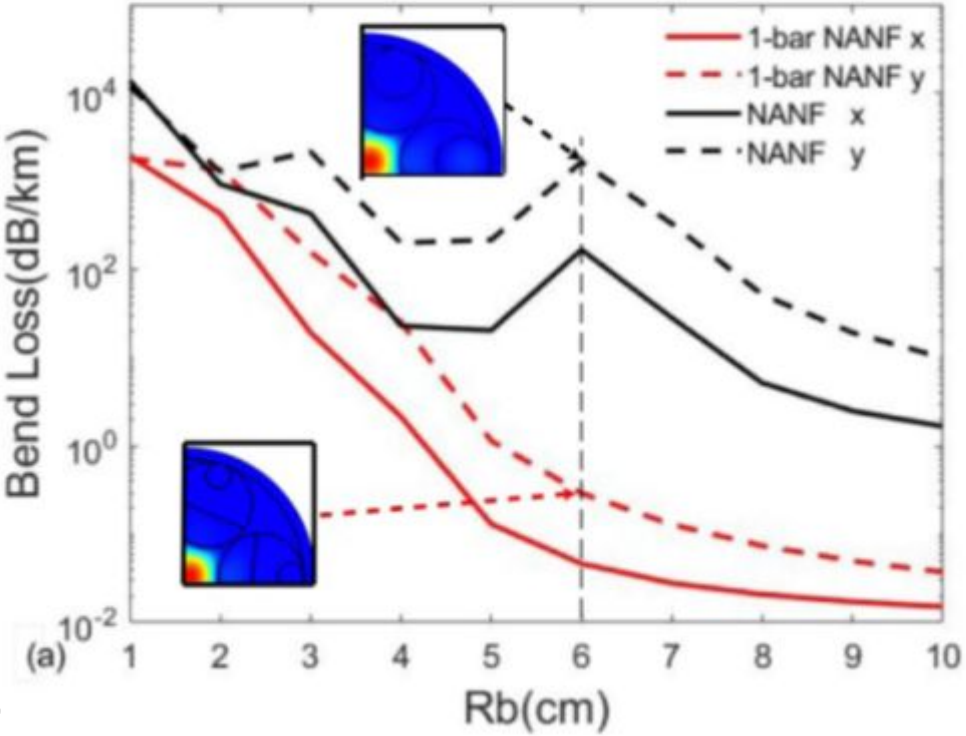
D. Penninckx, N. Beck, J. -F. Gleyze and L. Videau, "Signal Propagation Over Polarization-Maintaining Fibers: Problem and Solutions," in Journal of Lightwave Technology, vol. 24, no. 11, pp. 4197-4207, Nov. 2006

Hollow Core Fibers

- Decreased loss with hollow core fibers
  - 0.18 dB/km at 1550 nm
  - 0.22 dB/KM at 1310 nm
  - Potential for order of magnitude lower loss than common fibers today
- Lower nonlinear penalties

- Increased bend loss - limits applications in metro network systems
- Cannot create EDFA or Raman amplifiers



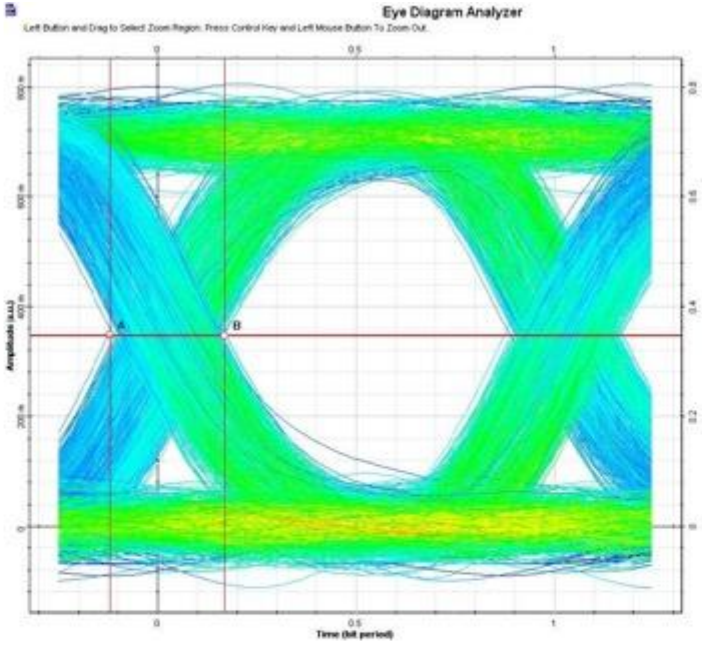


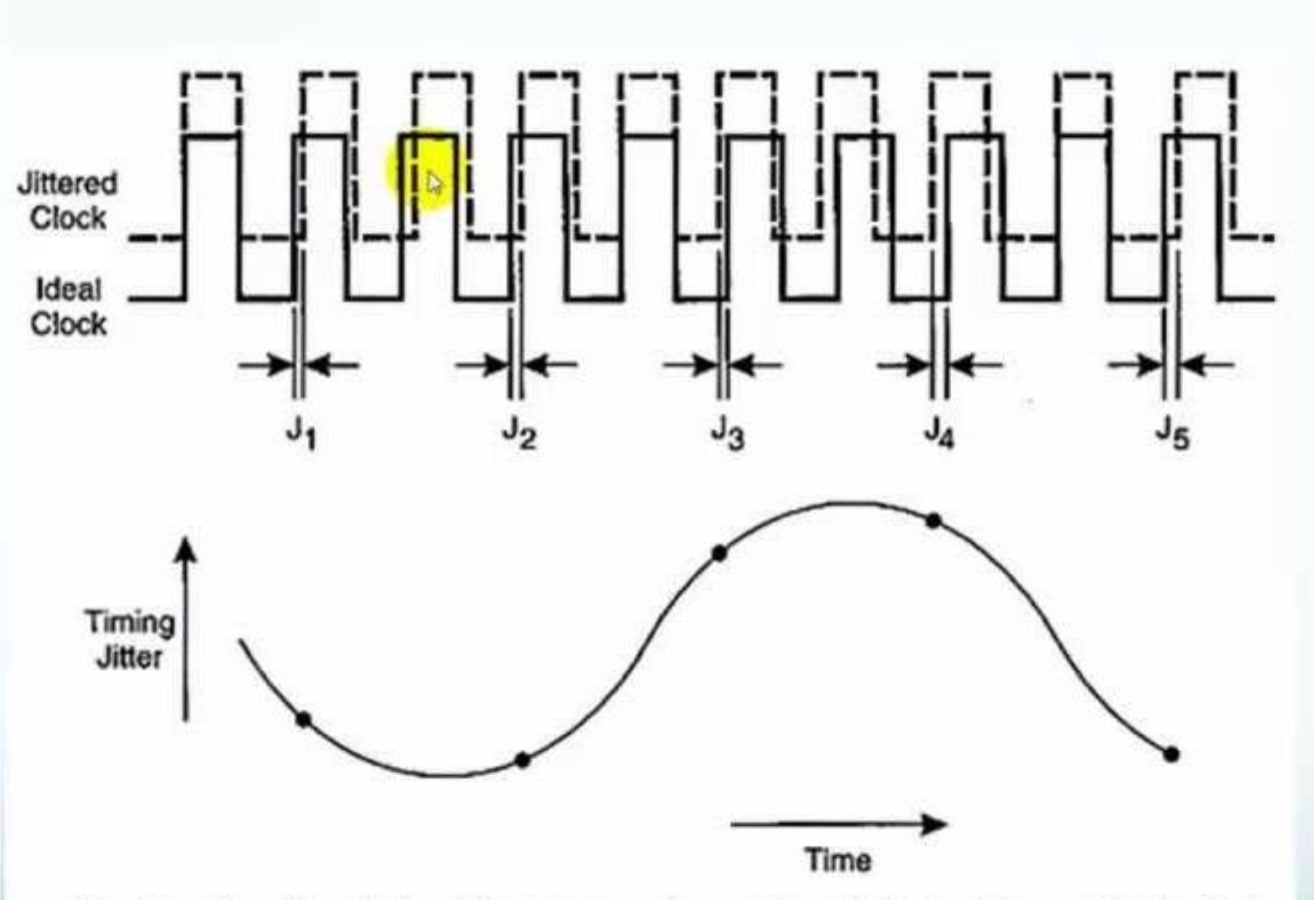
Jasion et. al. OFC 2020

Dispersion and propagation

Jitters in optical networks

- Nonlinear interference signals
- Group delay variation



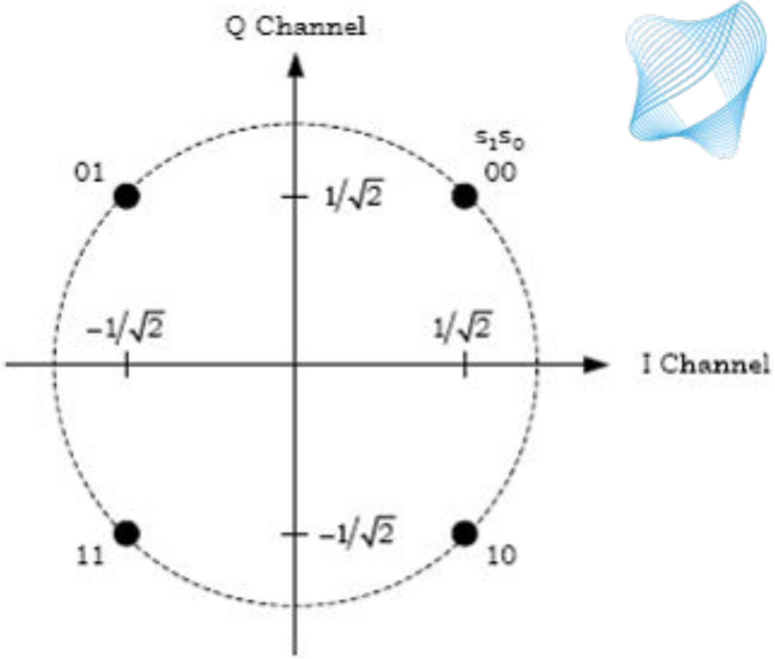


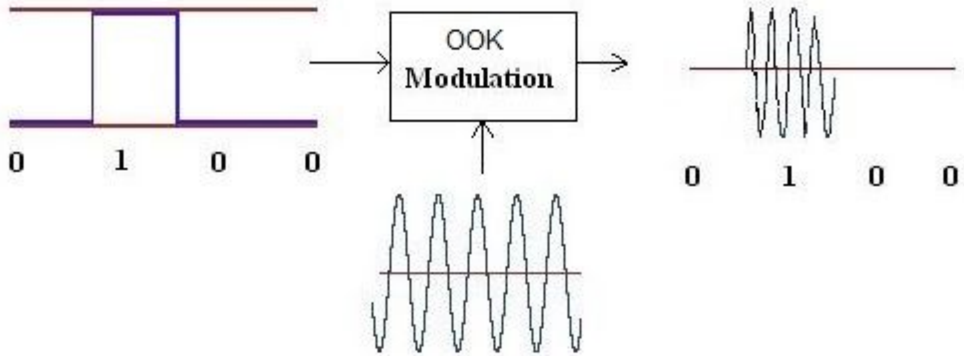
Jitter time function derived from comparing a jittered clock with an ideal clock.

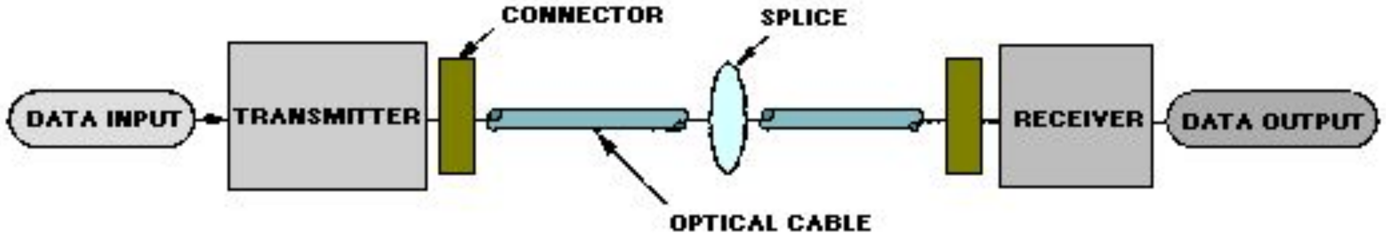
Optical transceivers

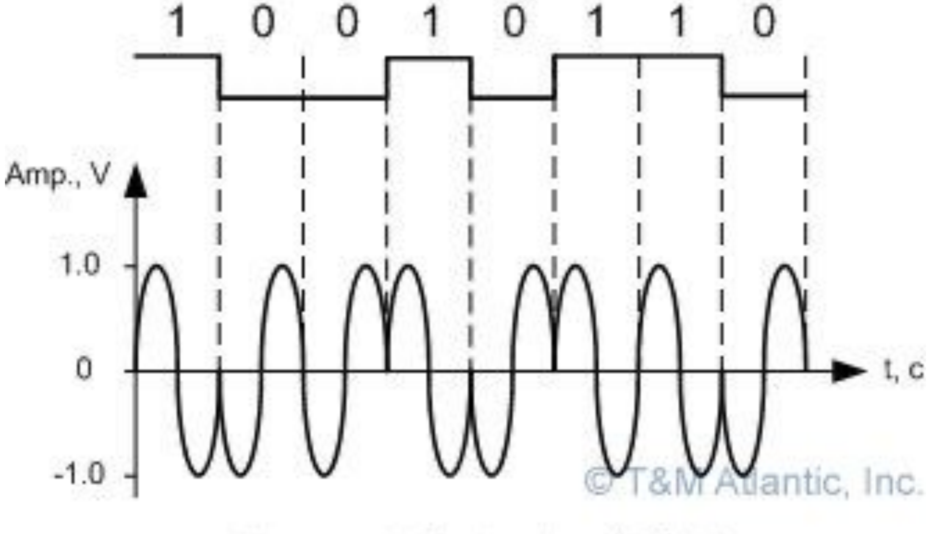
Modulation formats

- On/Off keying
- Phase shift keying
- QAM Keying









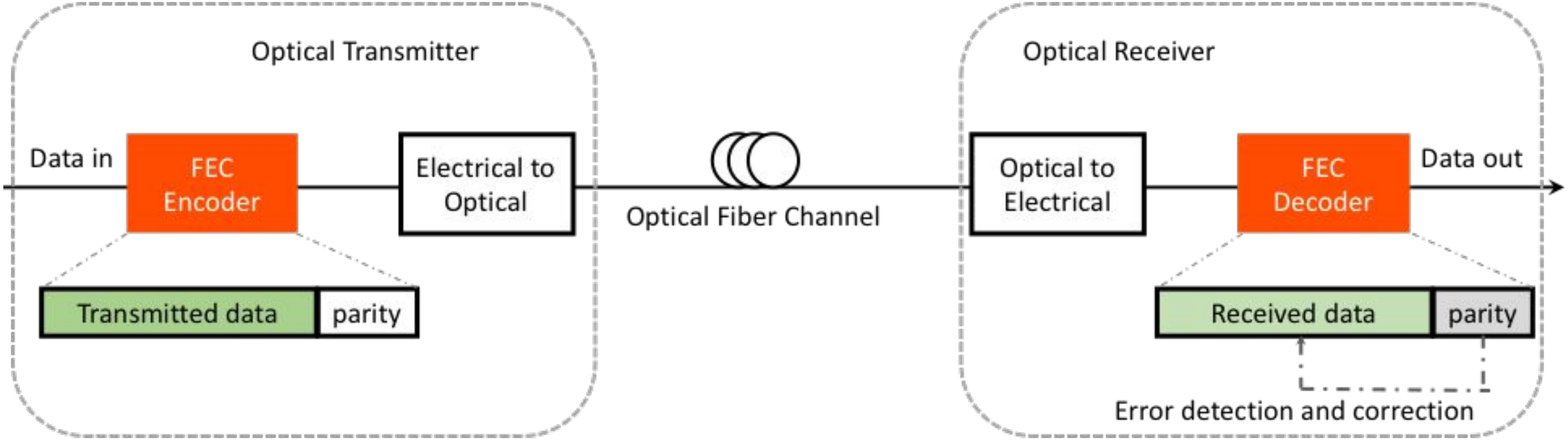
Phase shift keying (PSK)

Kishore et al. ICICSP 2019

Optical transceivers

Forward error correction

- Low density parity check (LDPC) in optical systems

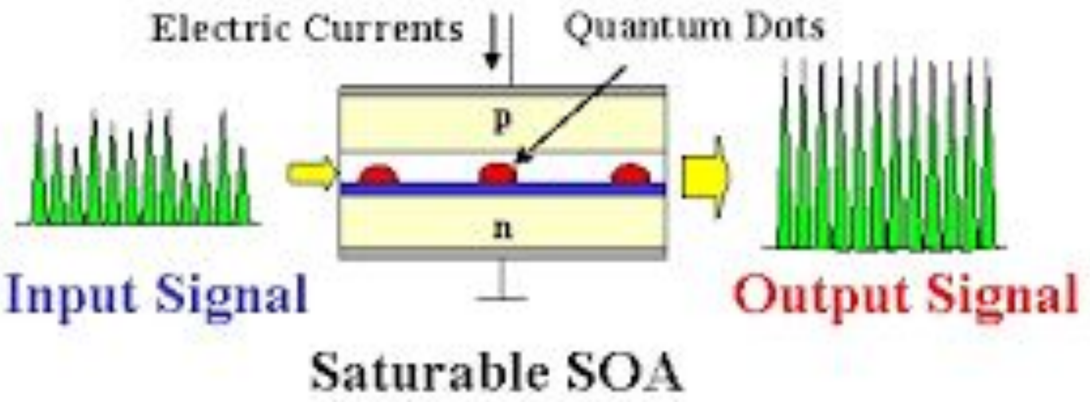


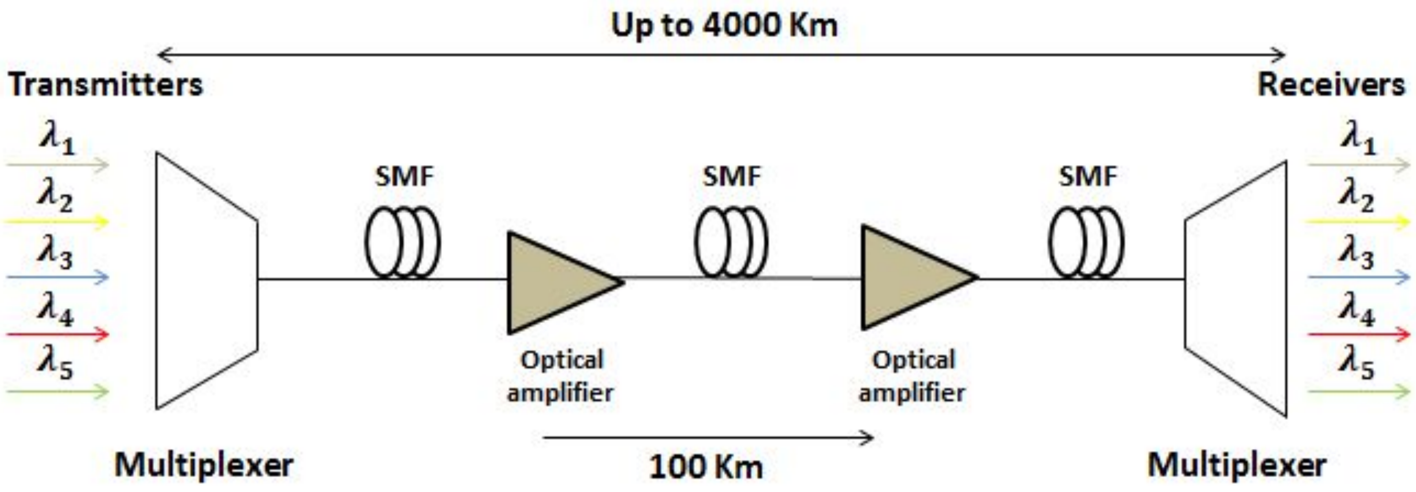
Optical amplifiers

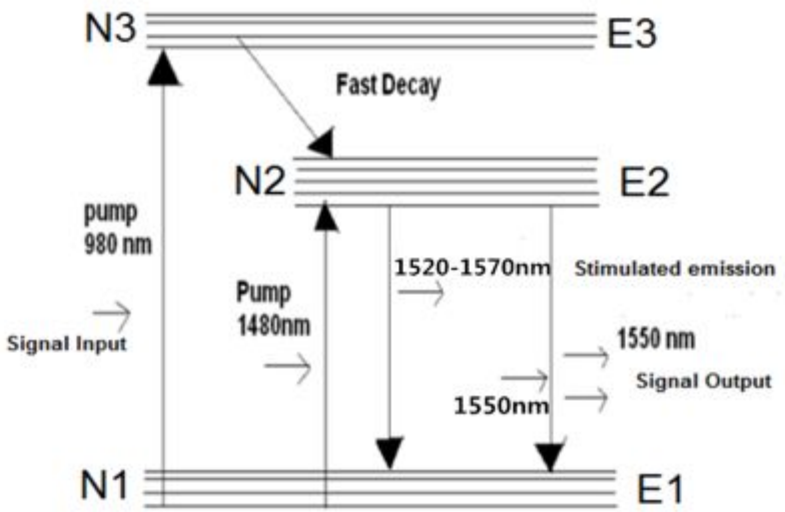
Applications in optical networks

EDFA

Semiconductor amplifiers







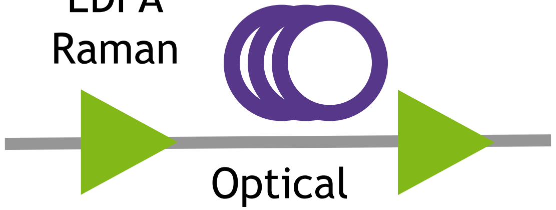
Mishra et al., IEEE Access, 2022.

Raman scattering

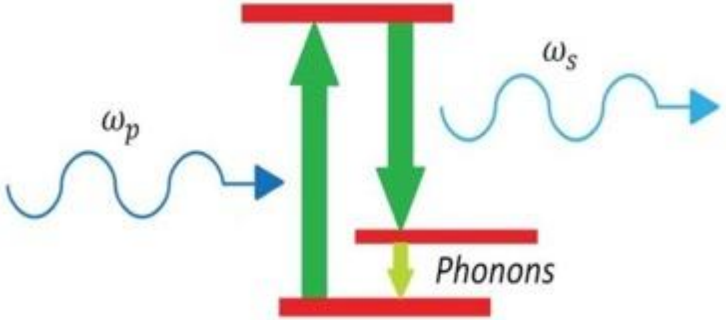
- Spontaneous raman scattering
- Stimulated raman scattering for amplification
- Distributed versus discrete raman amplifications

Optical Amplifiers: EDFA Raman

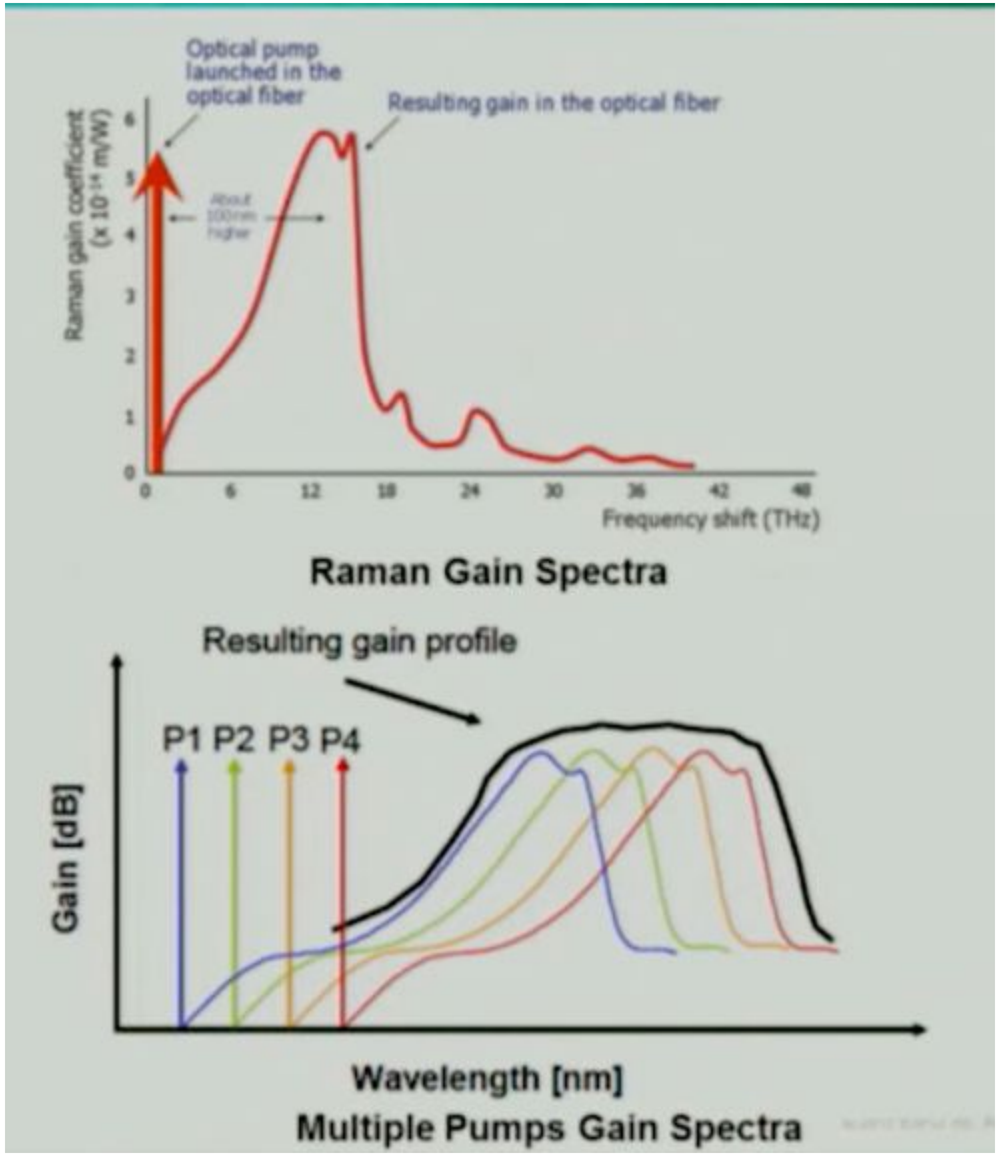
Long Haul: 500-4000 km
Metro: 4-500 km



Optical Fibers: SSMF, LEAF



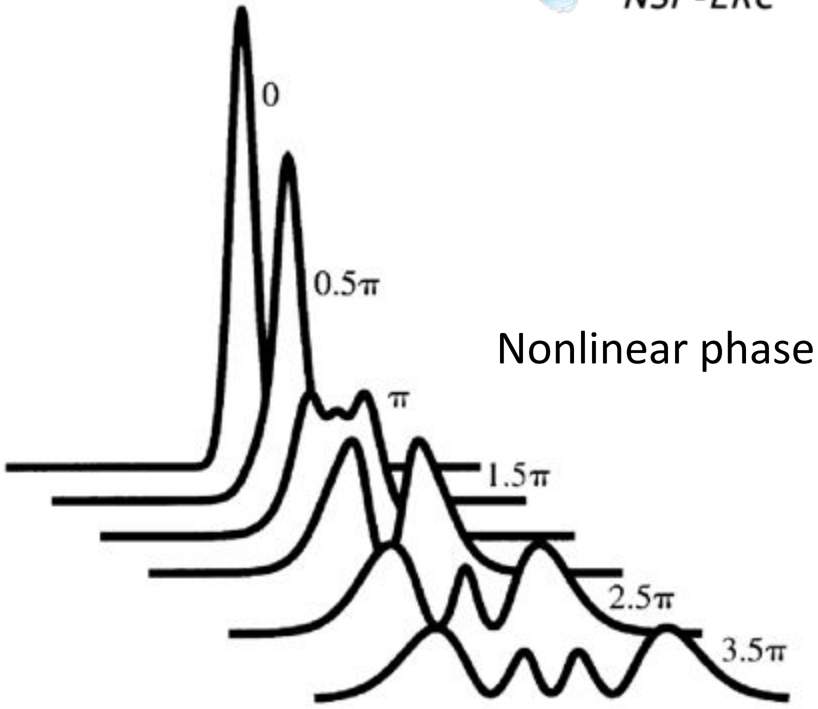
Krutin, et al., ELNANO 2020.



Nonlinear optical effects

- Optical Kerr effect
  - Self Phase modulation
  - Cross phase modulation
- Implications in optical networks
  - Cross talk

Spectral broadening at zero dispersion:



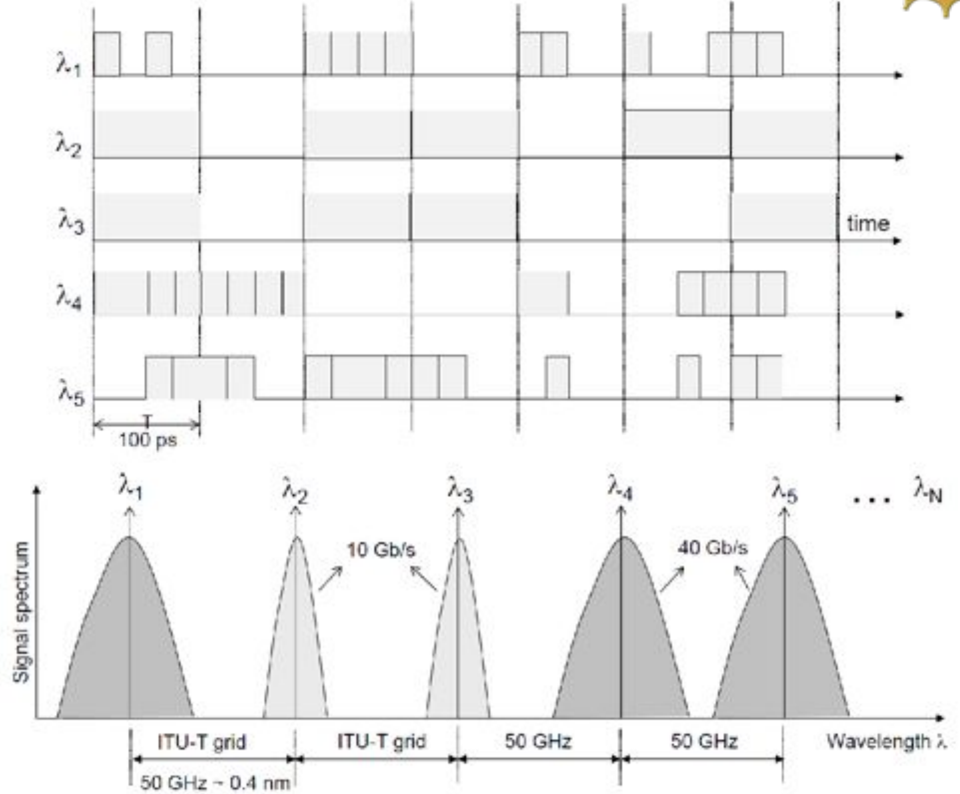
Nonlinear phase

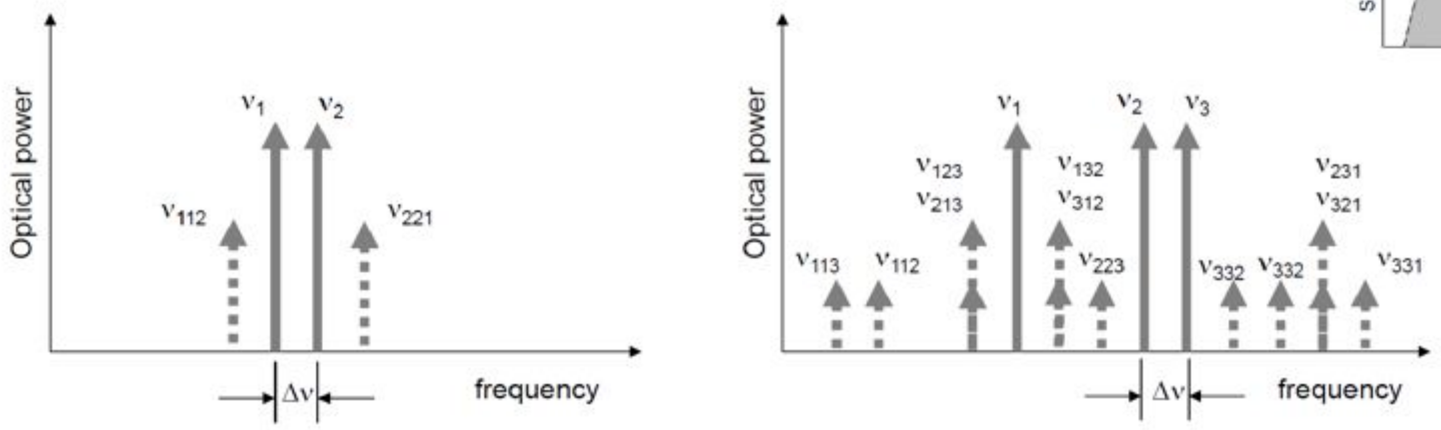
Table 3.1
Typical values of optical fiber nonlinear parameters

Fiber type	*Effective area* A_{eff} [μm^2]	*Nonlinear coefficient* γ [W^{-1}km^{-1}] *at* 1,550 nm
SMF-28	80	1.12–1.72
AllWave	80	1.12–1.72
LEAF	72	1.23–1.92
Vascade	101	0.9–1.36
TrueWave-RS	50	1.78–2.75
Teralight	65	1.37–2.11

Nonlinear optical effects

- Wavelength division multiplexing (WDM)
- Four wave mixing





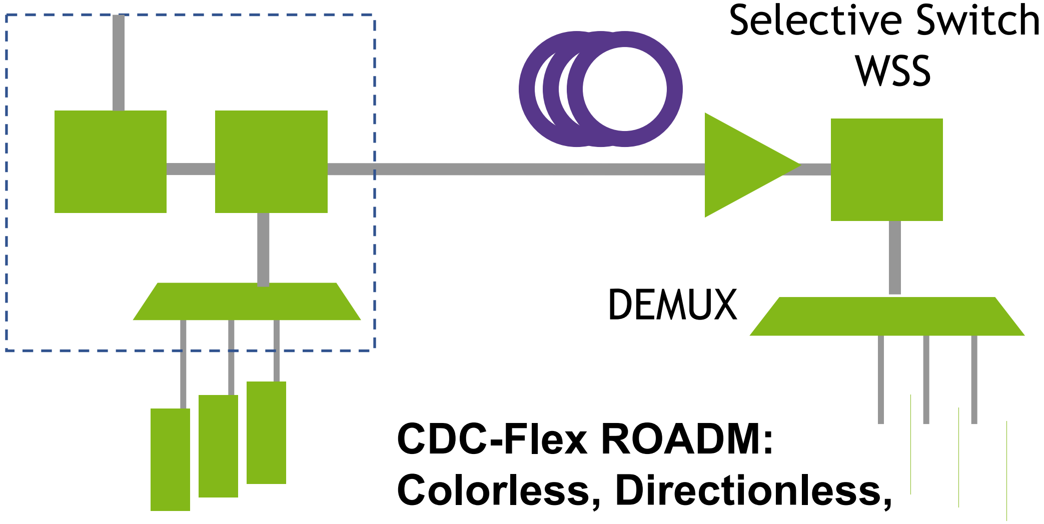
(a) Degenerate case

(b) Nondegenerate case

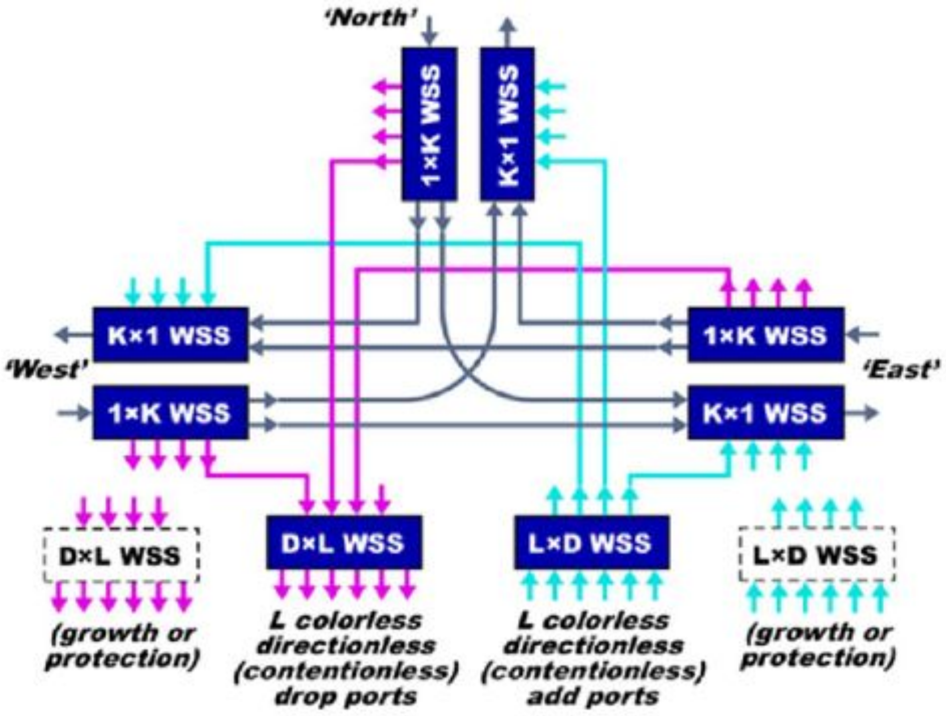
ROADM: Reconfigurable Optical Add Drop Multiplexer Node

Reconfigurable Optical Add Drop Multiplexer: ROADM

Wavelength Selective Switch: WSS



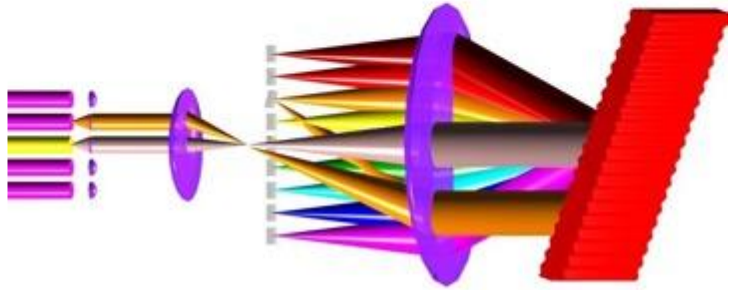
CDC-Flex ROADM: Colorless, Directionless, Contentionless, Flexgrid ROADM



Egress Traffic

Ingress Traffic

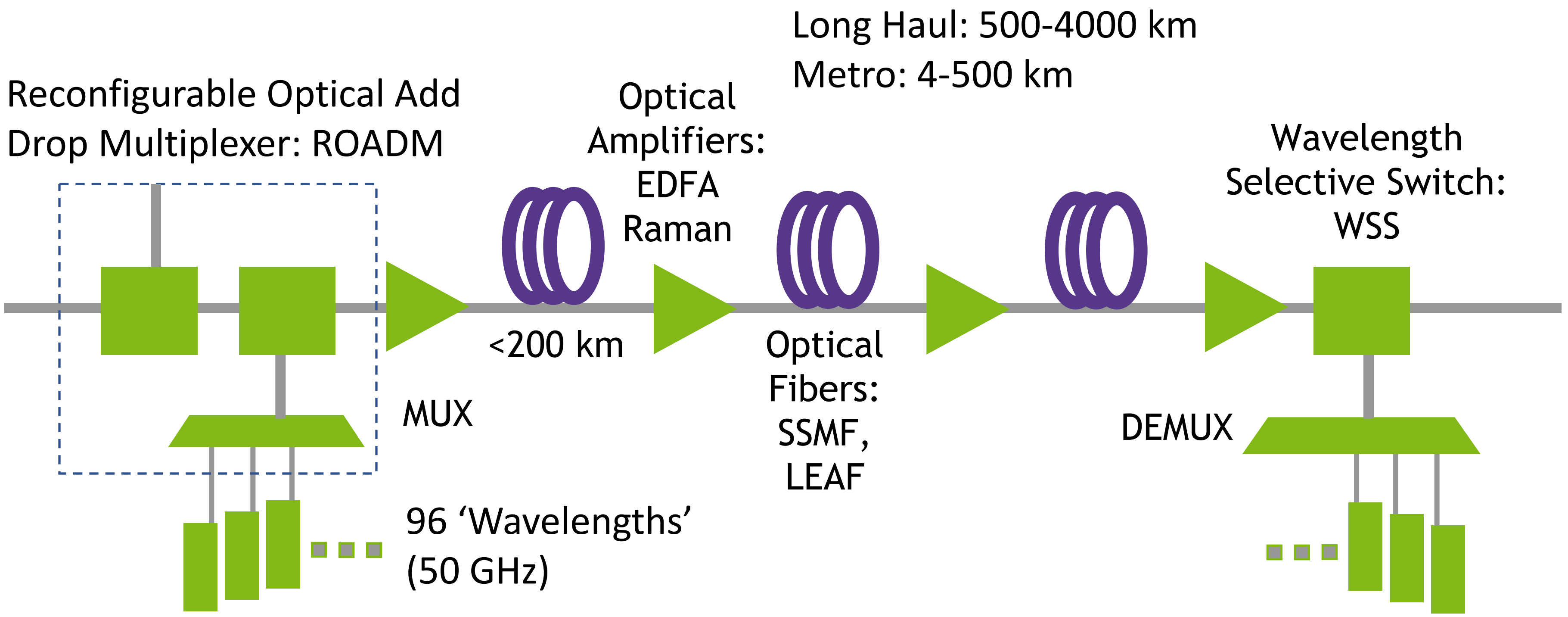
Wavelength Selective Switch (WSS):



Marom et. al. JOCN 2017

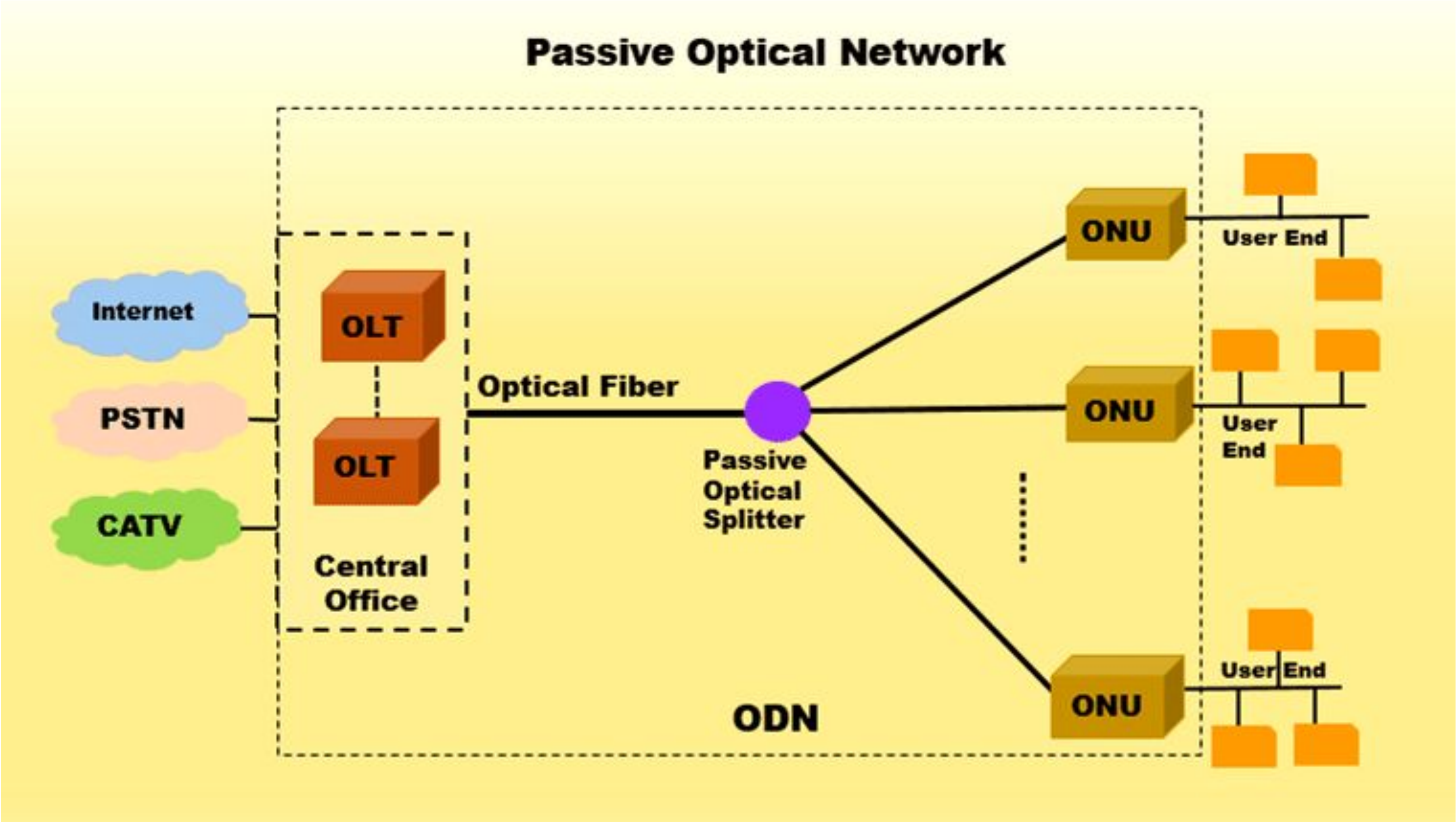
Classical optical network designs

- WDM/ROADM



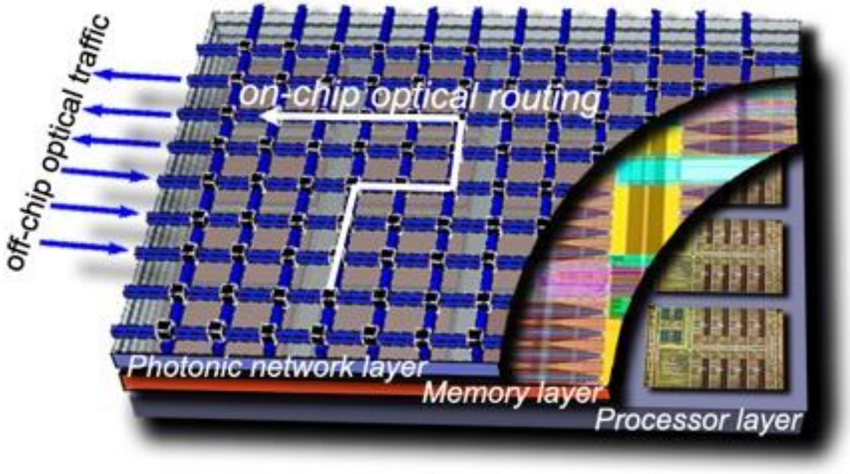
Classical optical network designs

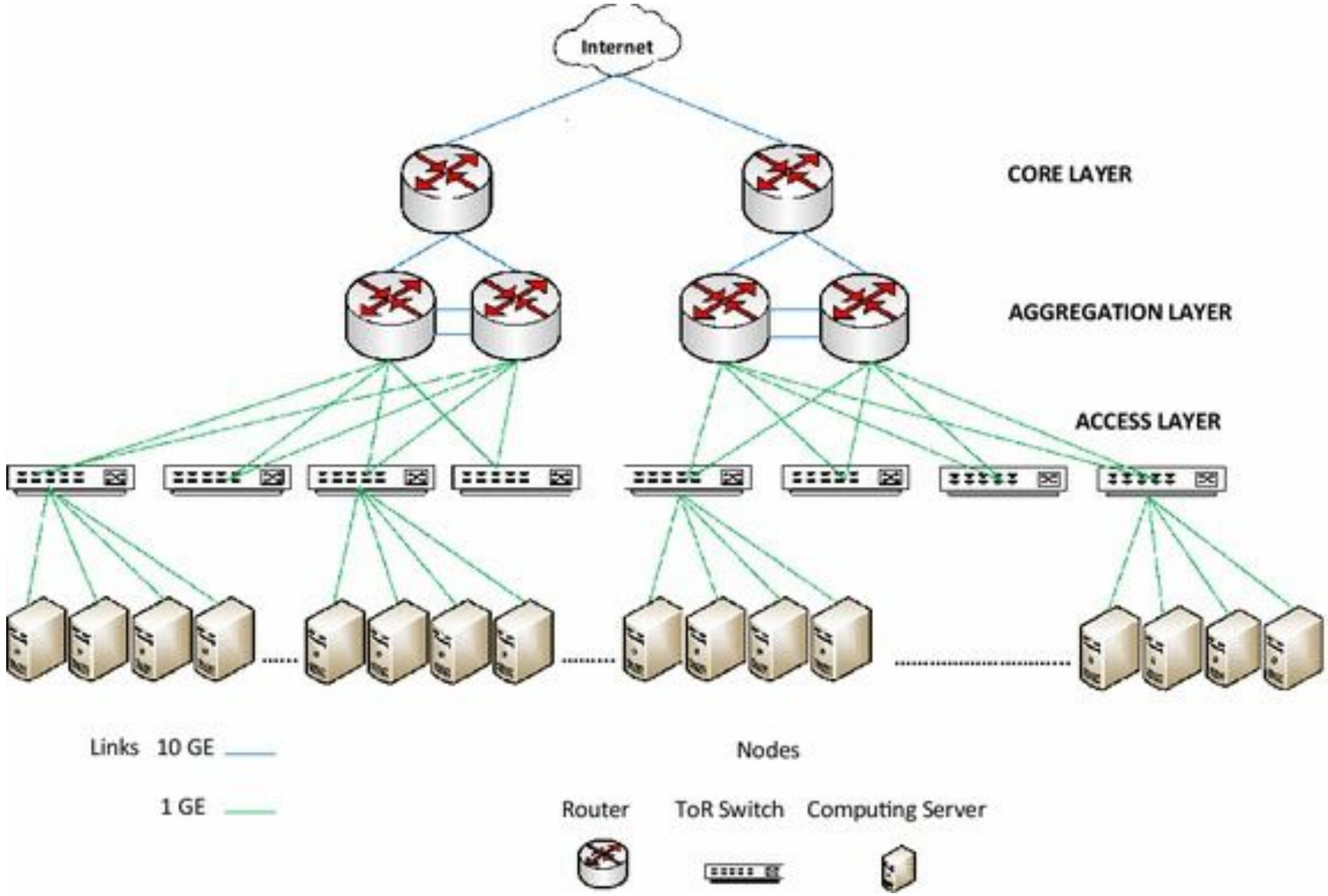
- Passive Optical Networking (PON) systems



Classical optical network designs

- Optical interconnects
- Data center networks





Communication systems and network engineering

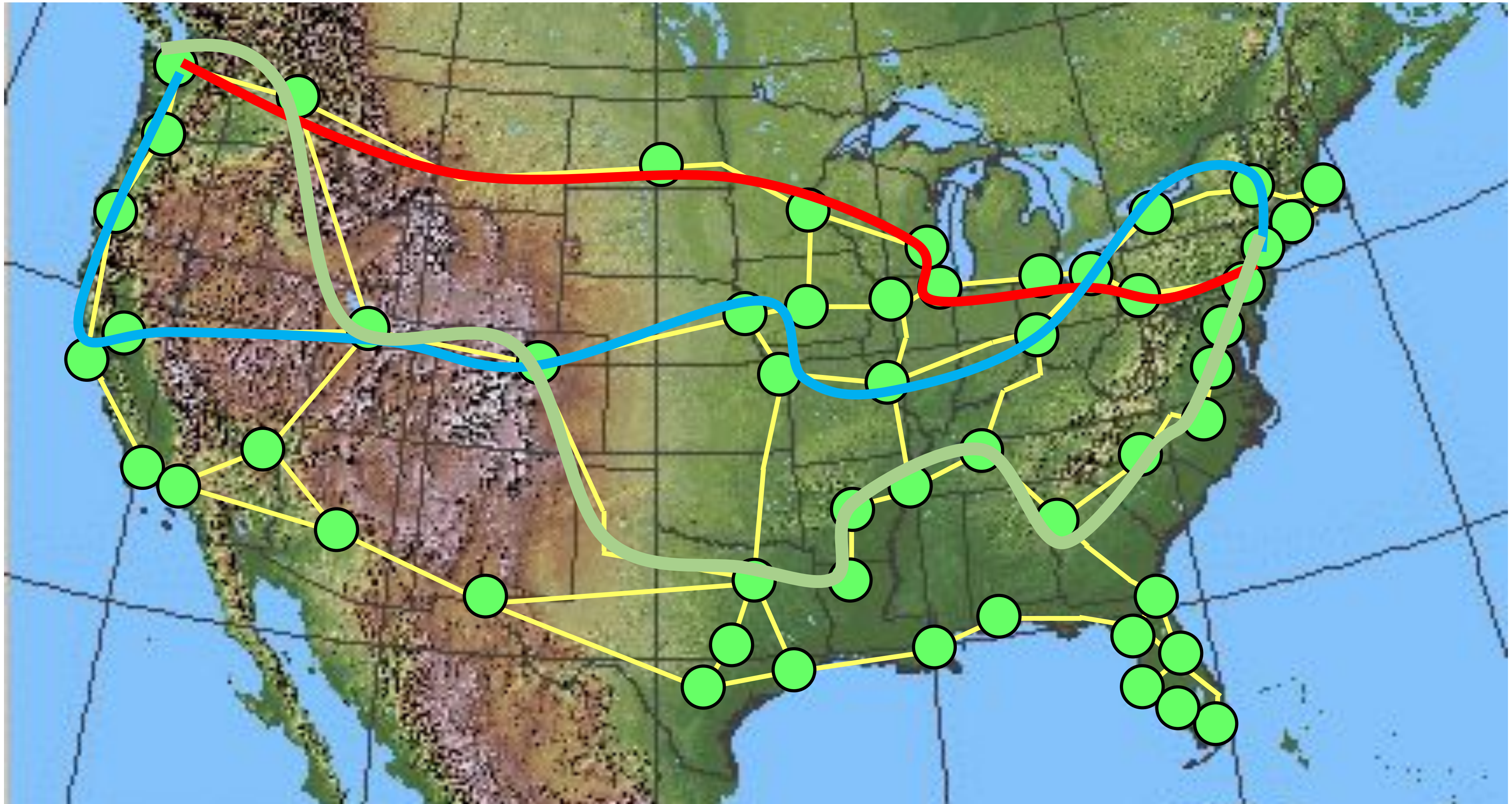
A Few Notes on Classical Optical Networks

- It doesn’t matter when bits or photons arrive at nodes nor what their polarization is
  - Clocks are synchronized after demodulation at end points
  - Data is only read at the end points, after full demodulation
- Amplified receivers: only care about the SNR, not the losses
- Control loops maintain optimum launch power into fibre spans for each channel and maintain constant gain in amplifiers
- Bits flow continuously, average optical power per channel is constant
- Optical switches are used to configure the system, not to switch bits (operate on minutes/hours time scales)

RWA (RSA): Routing & Wavelength (Spectrum) Assignment

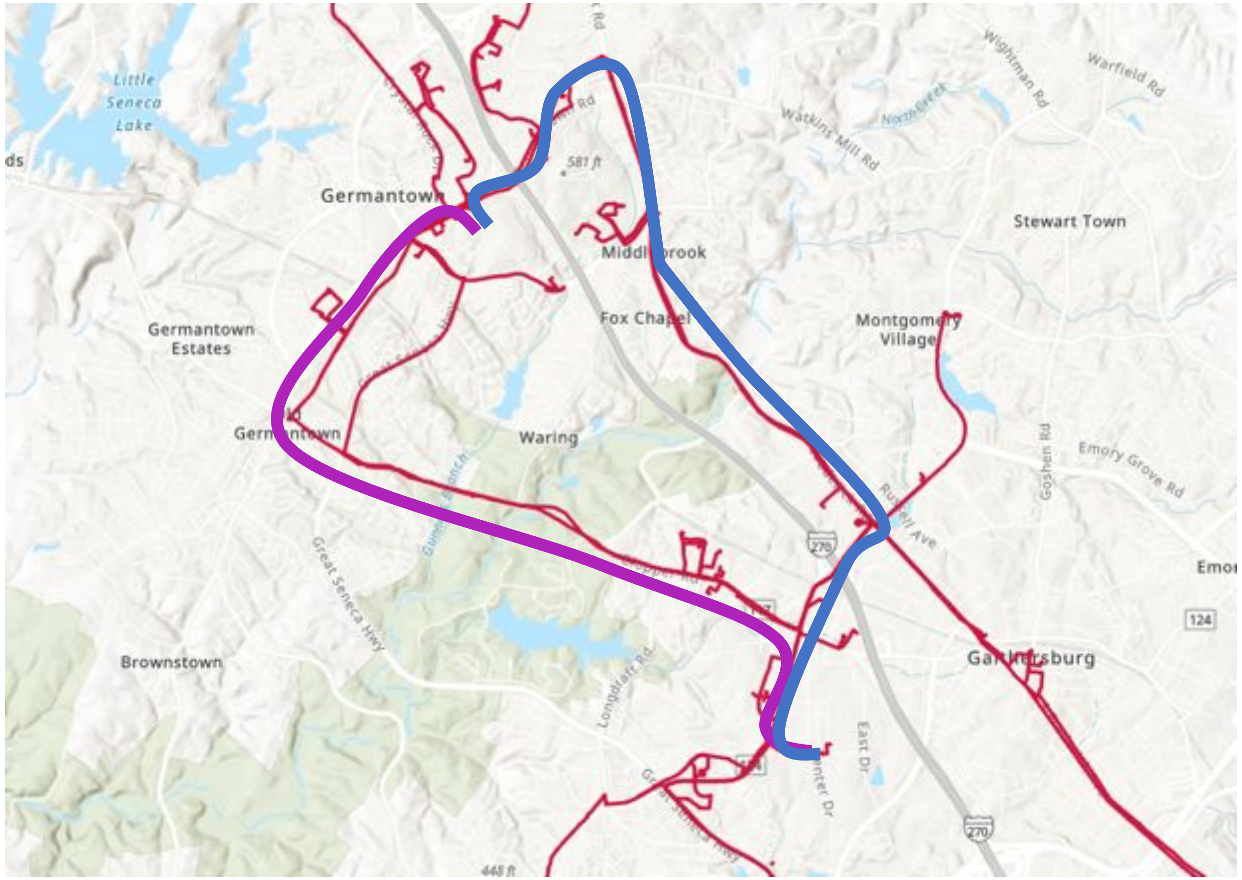
Center for Quantum Networks NSF-ERC

- How to connect Seattle to NYC?
- Use Quality of Transmission (QoT) estimate to choose route & wavelength



Metro/Regional Network RWA

- How to connect Quantum Computers at NIST and DOE?



crowncastle.com 2020

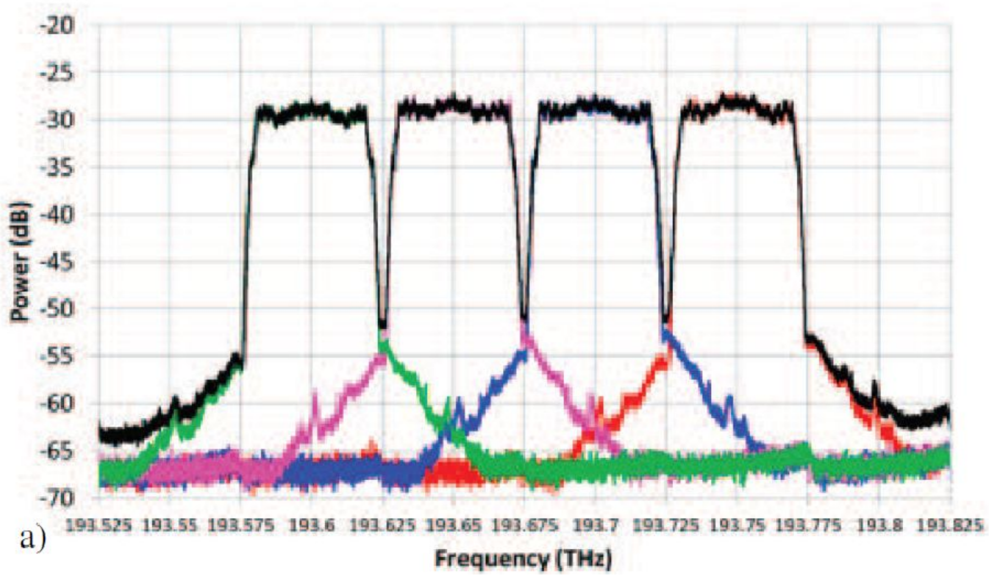
Constraints on Routing Wavelengths

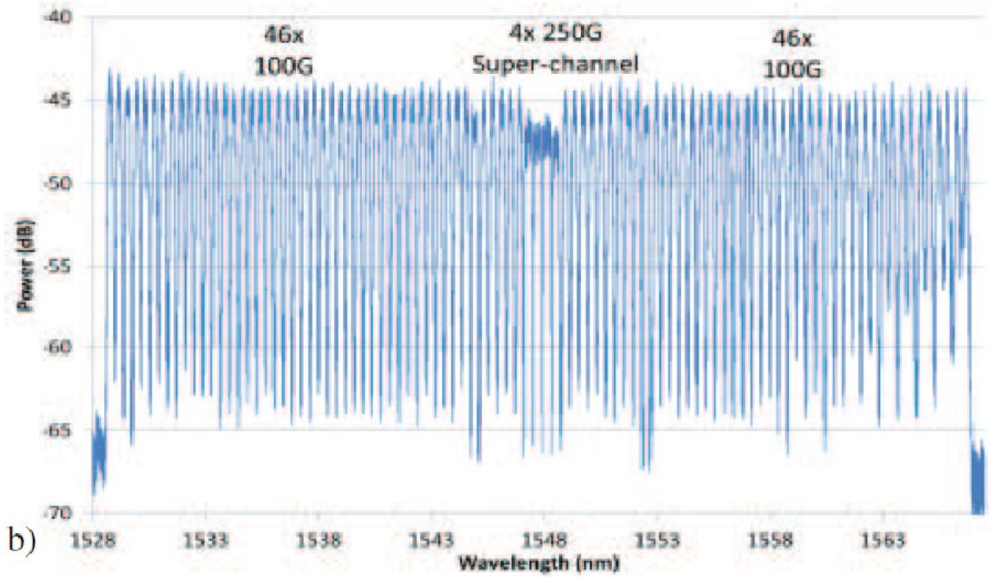
- Wavelength continuity: no wavelength switchers
  - Results in ‘wavelength blocking’
- No closed loops: create a laser
- Timing jitter: refractive index variations along fiber
  - Use sync bits in header
- Accumulation of amplifier noise
  - Optical signal to noise ratio
- Nonlinear fiber response
  - Scramble bits to remove pattern effects, keep power low
  - Self-phase modulation (SPM) and cross-phase modulation (XPM)
  - Raman scattering: tilt amplifier gain to compensate
- Other effects:
  - Dispersion: handled by DSP in receiver
  - Polarization dynamics (PDL/PDG): polarization diversity, margins
- Dynamic effects:
  - Optical power dynamics: cross-channel
  - Gain saturation: EDFA & Raman

How dense is WDM?

92x100 Gb/s PM-QPSK + 1 Tb/s Superchannel

800 Gb/s transceivers in commercial production





4x40Gbaud 1 Tb/s PM-16QAM Superchannel:

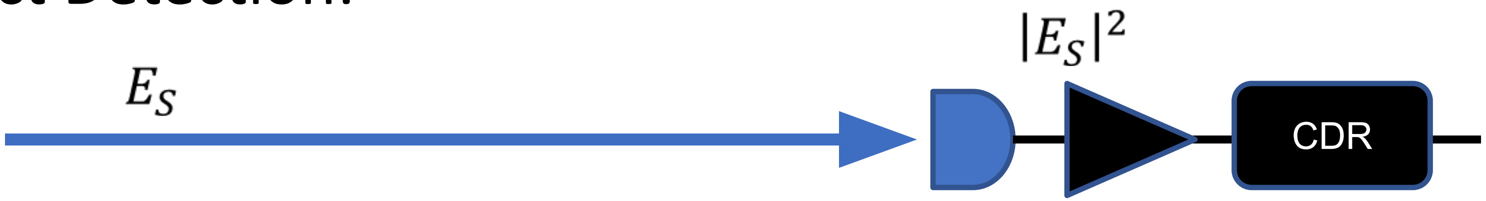
625 km, 6 spans w/ Raman

CFP2-ACO

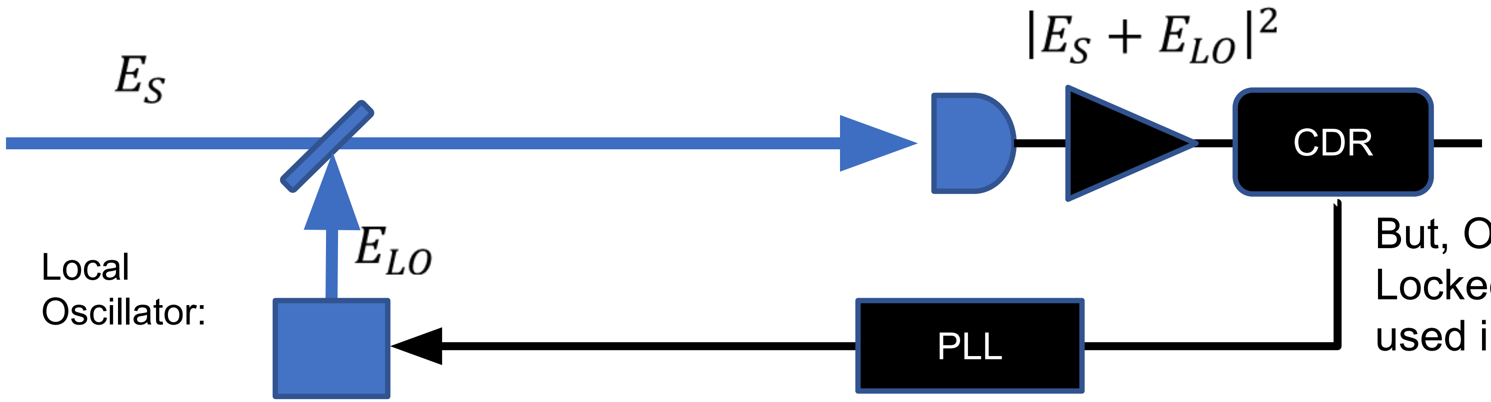
Fludger, et. al. OFC 2016

Detection Methods

- Direct Detection:



- Coherent or Phase-Sensitive Detection:

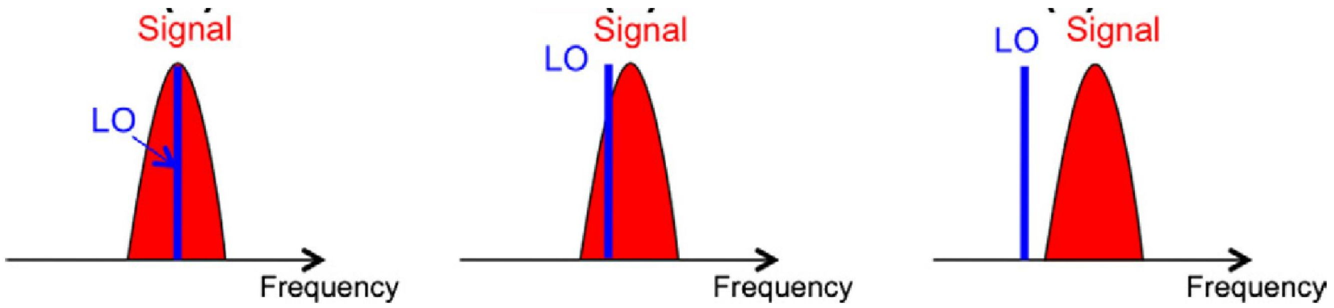


But, Optical Phase Locked Loops not used in practice

- Problem: After fiber transmission polarization and phase are both rapidly varying!!

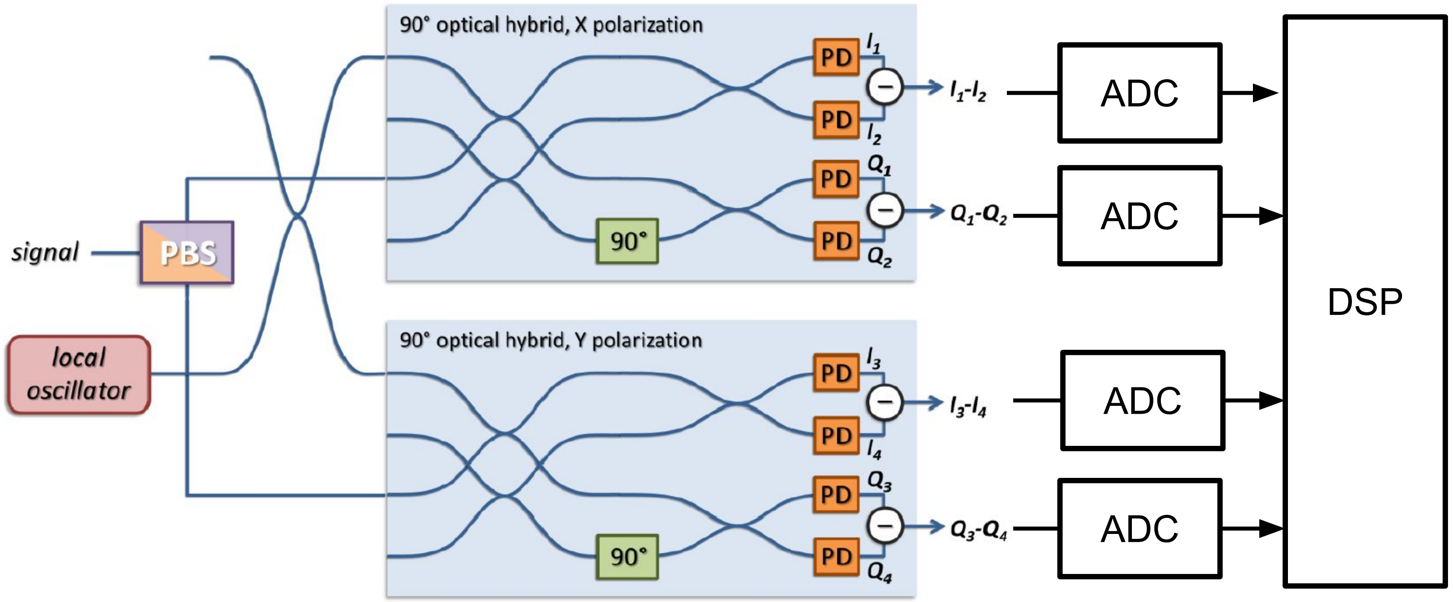
Types of Coherent Detection

- Homodyne: Signal and LO are at the same frequency
- Heterodyne: Signal and LO are at different frequencies—create a new signal at frequency difference, ‘IF’: intermediate frequency
- Intradyne: Signal and LO different in frequency by a small amount that can be corrected for in the electronics
  - Use fast digital signal processing (DSP) to track signal phase and frequency
  - DSP provides carrier phase recovery: replaces PLL



‘Coherent Receiver’

- Polarization diversity
- Digital signal processing compensates: (in this order usually)
  - Group velocity dispersion
  - Timing jitter (clock recovery)
  - Polarization drift, PMD
  - Frequency and phase drift (carrier recovery)
  - Some single channel nonlinearities (SPM)



Classical Information Rates

- Bit Rate or Data Rate, R_B
  - Bits refer to binary information

$$R_B = R_S Log_2 M$$

- Symbol rate (Baud rate), R_S
- M Constellation Points

- Information Rate or 'data rate': R_I
  - Takes into account 'overhead' bits used for forward error correction
  - Actual rate at which application data is transmitted
  - η_C is code rate or fraction of data used for 'information'

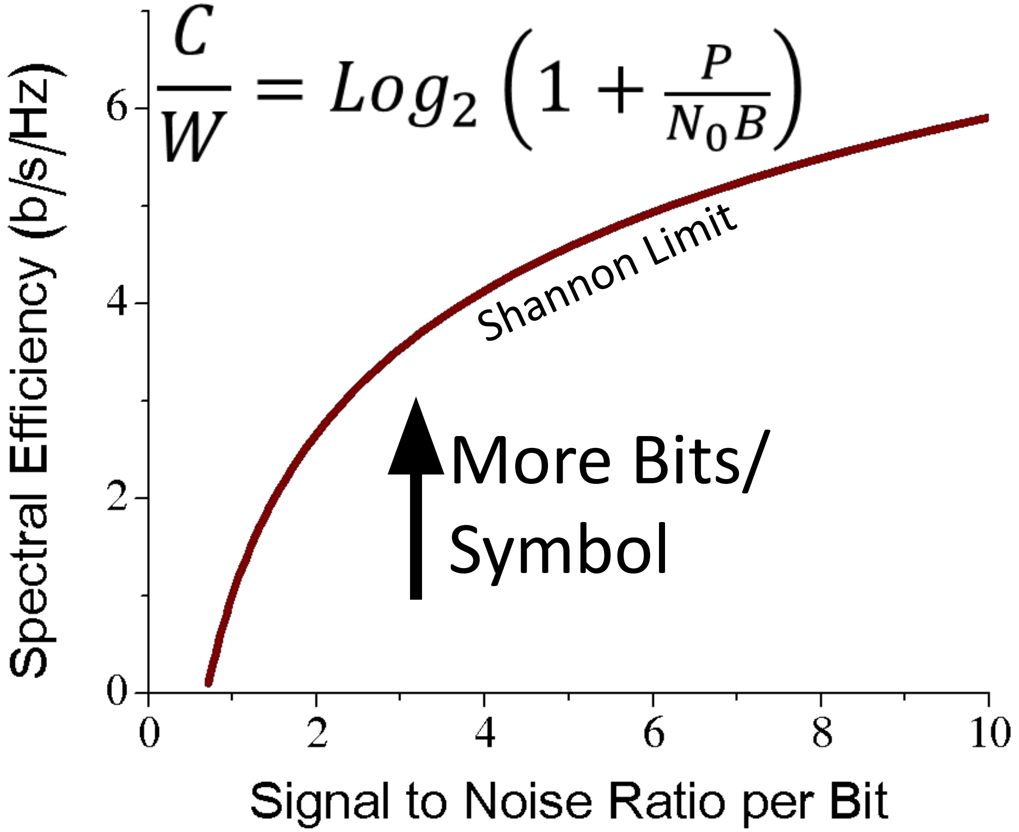
$$R_I = R_B \eta_C$$

Spectral Efficiency

Additive white Gaussian noise channel

$$\frac{C}{W} = Log_2\left(1 + \frac{P}{N_0 B}\right)$$

Mod. & Coding

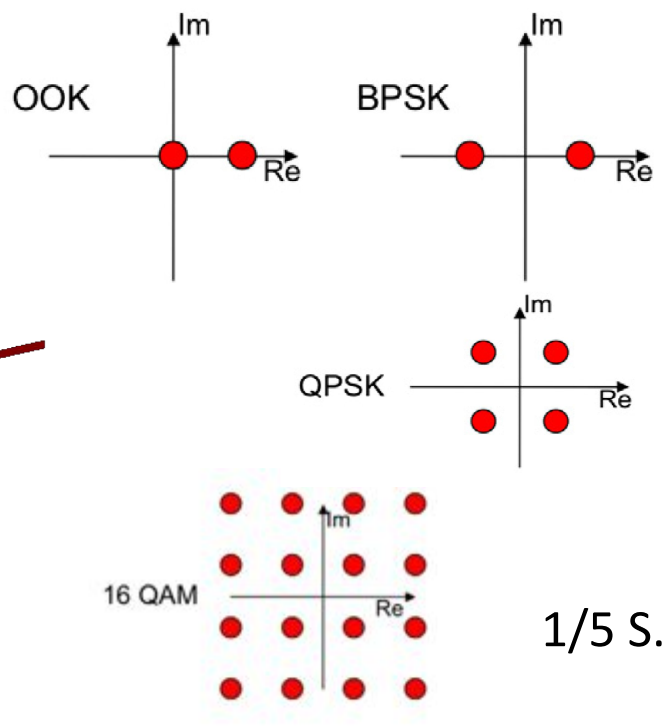


Transmission

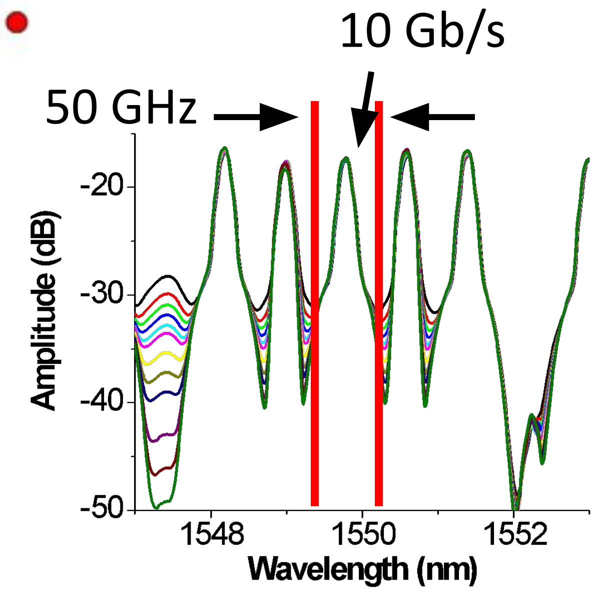
OSNR

Baud Rate = Symbol Rate

Symbols/Constellations:

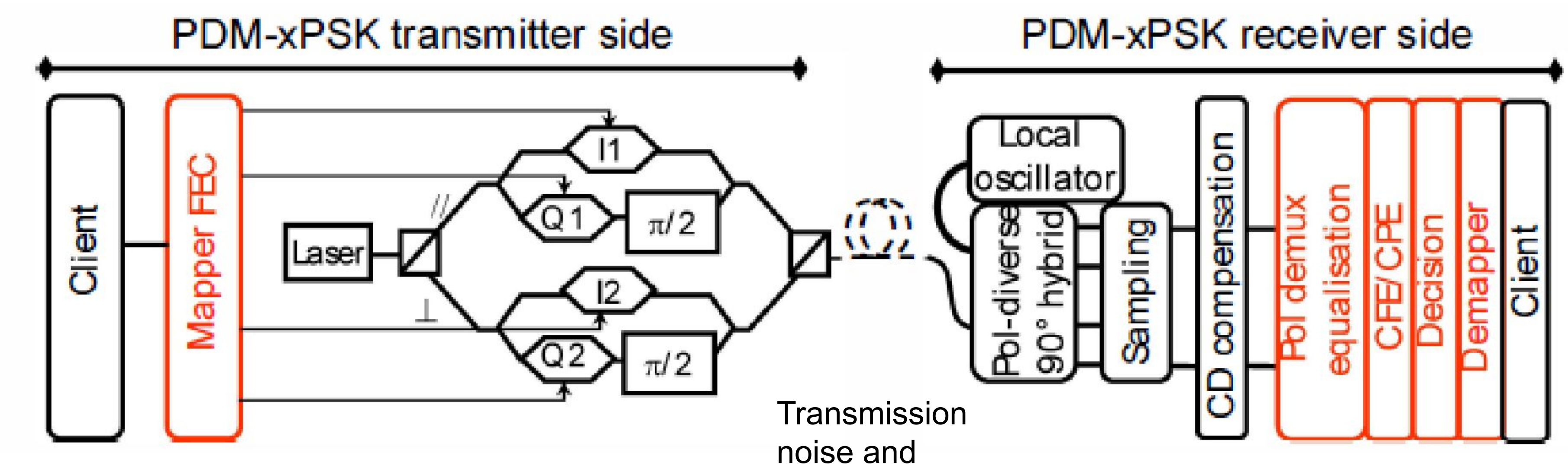


1/5 S.E.:



Optical Link: High-Capacity Channel

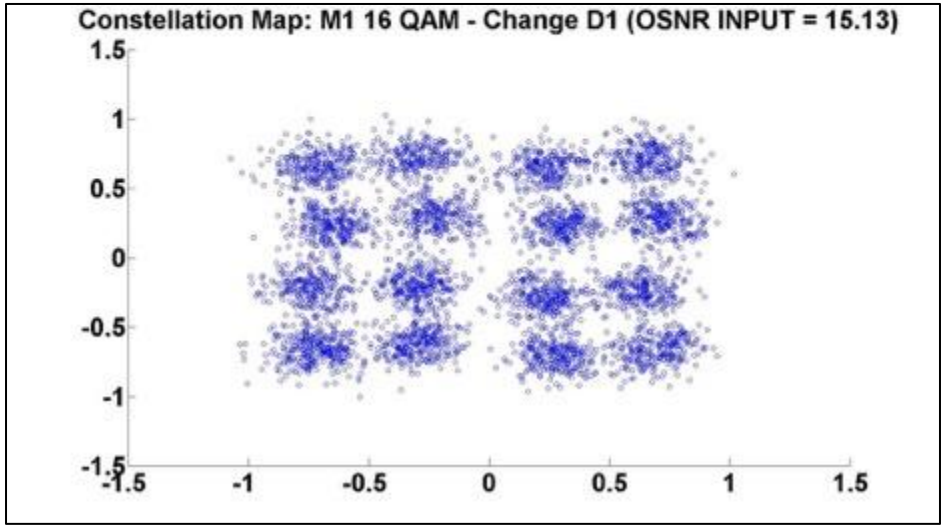
- Coherent Channel
  - Coherent receiver + Advanced modulation format transmitters



Transmission noise and distortion

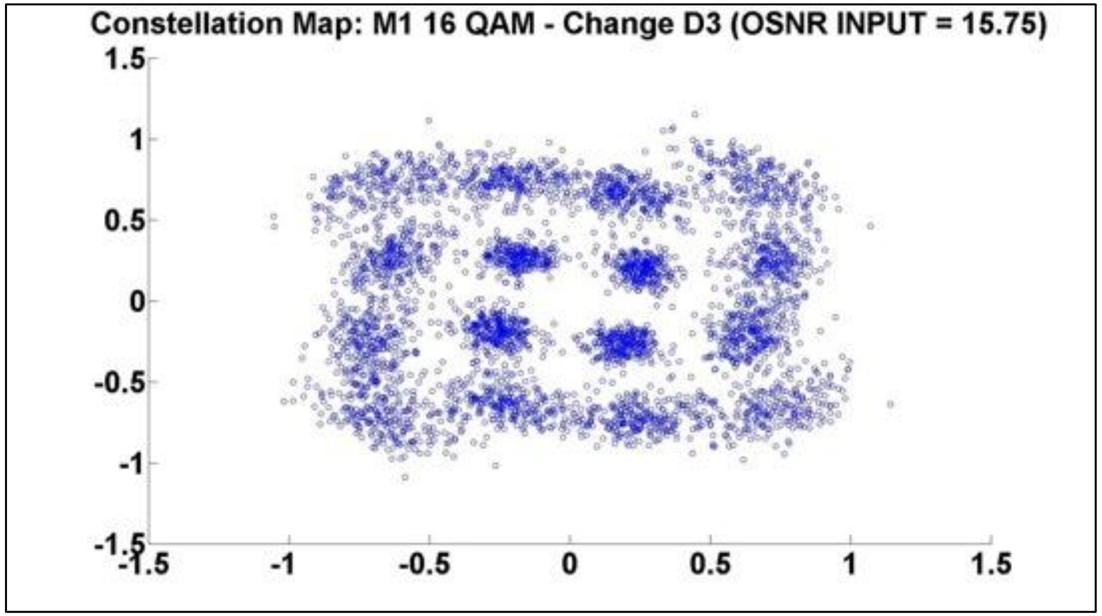
A. Morea ACP

Impaired Constellations

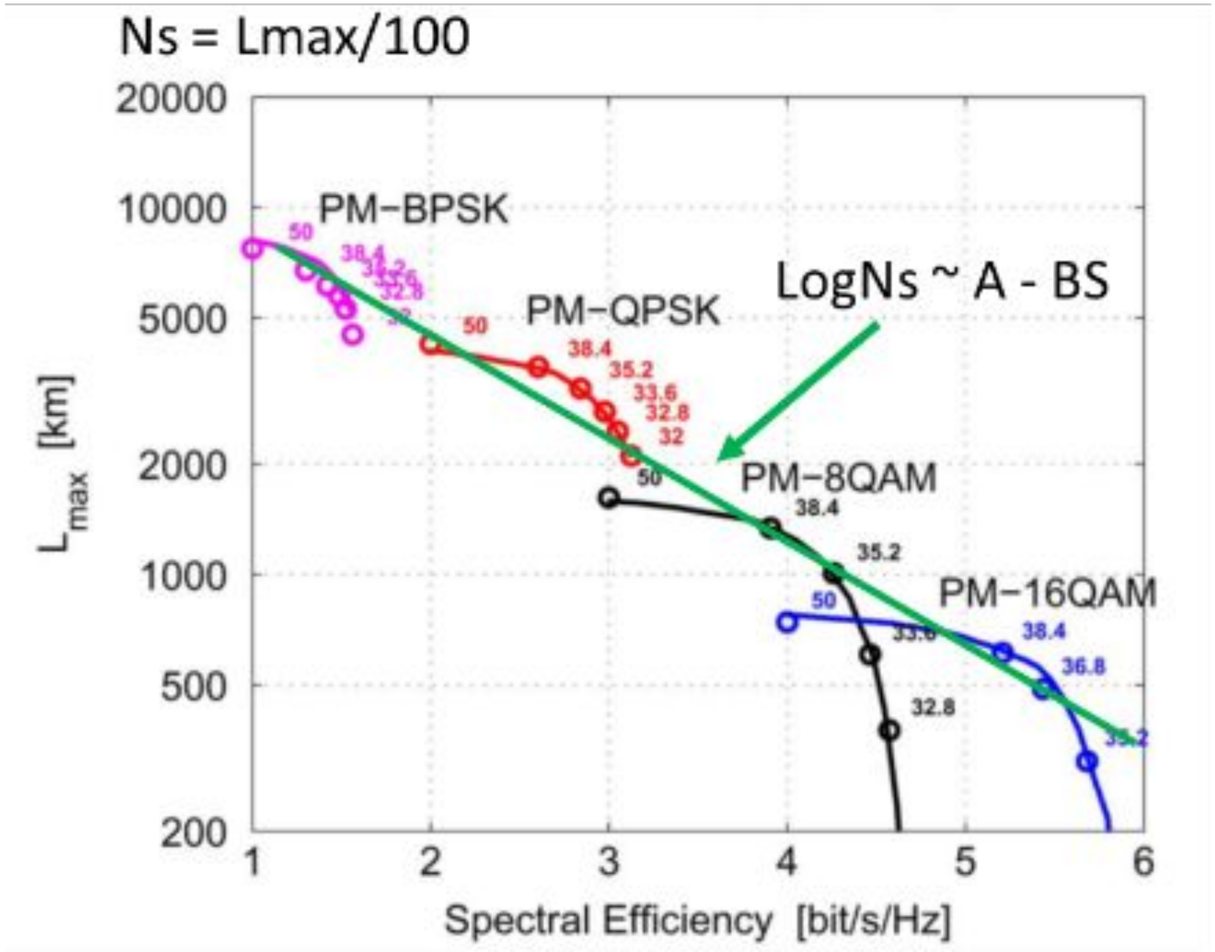


16 QAM: 15 dB OSNR

16 QAM: 16 dB OSNR
Nonlinear Phase Distortion



Transmission Reach: Advanced Modulation



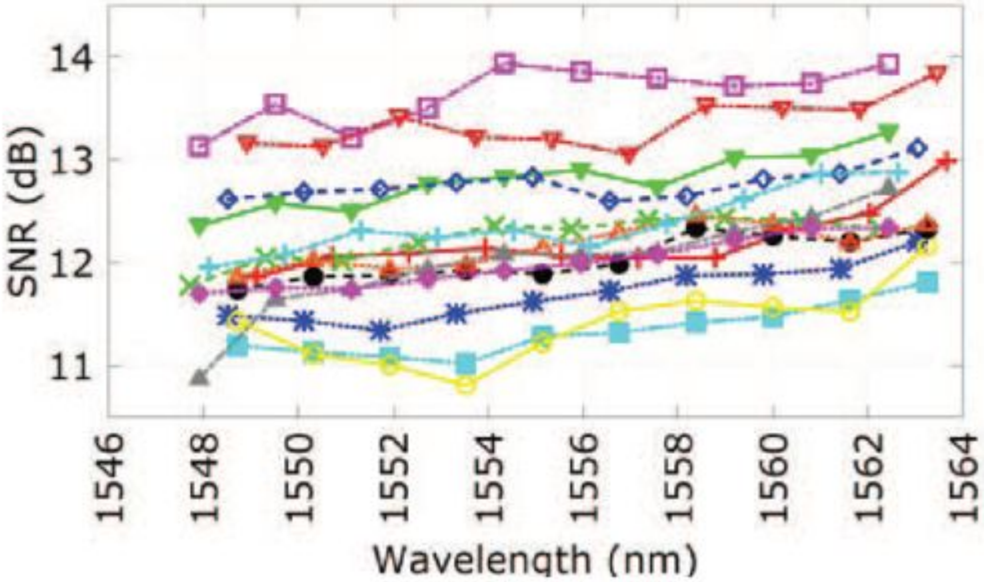
In metro & data center networks:
Distance = # Hops
2000 km ~ 20 hops

G. Bosco, et. al. J. Lightwave Technol. 29, 1, 53-61, 2011.

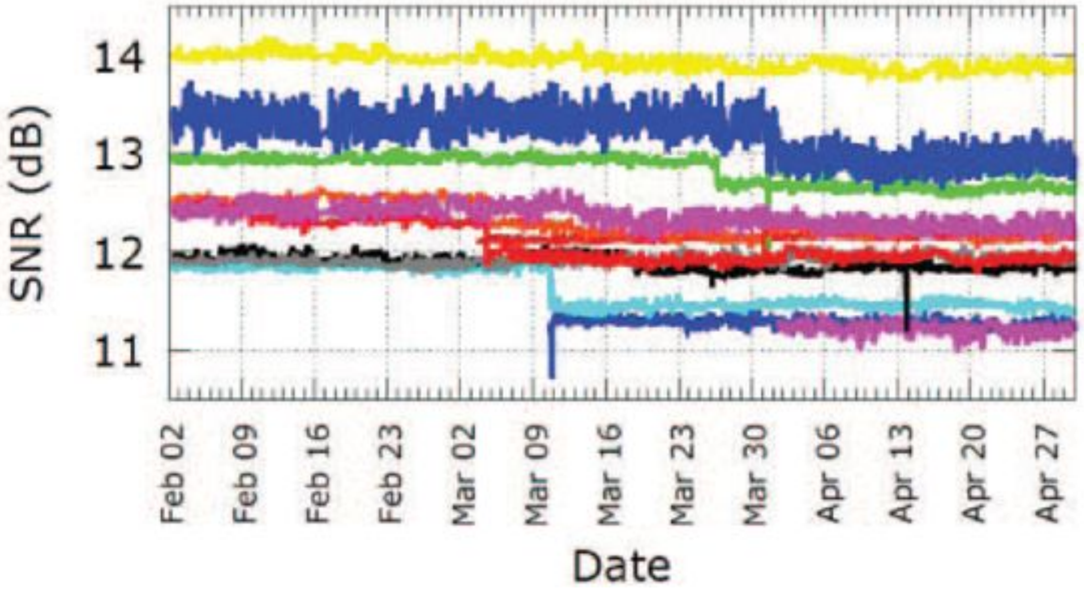
Variations in the Field

- Production system measurements
- Performance varies by wavelength & route over time

Wavelength & Route Dependence:



Time Dependence:

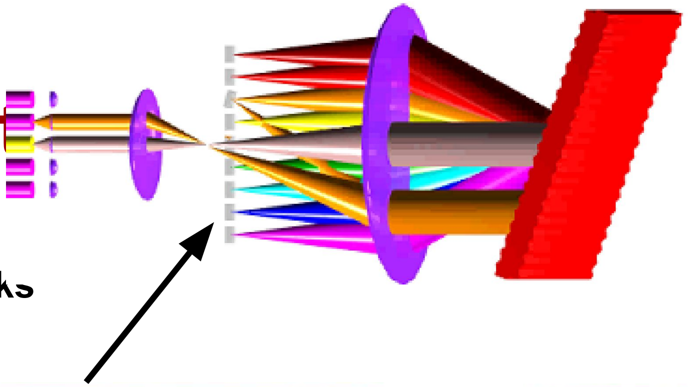


Ghobadi, et. al. OFC 2016

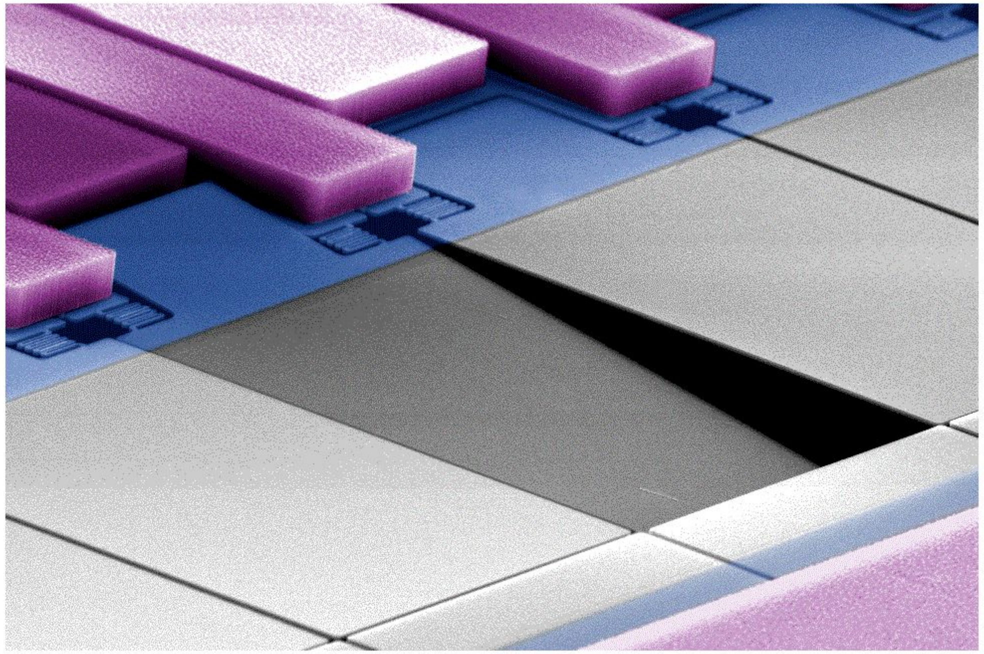
Center for Quantum Networks NSF-ERC

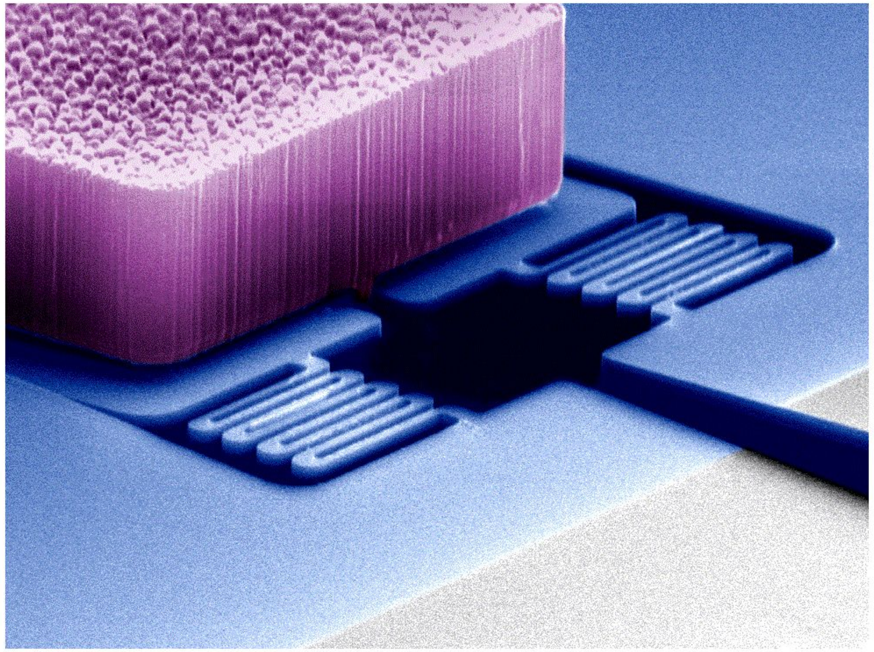
MEMS-based Wavelength Select Switch

Technology for Transparent Networks



packaged switch assembly



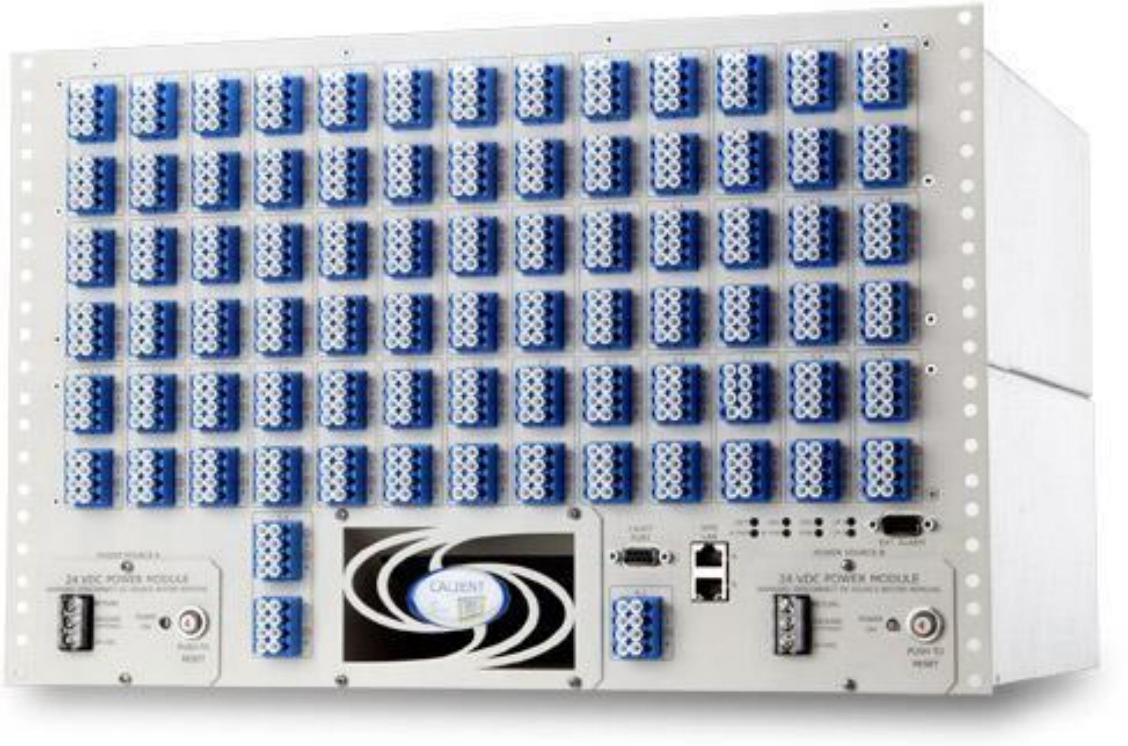


Linear Array of Mirrors

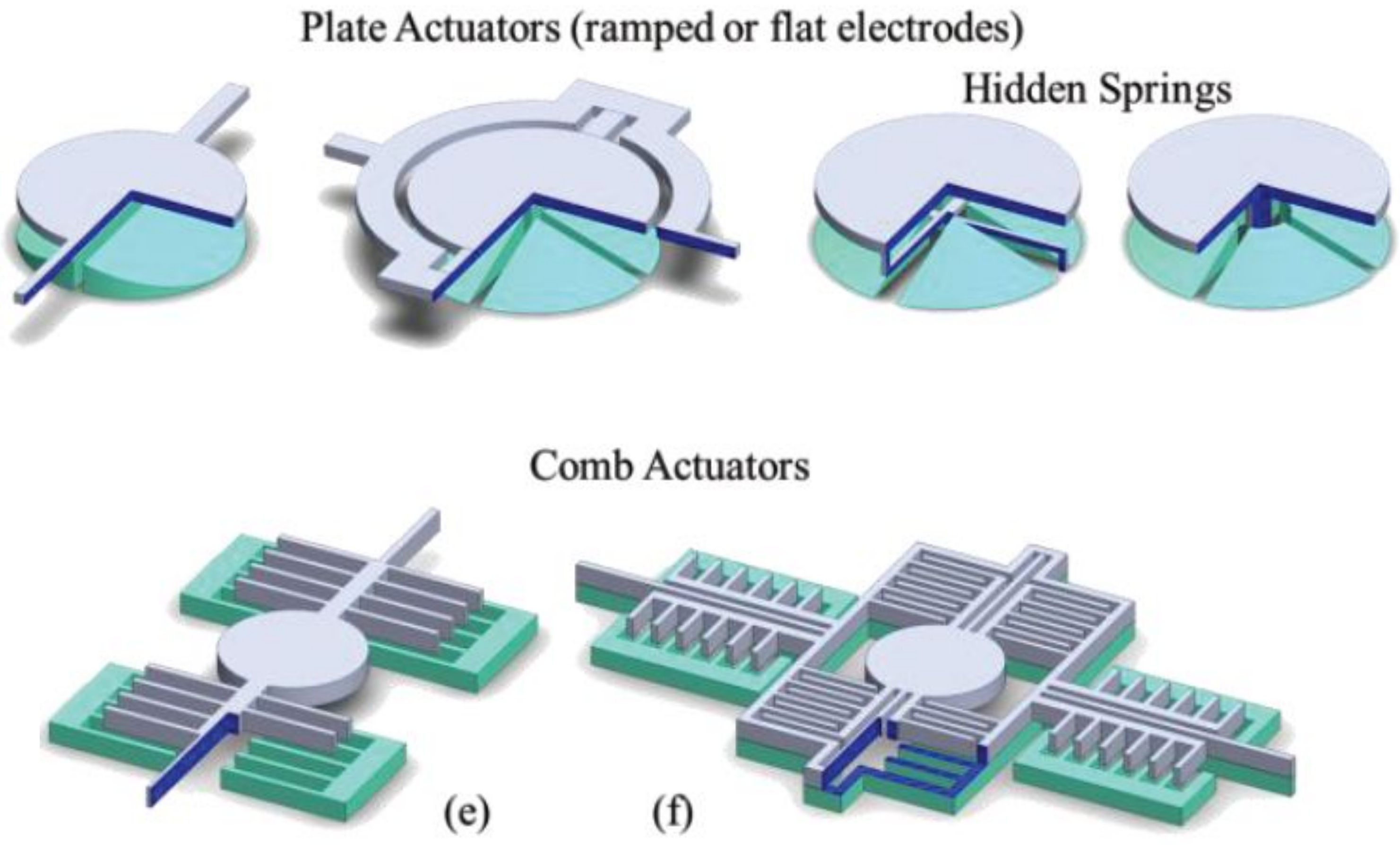
MEMS capabilities enable broad design scope for optical switch technology; Images courtesy of D. Marom

Optical Space (Fiber) Switch

- MEMS-based
- Calient S320:
  - 320 bi-directional ports
  - 45 W total
- Using 100 Gb/s:
  - 1.4 pJ/bit
  - 5 ns delay
- Insertion Loss:
  - 3.5 dB loss fiber to fiber



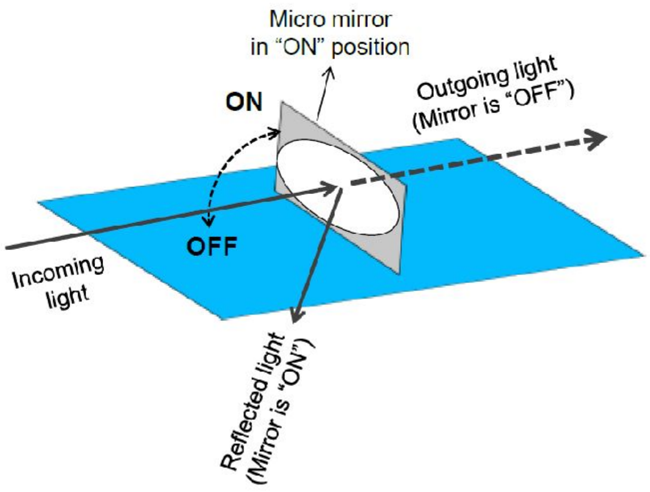
MEMS Mirrors

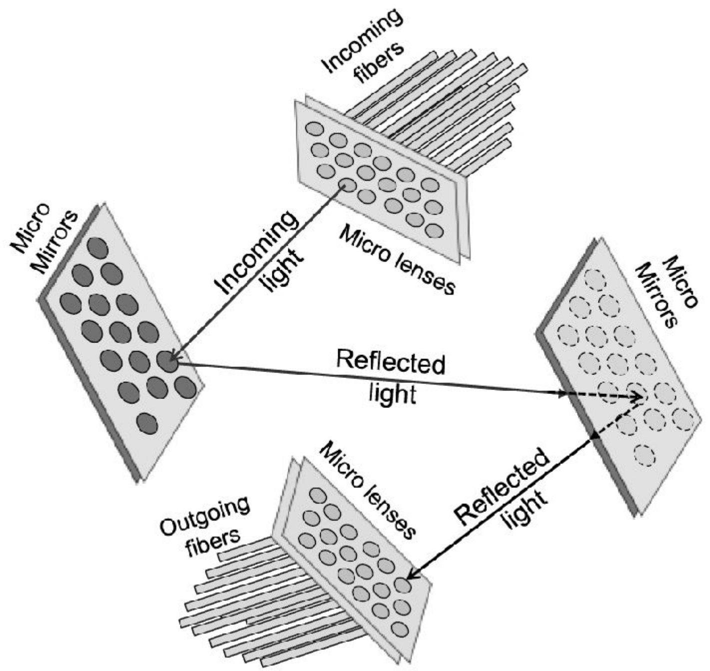


J. Ford OFC 2015

2D vs 3D

- 3D MEMS allow for NxN switch fabrics
  - Require mirror position holding
  - Often use active feedback and dithering to reduce loss to fiber
  - Mirror holding reduces speeds to ~ ms or longer
- 2D MEMS provide on/off switching
  - Use high voltage to move mirror rapidly: ~ microseconds
  - Use diffraction effects as well as reflection





Limits to MEMS Switches

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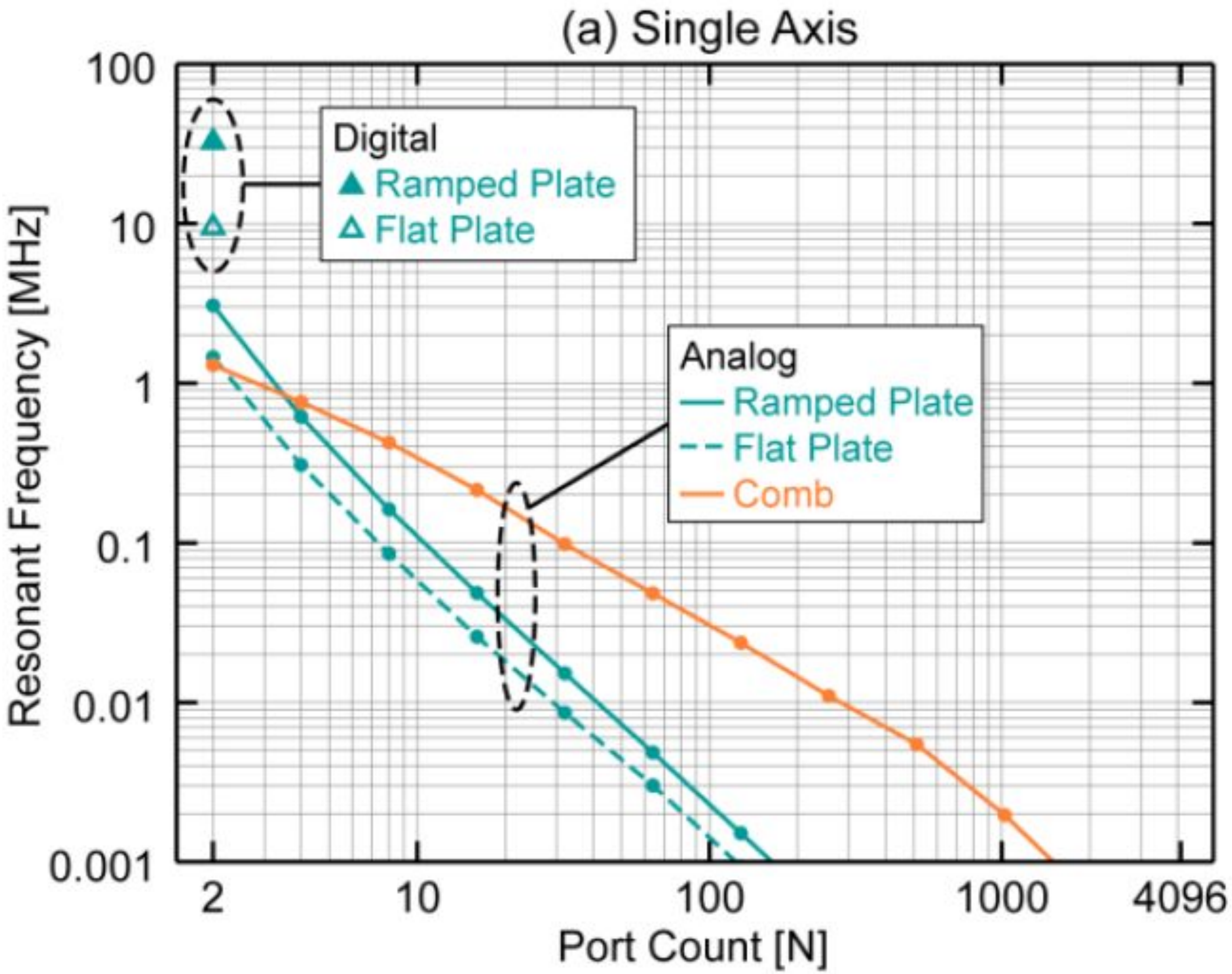
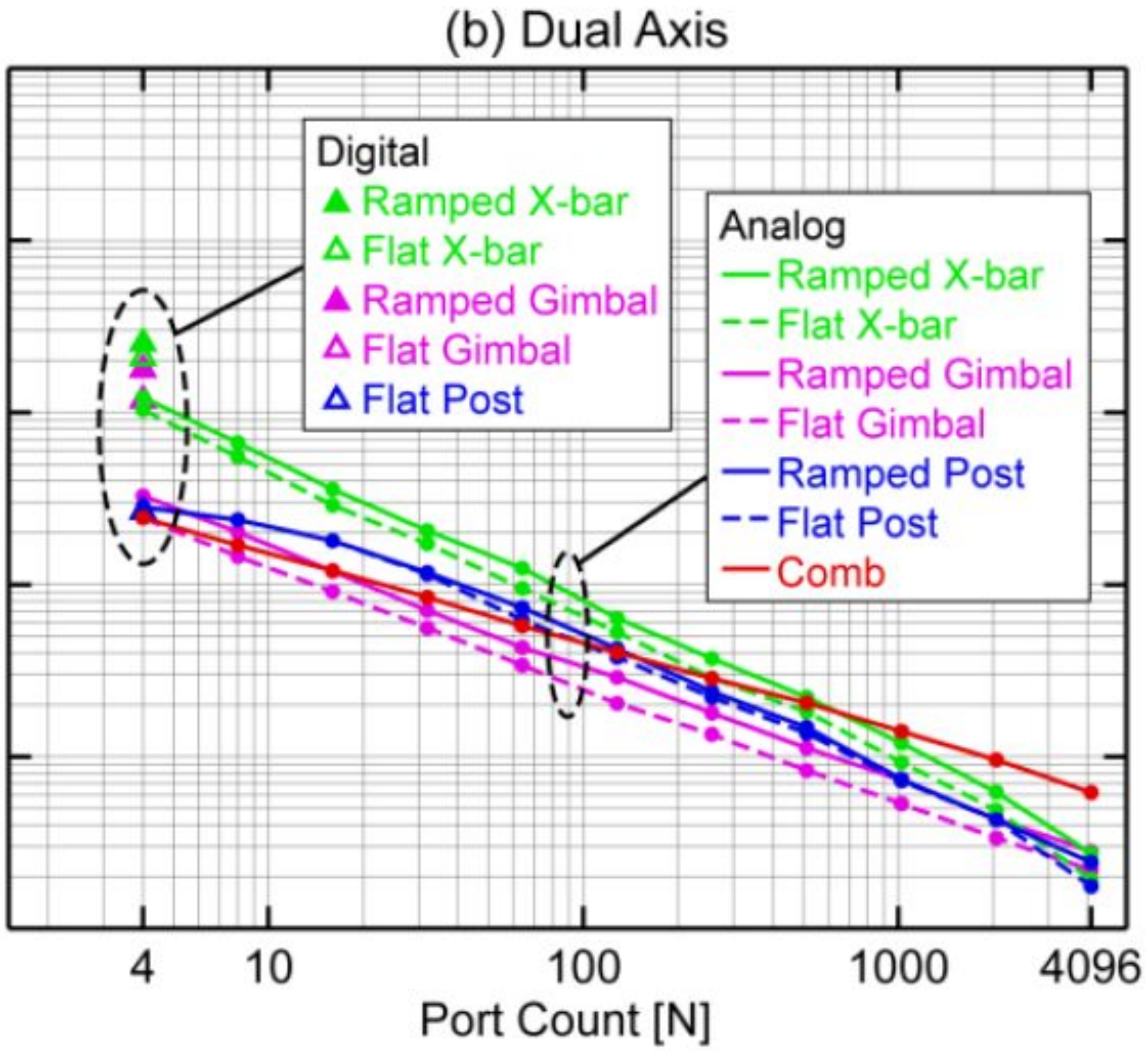


J. Ford OFC 2015

Limits to MEMS Switches

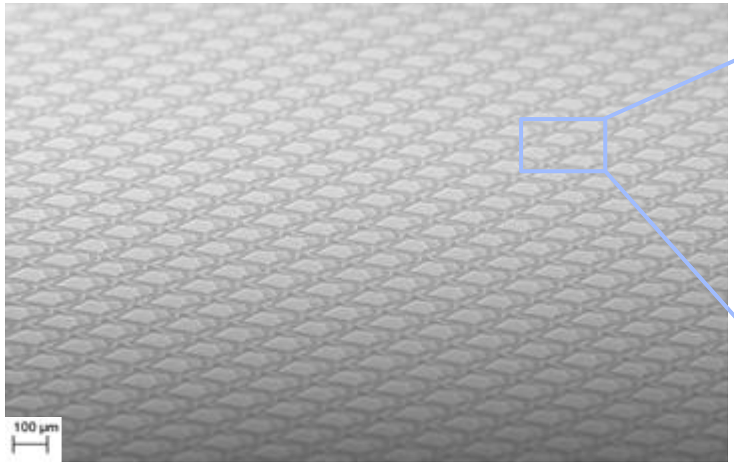
Same axis
previous slide

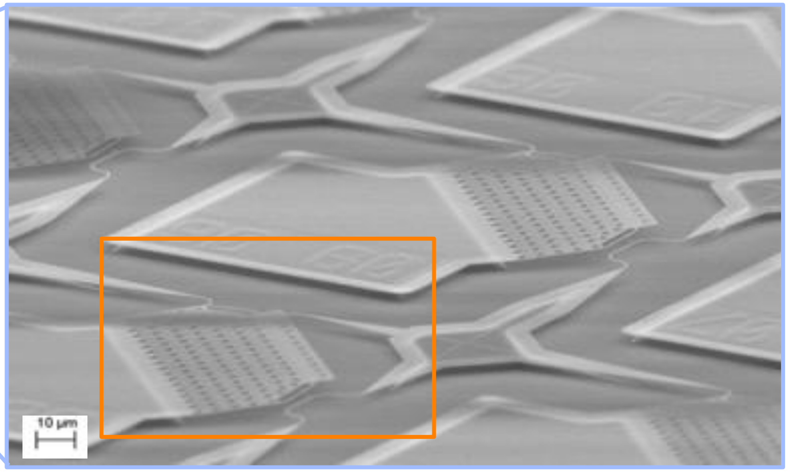


J. Ford OFC 2015

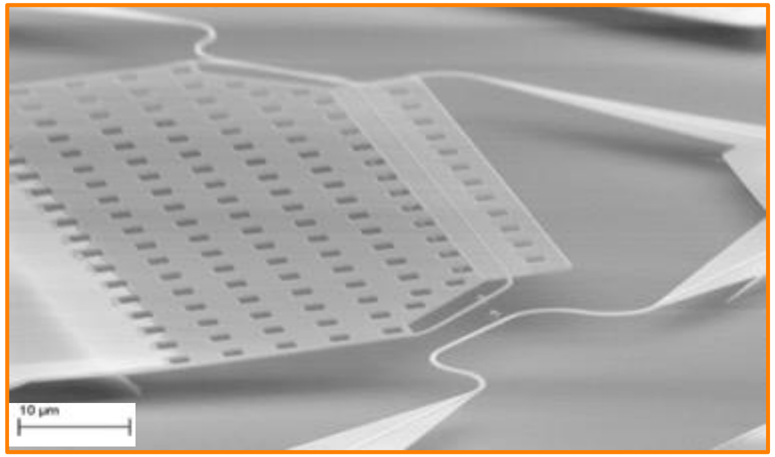
Silicon Photonic MEMS Crossbar Switch

Potential for new low loss switch technologies





- 2,500 MEMS-actuated switches integrated on 9mm x 9mm chip
- **2.5 µs switching time**
- **OFC 2015: < 1 µs**
- Power losses only during switching
- Energy is in control plane



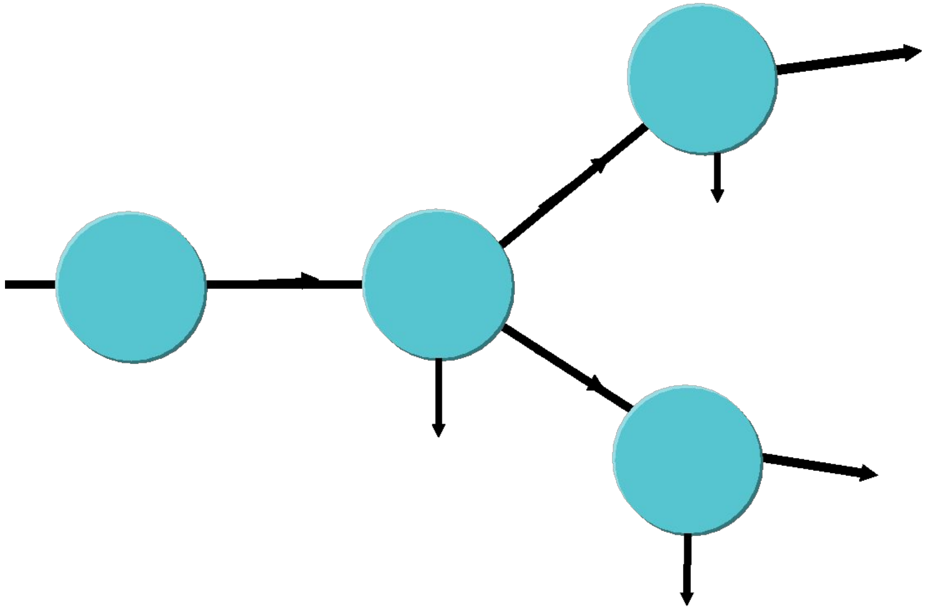
Ming Wu, UC Berkeley

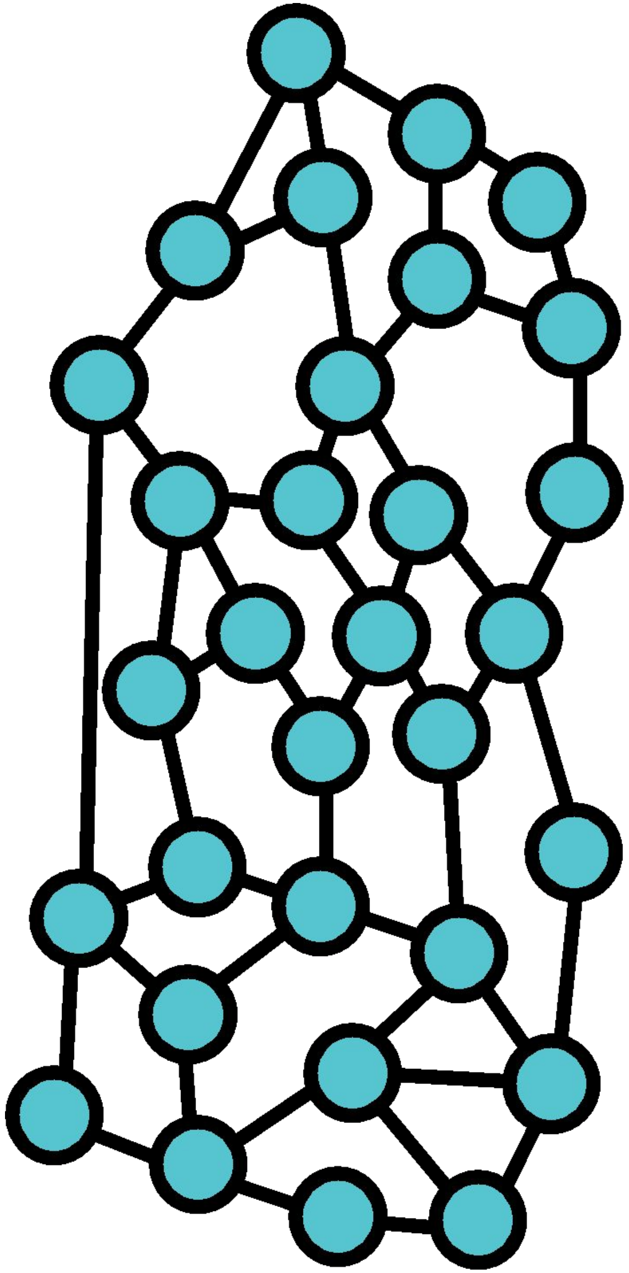
Optical System Control & Management

- Control plane: software controls that actuate system functions, usually ‘real time’, often autonomous, e.g. IP router control plane
- Management system: operator interface for ‘offline’ management functions such as maintenance, provisioning, fault isolation, set policy for control plane, etc.
- Intelligent Optical System, Cognitive Optical Networks, Programmable Optical System, Agile Optical Networks, Software Defined Optical Networks: all refer to some form of automated or autonomous control plane operations
  - Current commercial systems are all statically provisioned: no switching

Dynamic Domain Power Control Algorithm

- Power drifts over time and new channels are provisioned: need periodic power control to stay within margins
- Adjust nodes in parallel within ‘optically’ isolated domains
    - Node ordering based on channel routes

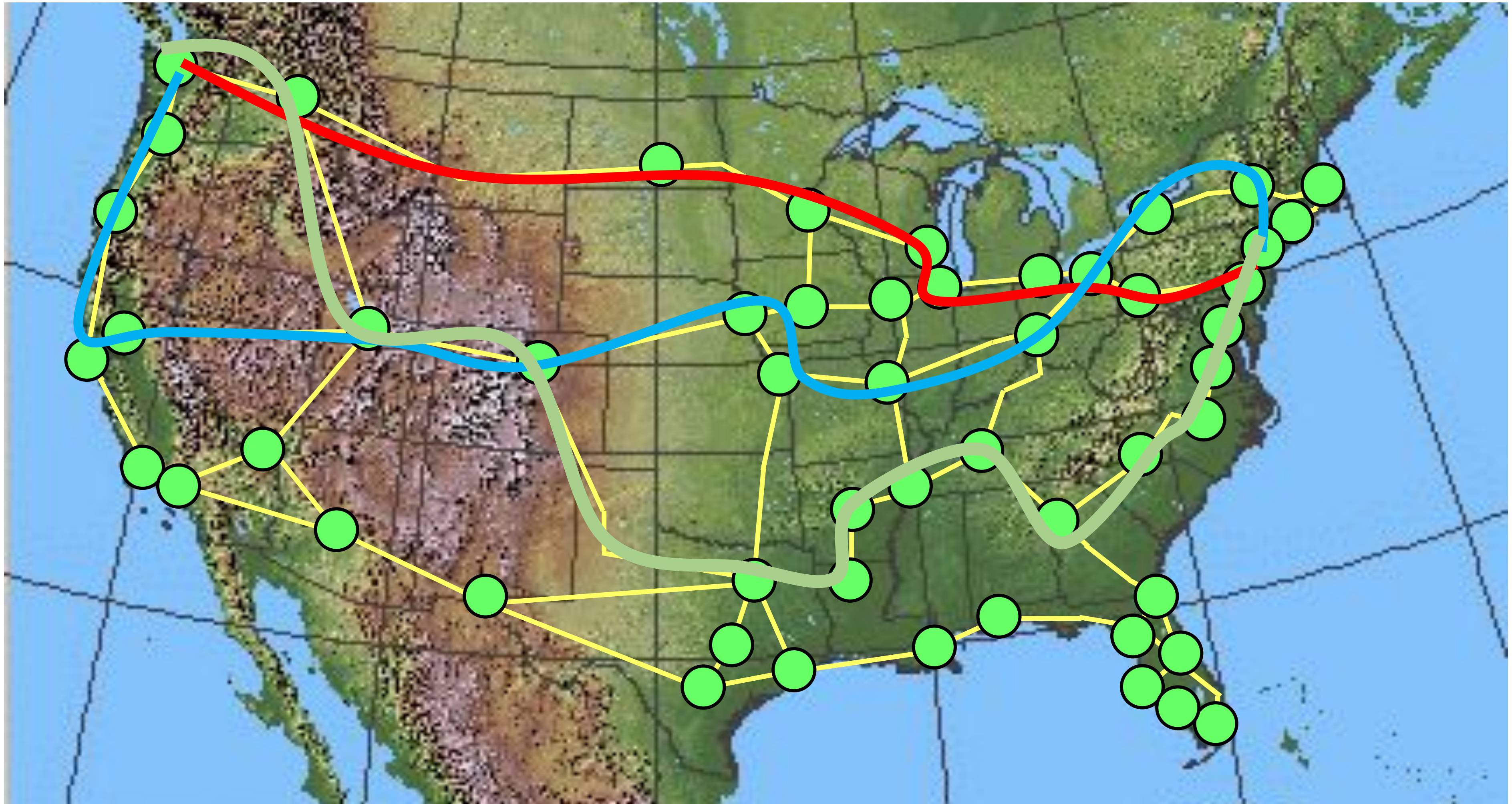




Kilper & White OFC 2007

RWA & QoT: How does it work?

- How to connect Seattle to NYC?
- Use Quality of Transmission (QoT) estimate to choose route & wavelength



What Determines QoT?

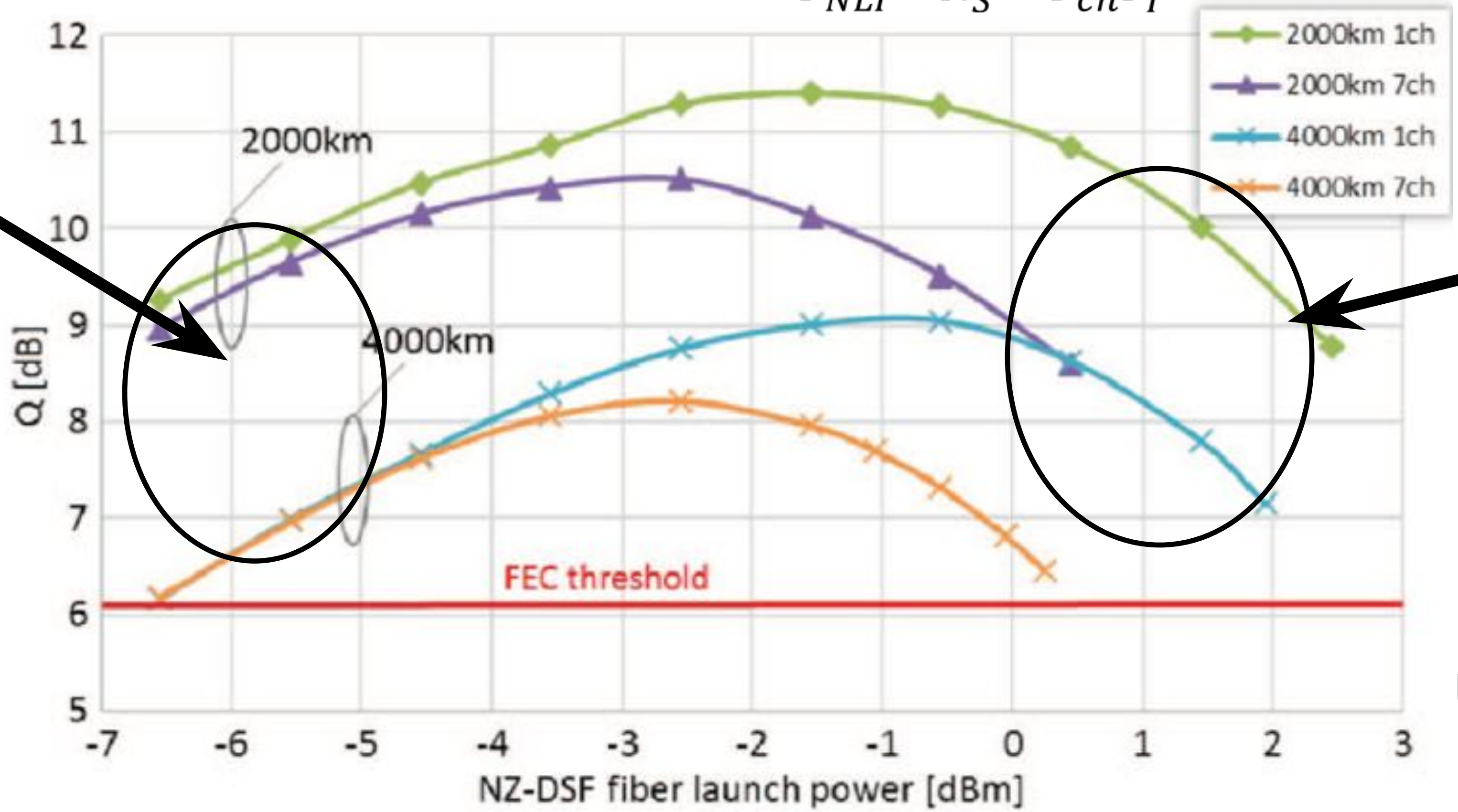
- Generalized Optical Signal to Noise Ratio Metric:

$$gOSNR = \frac{P_{ch}}{P_{ASE}+P_{NLI}} \sim Q$$

$$P_{ASE} = N_{Amp} NF(G-1)h\nu B$$

$$P_{NLI} \sim N_S^{1+\varepsilon} P_{ch} P_I^2$$

$$\frac{P_{ch}}{P_{ASE}}$$

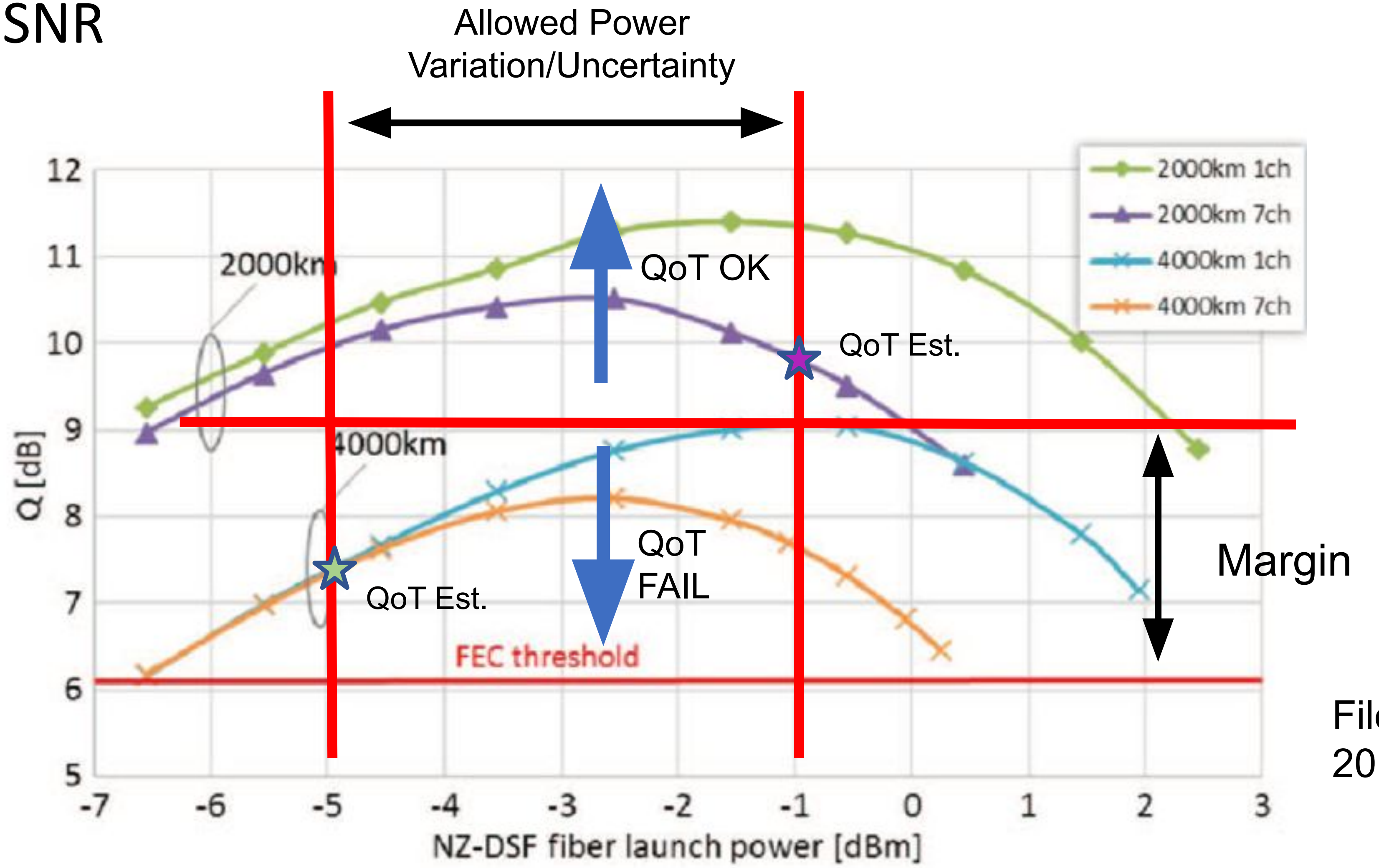


$$\frac{P_{ch}}{P_{NLI}}$$

Filer, et. al. JOCN 2016

Q-Factor, Power Dependence

- Optical Q depending on channel config & distance
- Q ~ SNR



Filer, et. al. JOCN 2016

Generic Wavelength Provisioning Protocol (every vendor has their own protocol)

- Get request for connection between A and B
- Run RWA to determine route and wavelength
  - Estimate QoT to ensure RWA meets performance requirements
- Gradually open up first link and adjust amplifiers and optical powers
  - Gradually open up second link, etc.
  - Freeze or minimize adjustments on other links
- Measure final bit error rate of end-to-end connection
- Let soak for days or weeks
- Add new connection to routing tables to start carrying traffic

Functions of Optical Physical Layer Controllers

- Control diverse set of optical transmission hardware to operate network
  - Provision channels
  - Tune amplifiers
  - Tune channel powers
  - Manage faults, e.g. node loss, transient recovery
  - Tune/control transceivers
  - Real time elastic bandwidth/flex grid management
  - Real time route selection
  - Real time optical circuit switching
  - Wavelength layer link/segment protection switching
  - Defragmentation
  - ….

Current proprietary solutions

Future

SDN Across Multi-Domain Networks

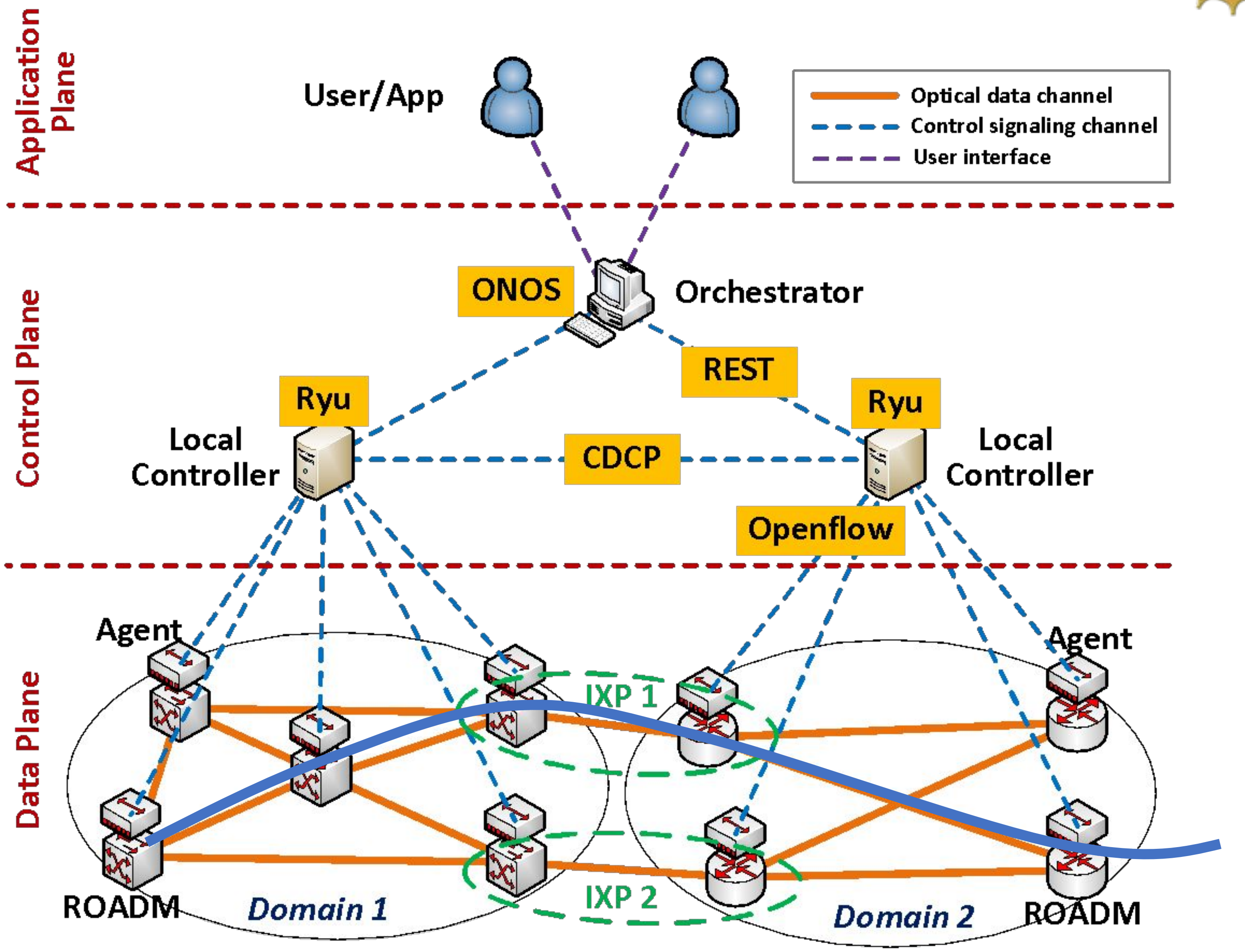
Center for Quantum Networks NSF-ERC

Ongoing area of research

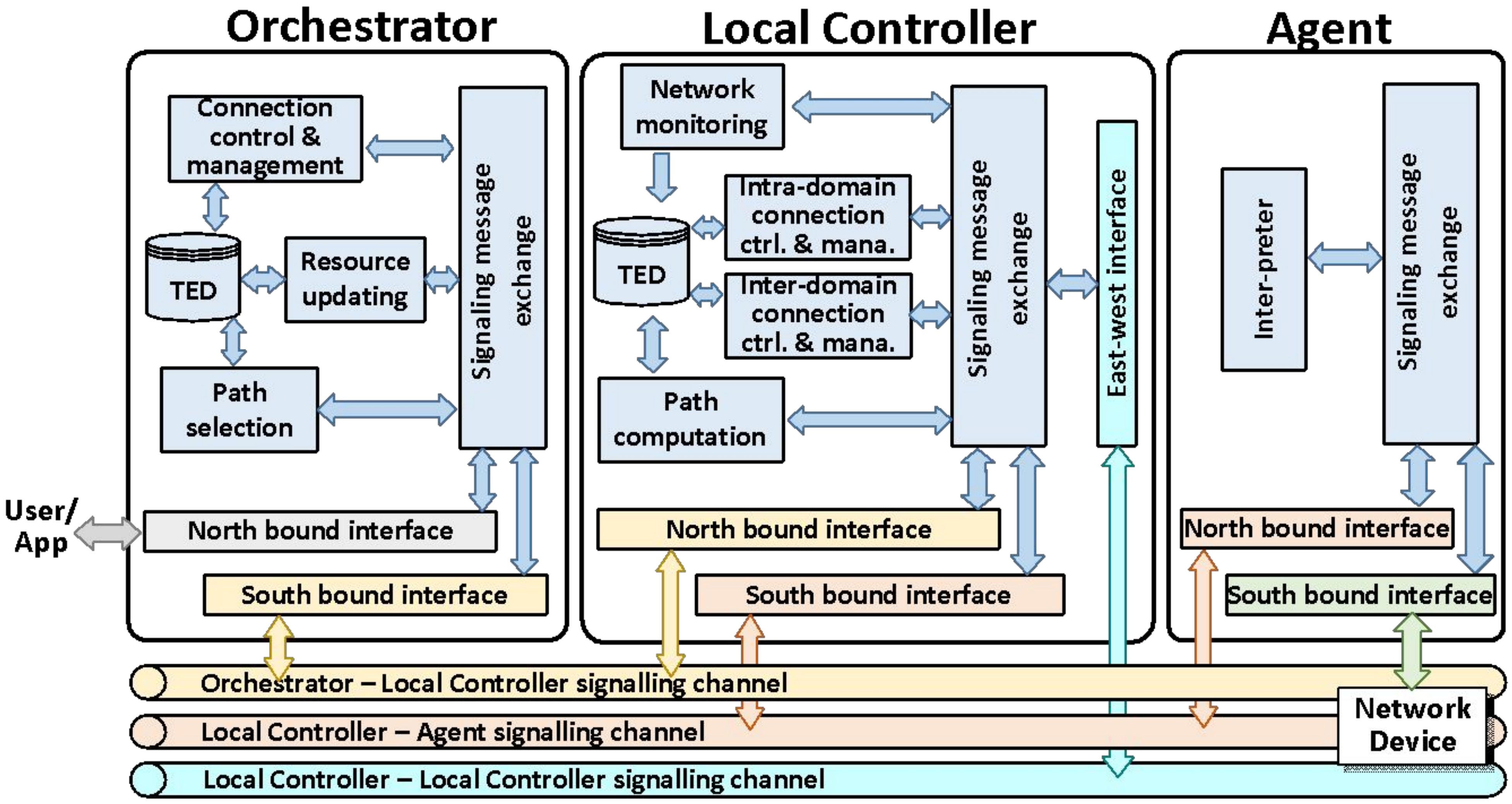
- How to route wavelengths through proprietary networks (unknown topology)?
- How to guarantee signal performance?
- How to scale control operations across domains?

Many benefits

- Low-latency, low cost end-to-end optical connections



Control Plane Elements



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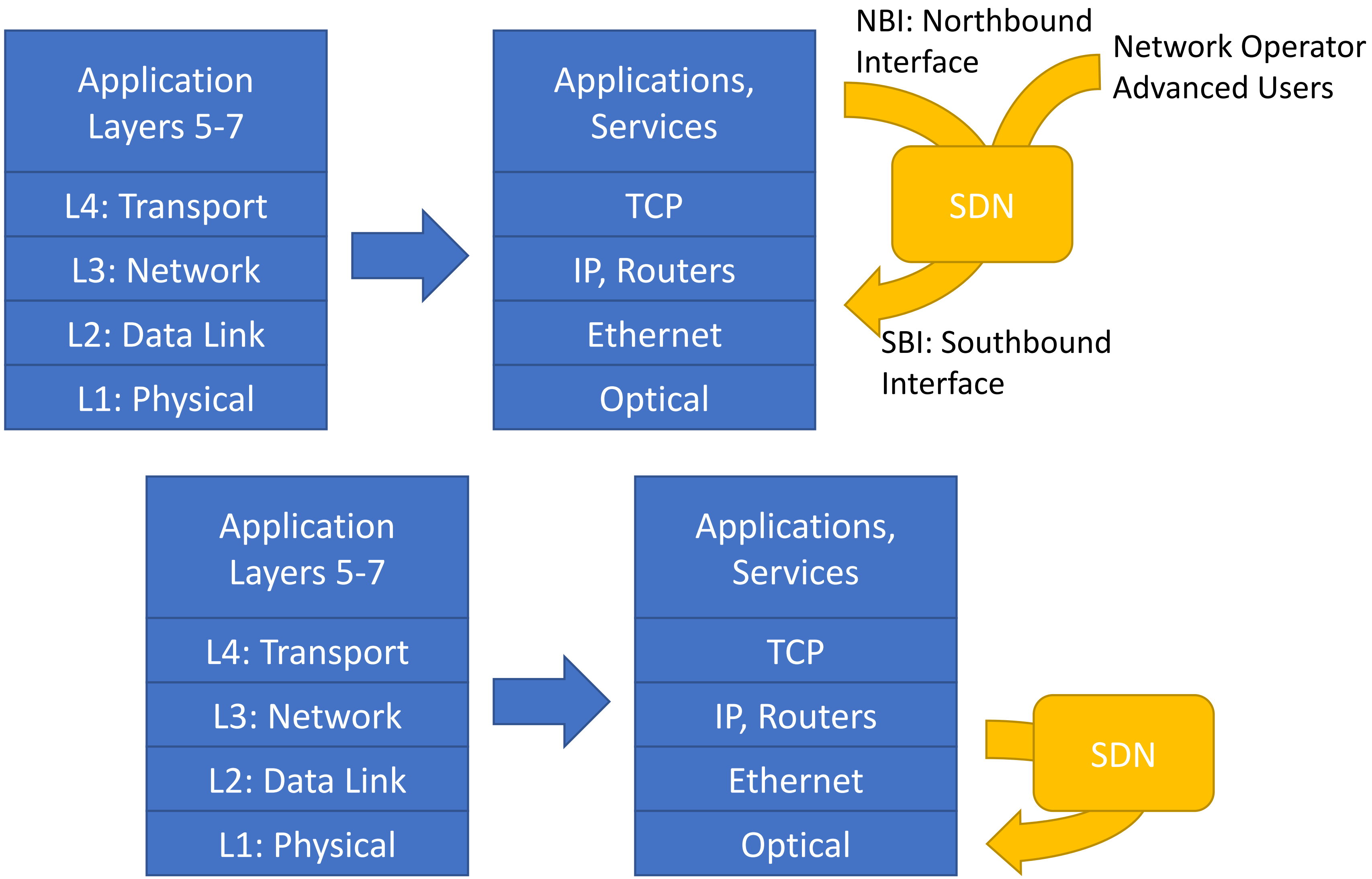
Control and management

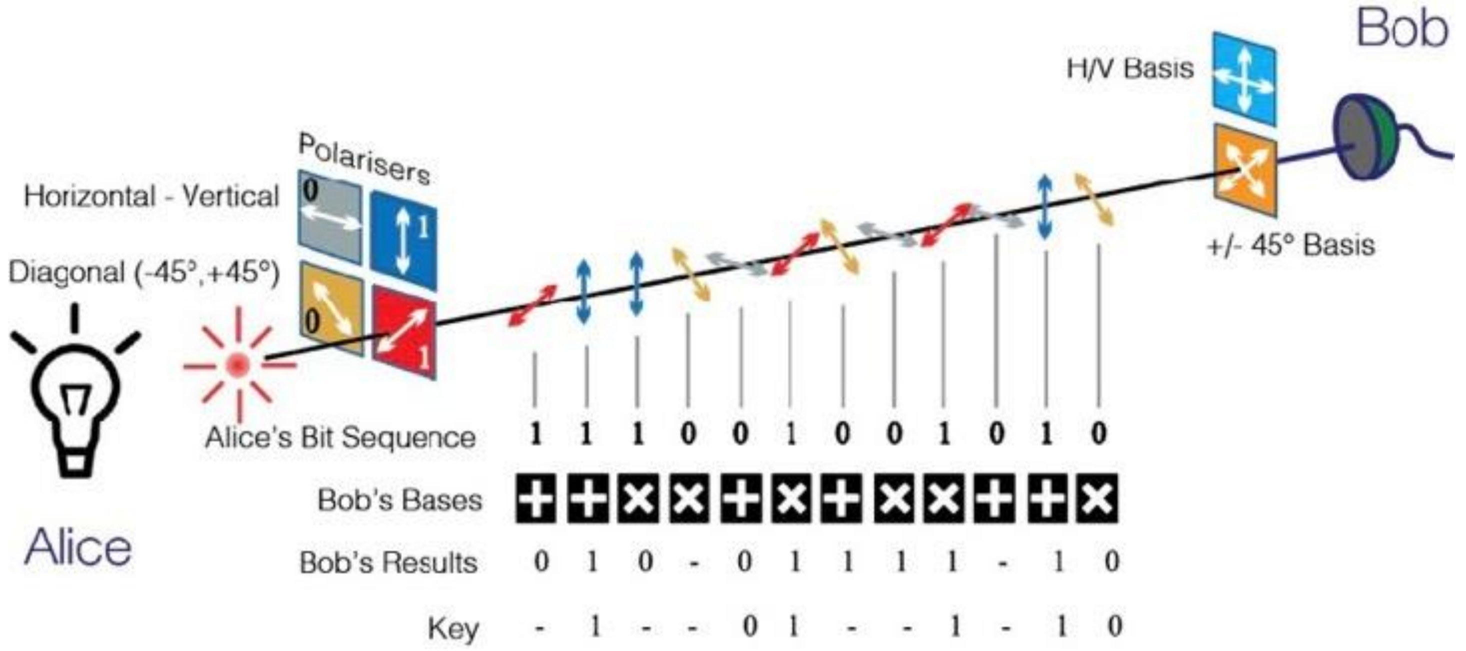


Quantum systems and coexistence

Quantum signals

- Quantum Key Distribution (QKD) signals
- Discrete variables (DV) and continuous variables (CV)

DV-QKD:

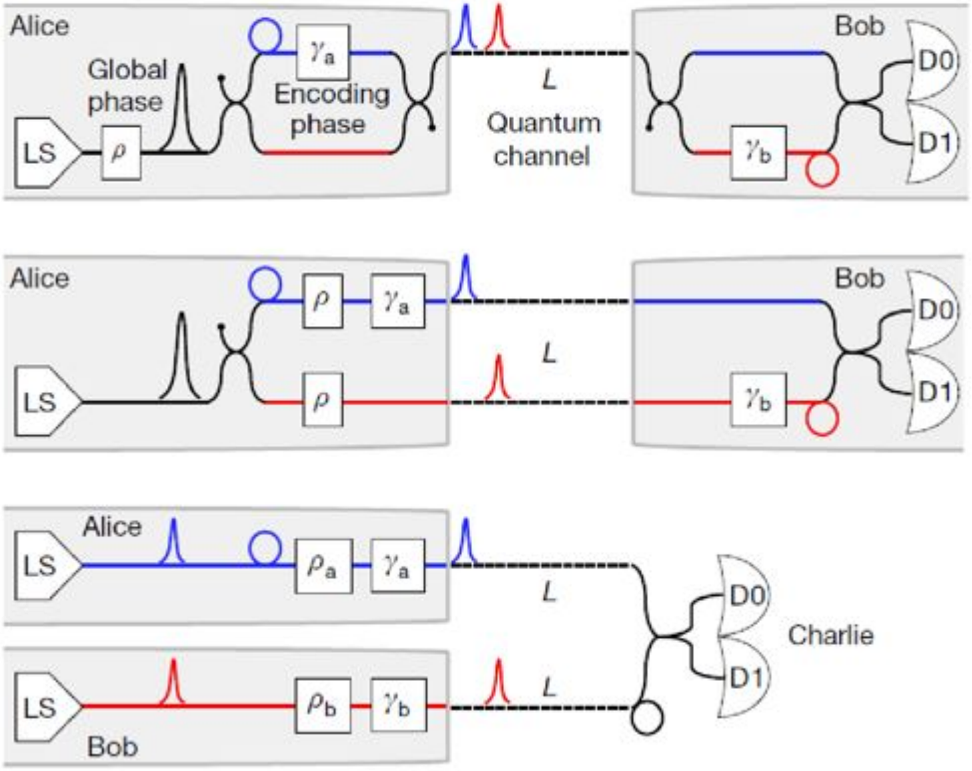


Iqbal et al., "Quantum Cryptography: A brief review of the recent developments and future perspectives", DIPEWC 2016

Continuous Variable Systems

- Use phase encoding of attenuated laser pulses
- Propagate LO with the weak signal (few photon)
  - Homodyne detection
- MDI/TF: Use intermediate 'Charlie' measurement node

CV-QKD:



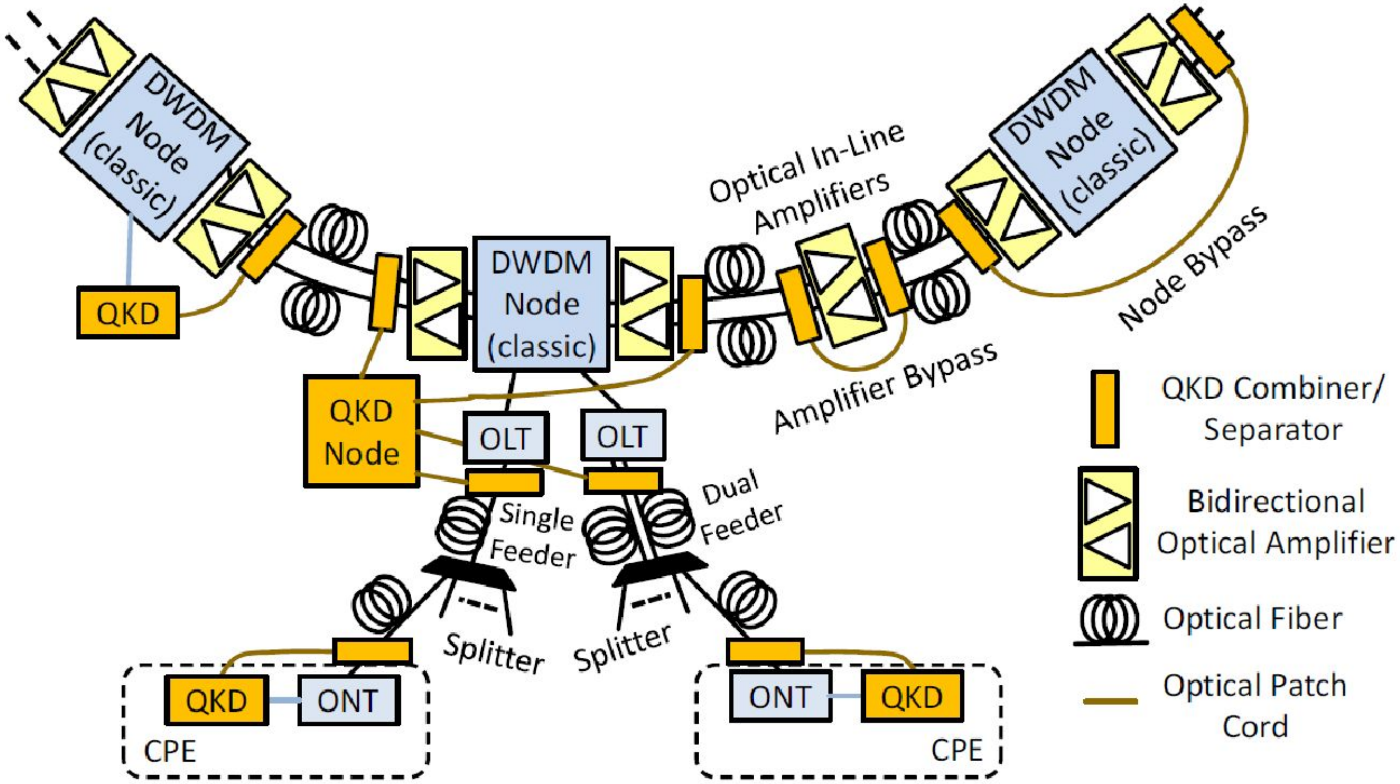
M. Lucamarini et. al. Nature 2018

Quantum signals: Entanglement Distribution

- Entanglement is a resource that can be 'distributed'
  - Use to perform quantum teleportation
  - Use for QKD protocols
- Photons can be used to distribute entanglement
  - Single rail:
    - Qubit memory (e.g. atom) is entangle with a presence of a photon
  - Dual rail:
    - Qubit is encoded on photon (e.g. H and V polarizations)
- Multipartite entanglement
- Quantum discord

Coexistence of classical and quantum signals

- Linear crosstalk
  - WSS, DWDM filters generally 30-40 dB isolation
    - Not enough for most quantum signals
  - WDM (metro & long haul)
    - Uni-directional fibre, full duplex
    - Need to bypass amplifiers
  - PON, PtP access
    - Bi-directional fibre
    - No-amplifiers

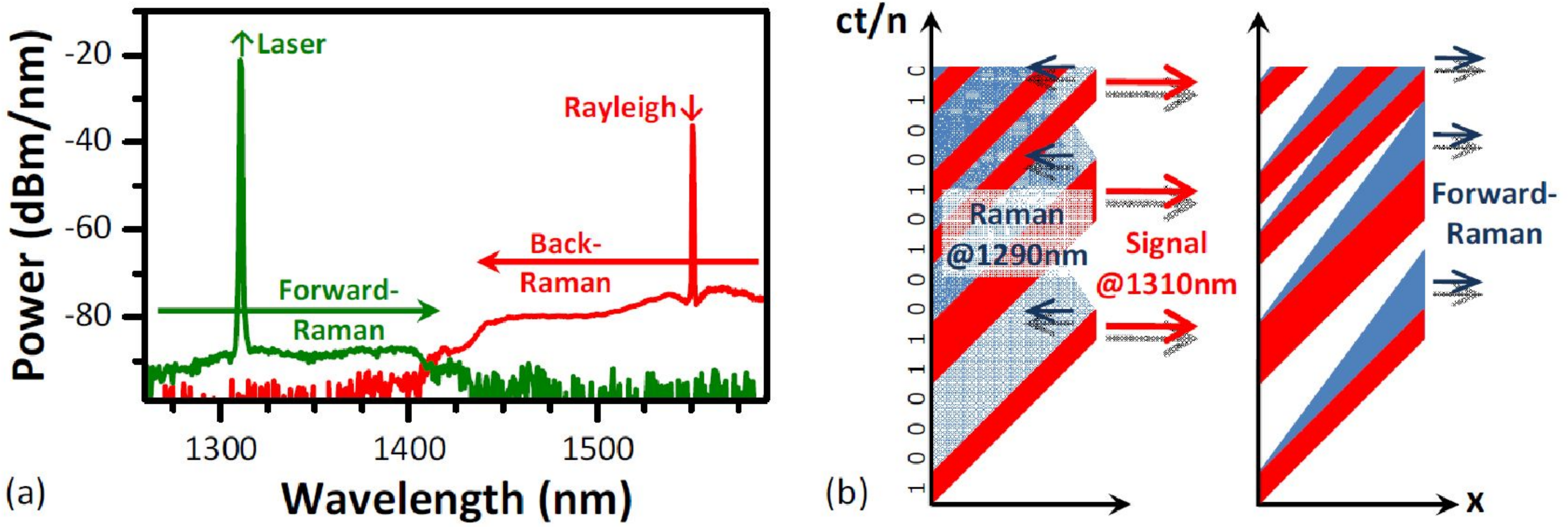


S. Aleksic, et. al. Opt Express 2015

Bi-directional Transmission (PON & PtoP)

- Backscattering is continuous

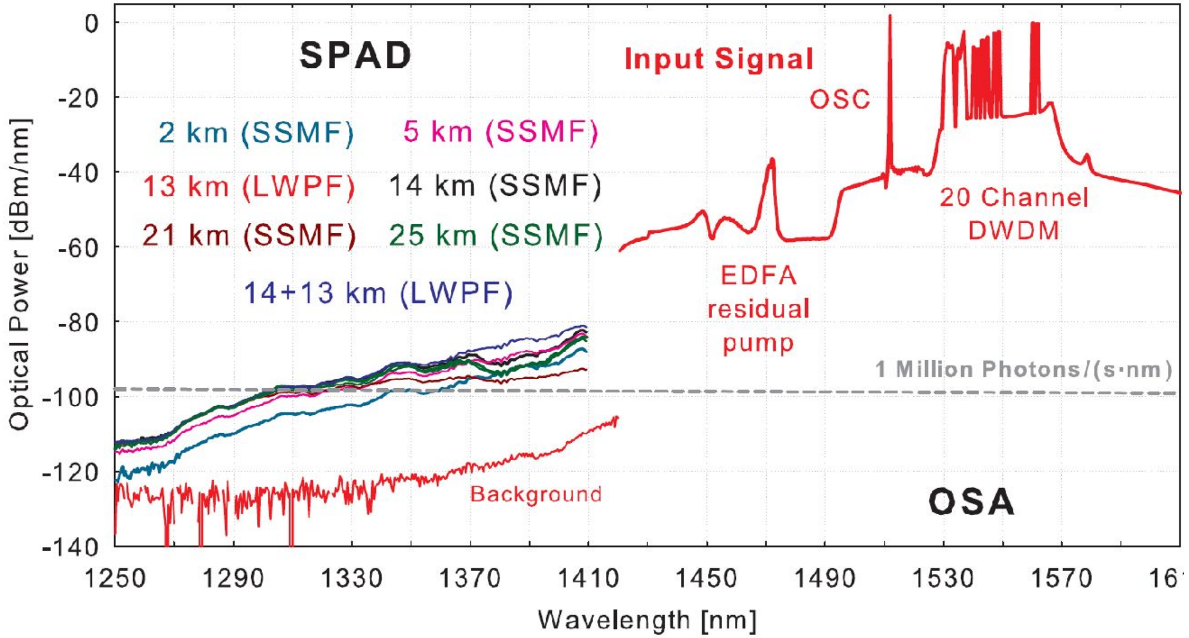
PON w/ 1550 nm downstream & 1310 nm upstream:

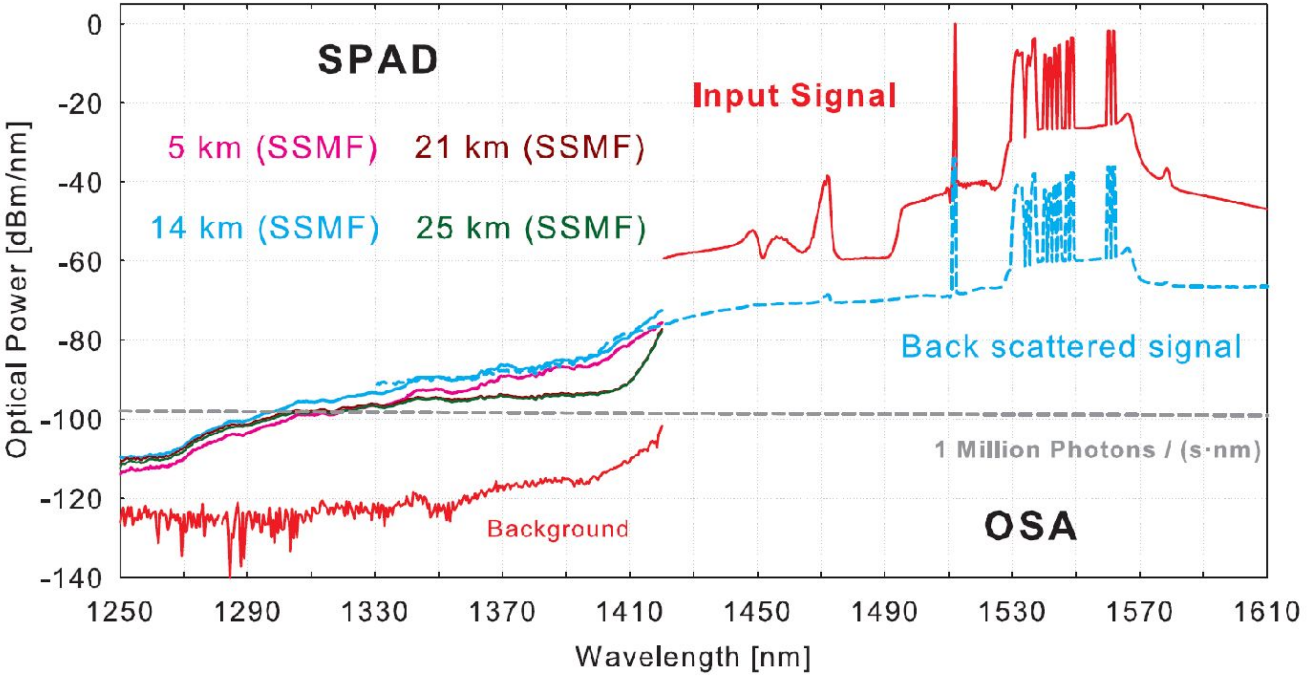


I. Choi, R. Young, P. Townsend, ECOC 2011

Raman Scattering

- Raman Scattering (Forward & Backward)
  - Also Rayleigh backscattering
  - Broadband (need to account for measurement BW)

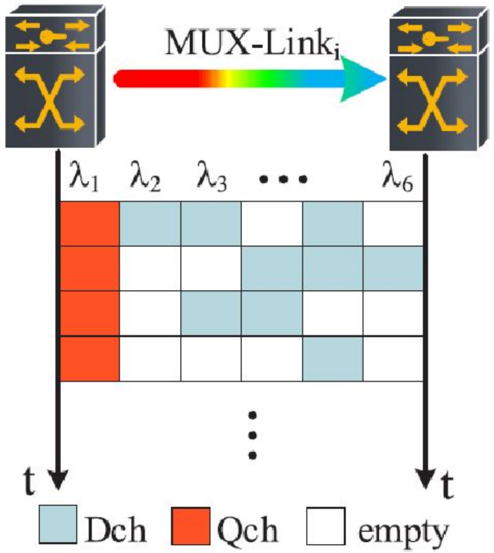


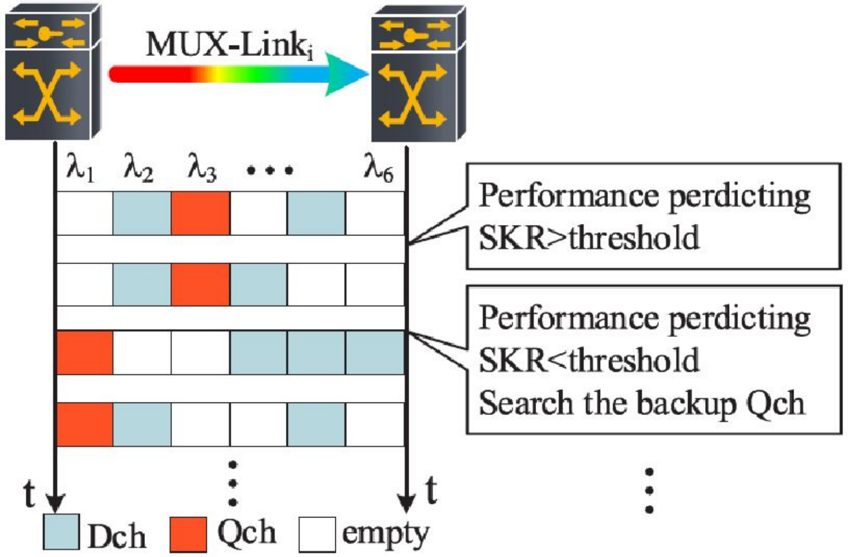


S. Aleksic, et. al. Opt Express 2015

Coexistence Strategies

- Separate fibers/cores
  - Multi-core fiber
- Hollow core fiber
- Time-slotted transmission

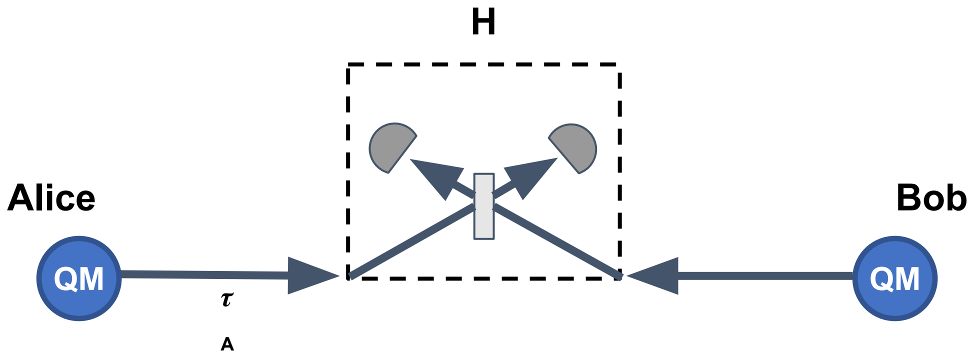




J. Niu, Y. Sun, Y. Zhang, Y. Ji, Optics Express 2019

Entanglement distribution

- Single hop link, QM’s are essentially small quantum computers
- Need to maintain equal propagation times to interfere photons at Heralding node
  - Can place Heralding measurement at one of the two end nodes
- What are potential challenges for this scheme?
  - Loss, polarization, timing jitter, synchronization, delay,…

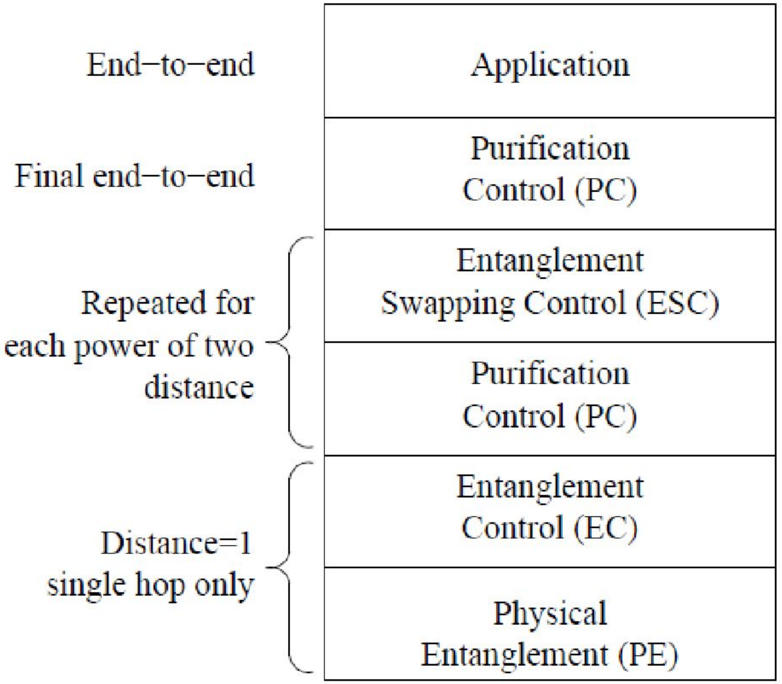


Identifying layers in quantum networks

- Network layers
  - Still open question how to define layers
  - Layers can typically be engineered and operated independently
  - Hard to identify independent quantum layers

Application	
Transport	Qubit transmission
Network	Long distance entanglement
Link	Robust entanglement generation
Physical	Attempt entanglement generation

Dahlberg, et. al. ARXIV 1903.09778v1



Van Meter, et. al. ARXIV 0705.4128v2

Layer-independent methods

Software defined networking (SDN)

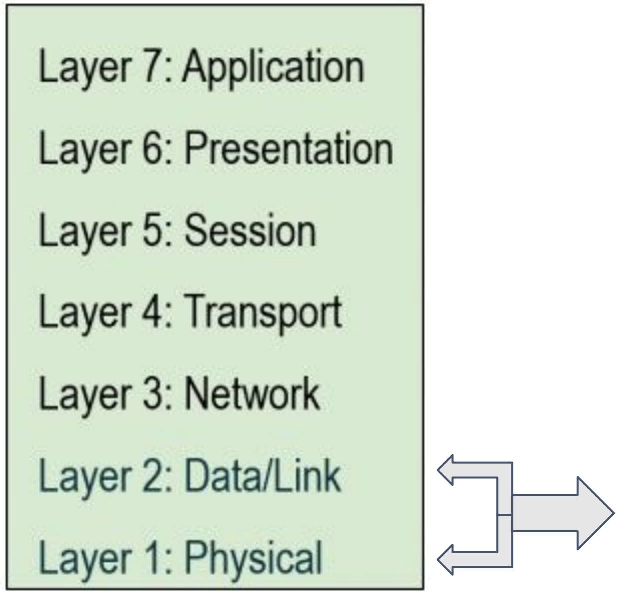


Figure 1: Networking layers

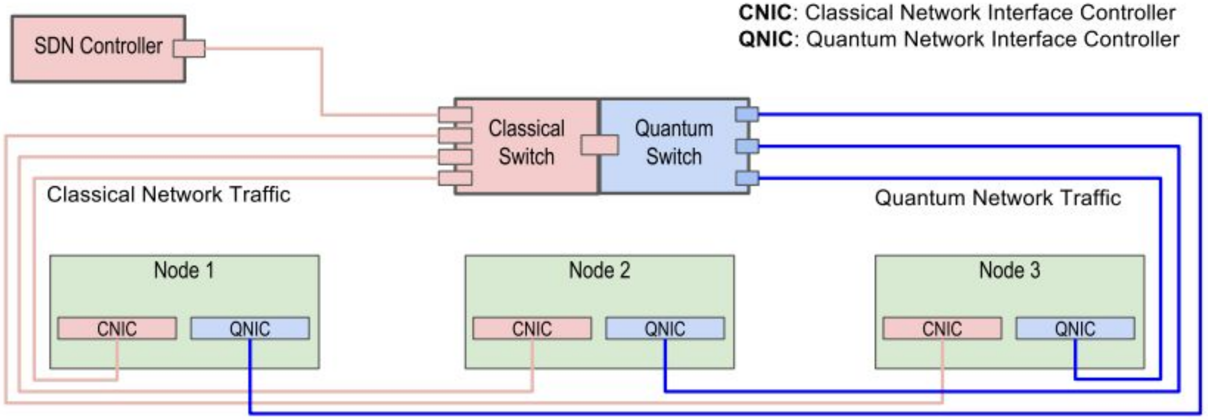


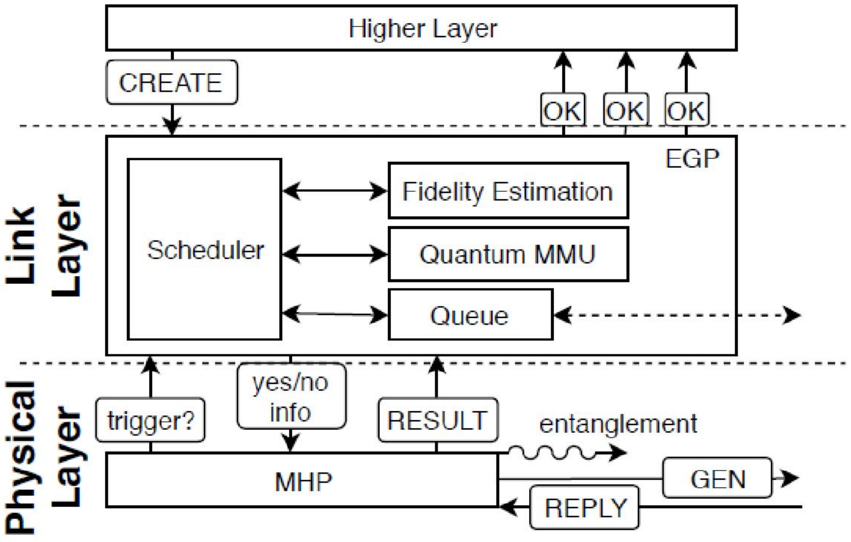
Figure 2: A schematic of a 3-node network including switch and network controller.

General quantum switching scheme studied through simulations

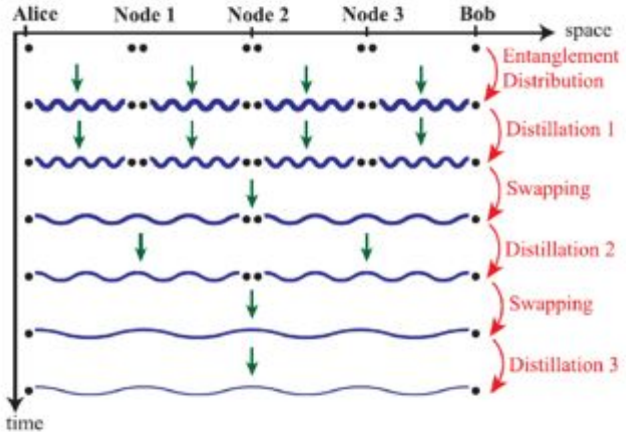
T. S. Humble et al., Oak Ridge National Laboratory, 2019

CV Quantum Repeater Protocol

- ‘Link Layer’ manages and schedules creation of ebits
- ‘Physical Layer’ establishes entanglement
- Requires coordination between layers
  - More of a cross-layer, SDN approach



Dahlberg, et. al. ARXIV 1903.09778v1



Field trials and test bed experiments

MONET Project 1996

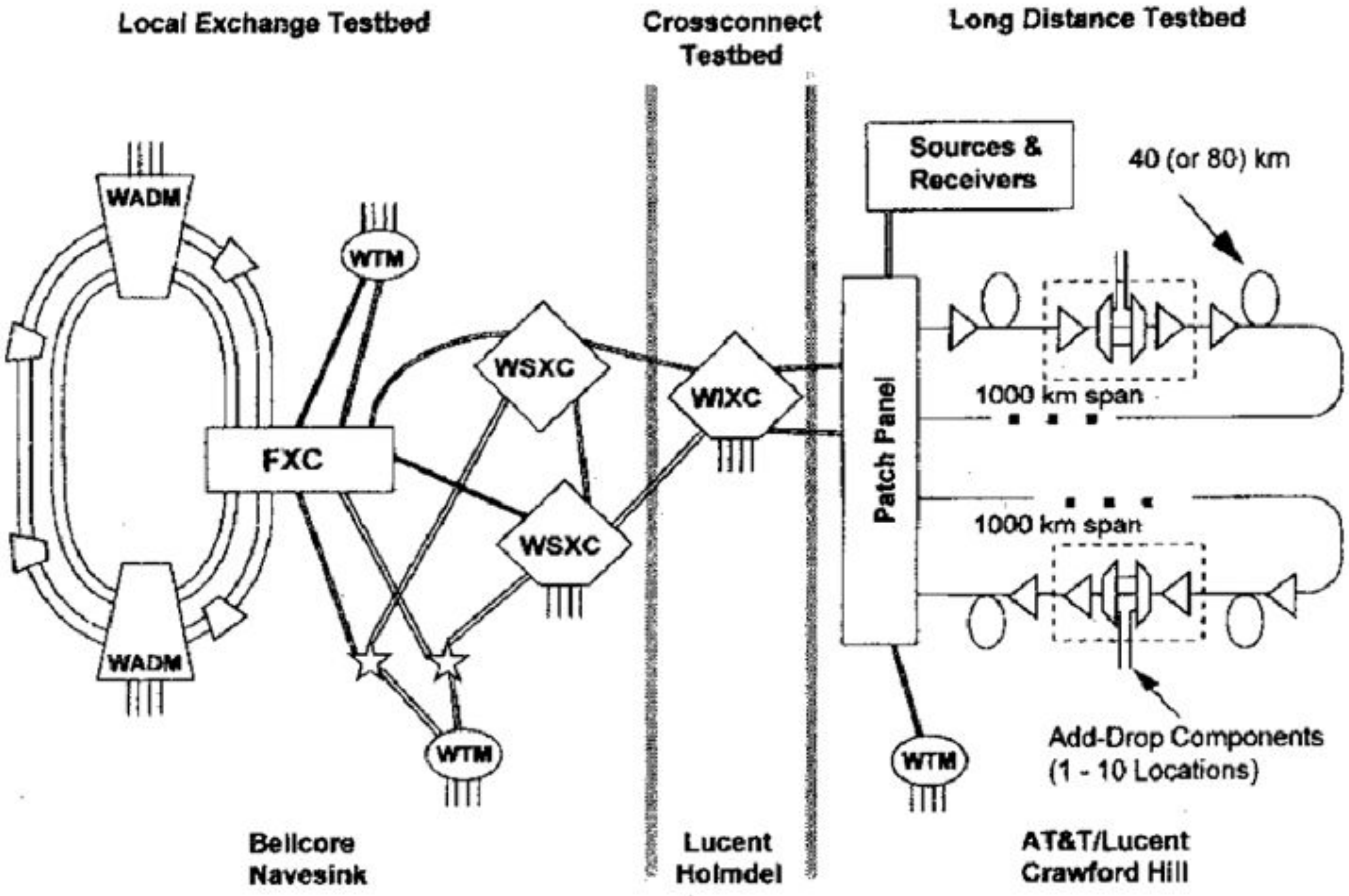
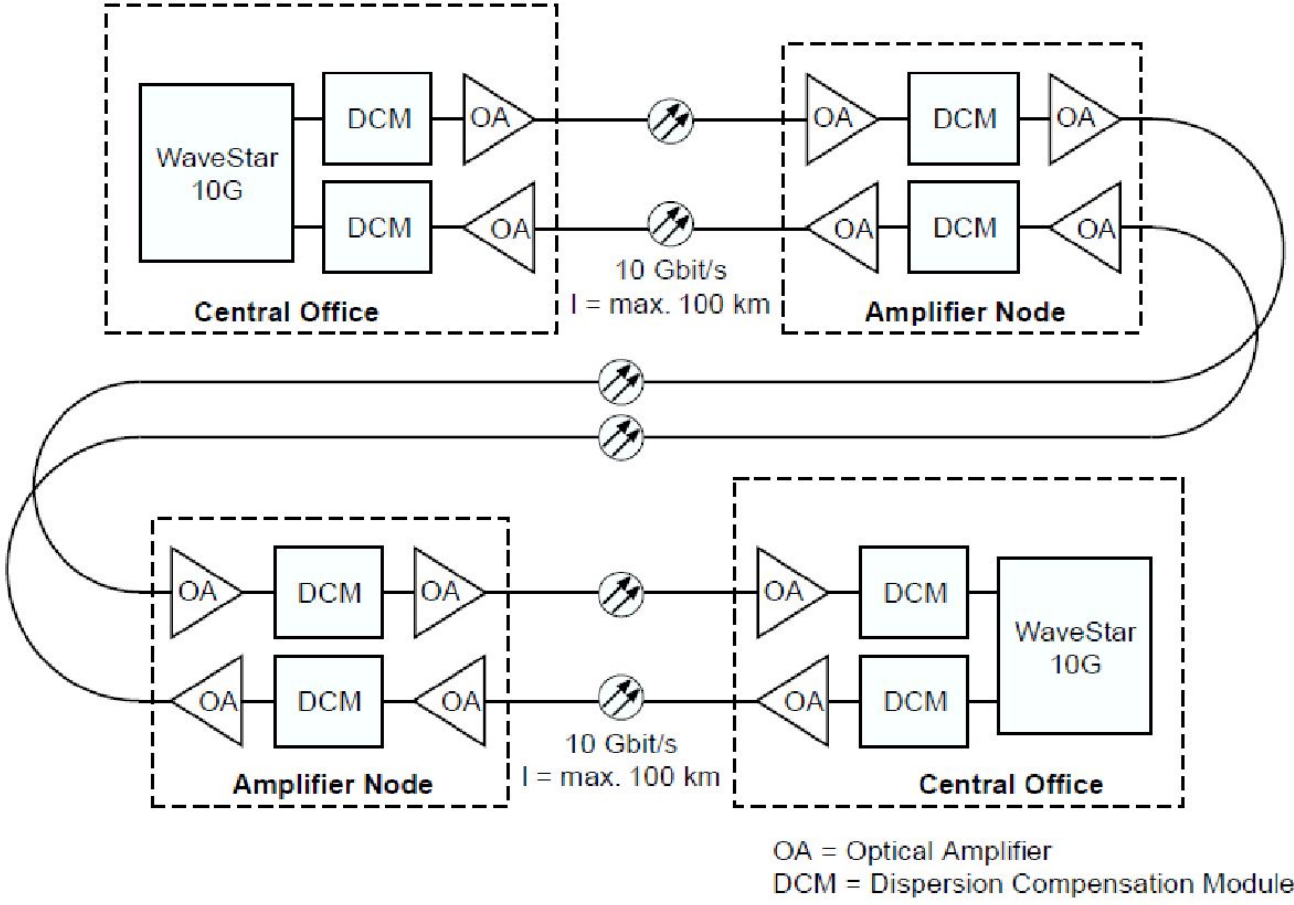


Fig. 4. The MONET New Jersey network.

R. Wagner, et. al., JLT 1996

What they built

- Point to point systems
- <6 fiber spans
- Each system manually designed and tuned for deployment



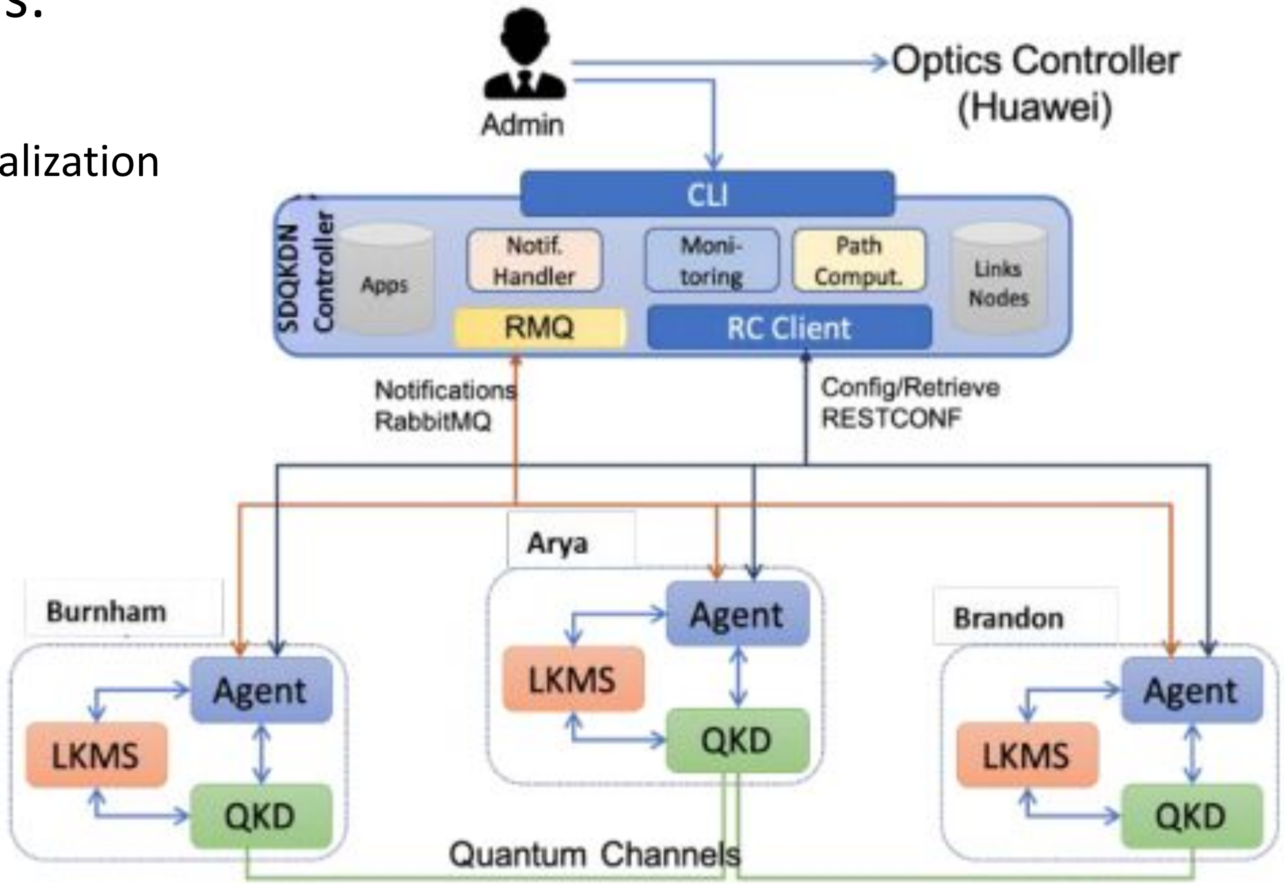
Technologies that got dropped

- Acousto-optic Tunable Filters
- Coherent transceivers (to return 20 years later)
- Wavelength cross-connects & ADMs (to return 10 years later)
- Tunable Transceivers (to return 10 years later)
- Mesh networks (to return 15 years later)
- SDM is becoming multiple parallel fibers

Metro Network Demonstration

- QKD integrated with classical network using SDN control
  - WDM CV-QKD along with classical signals (reduced power)
  - Used local QKD managers on each node
  - Showed multiple network functions:
    - Quantum secured data plane
    - Quantum secured control plane
    - Quantum secured network function virtualization

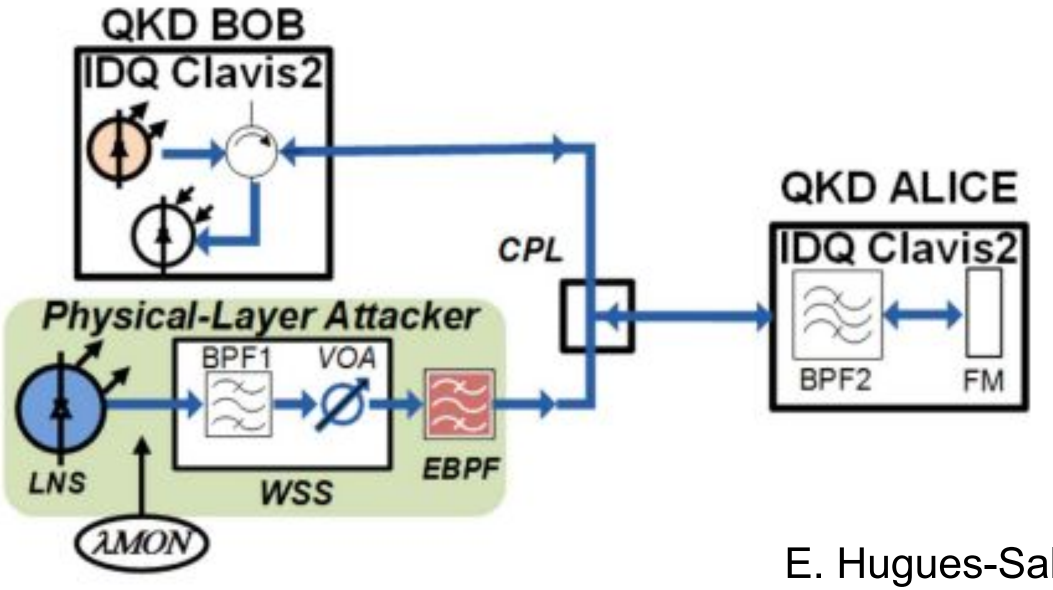
V. Martin et al., Center for Computational Simulation and ETSI Informáticos, Telefónica, Huawei, ICTON 2019

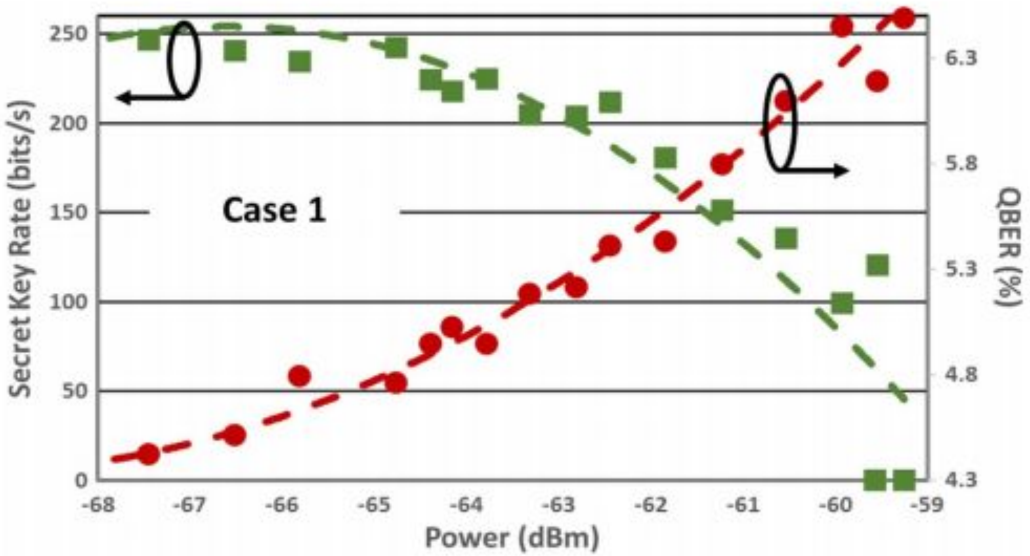


Bristol QKD SDN Experiments

Use SDN control functions to repond to different types of network attacks

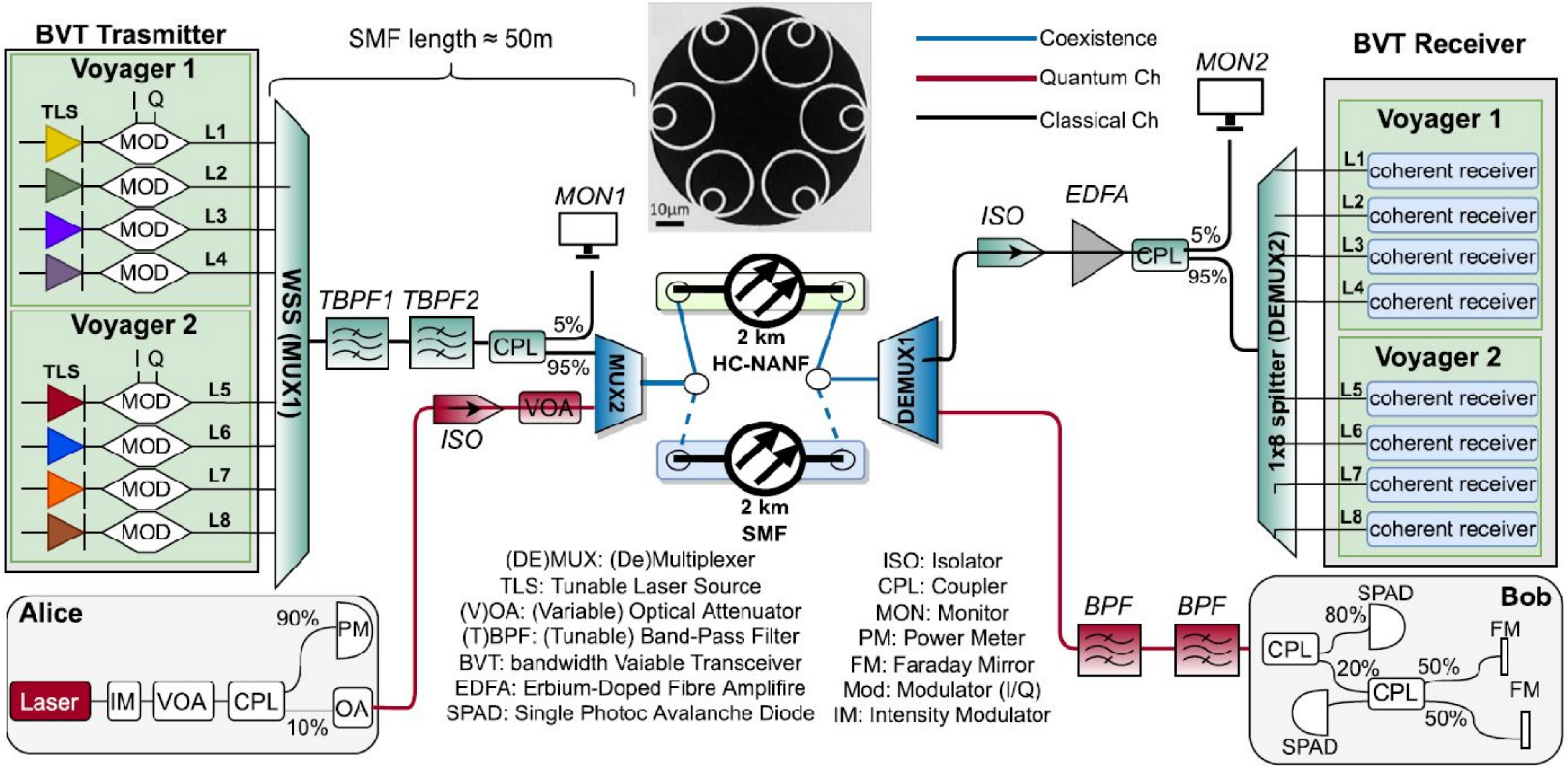
- Monitor SKR and QBER
- Respond to optical scattering from attacker into quantum channel





E. Hugues-Salas et al., University of Bristol, JOCN 2019

Hollow Core Fibre Experiments

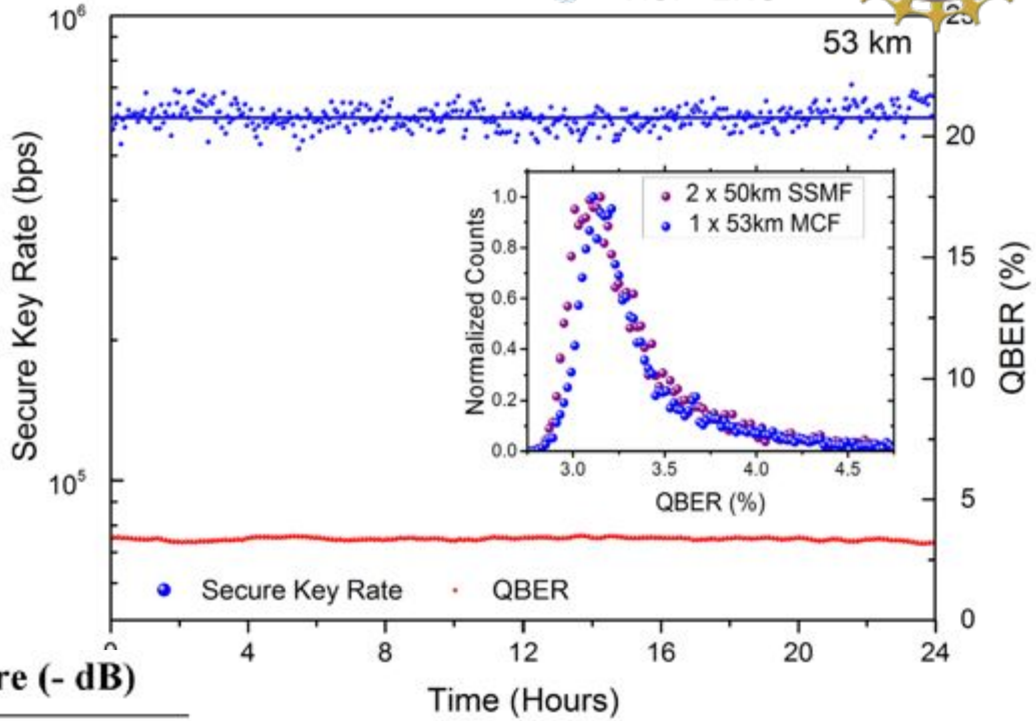


Bristol & Southampton: O. Alia et al., JLT 2022

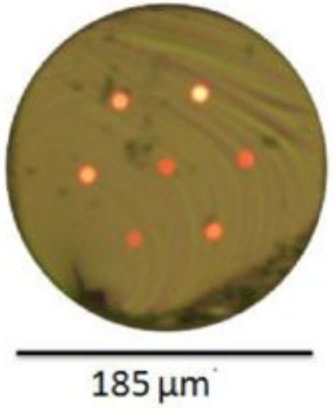
Multi-Core Fibre Experiments

Separate classical and quantum signals in different cores

- Linear crosstalk below 50 dB
- Use 10 Gb/s OOK signals at 0 dBm



(a)



(b)

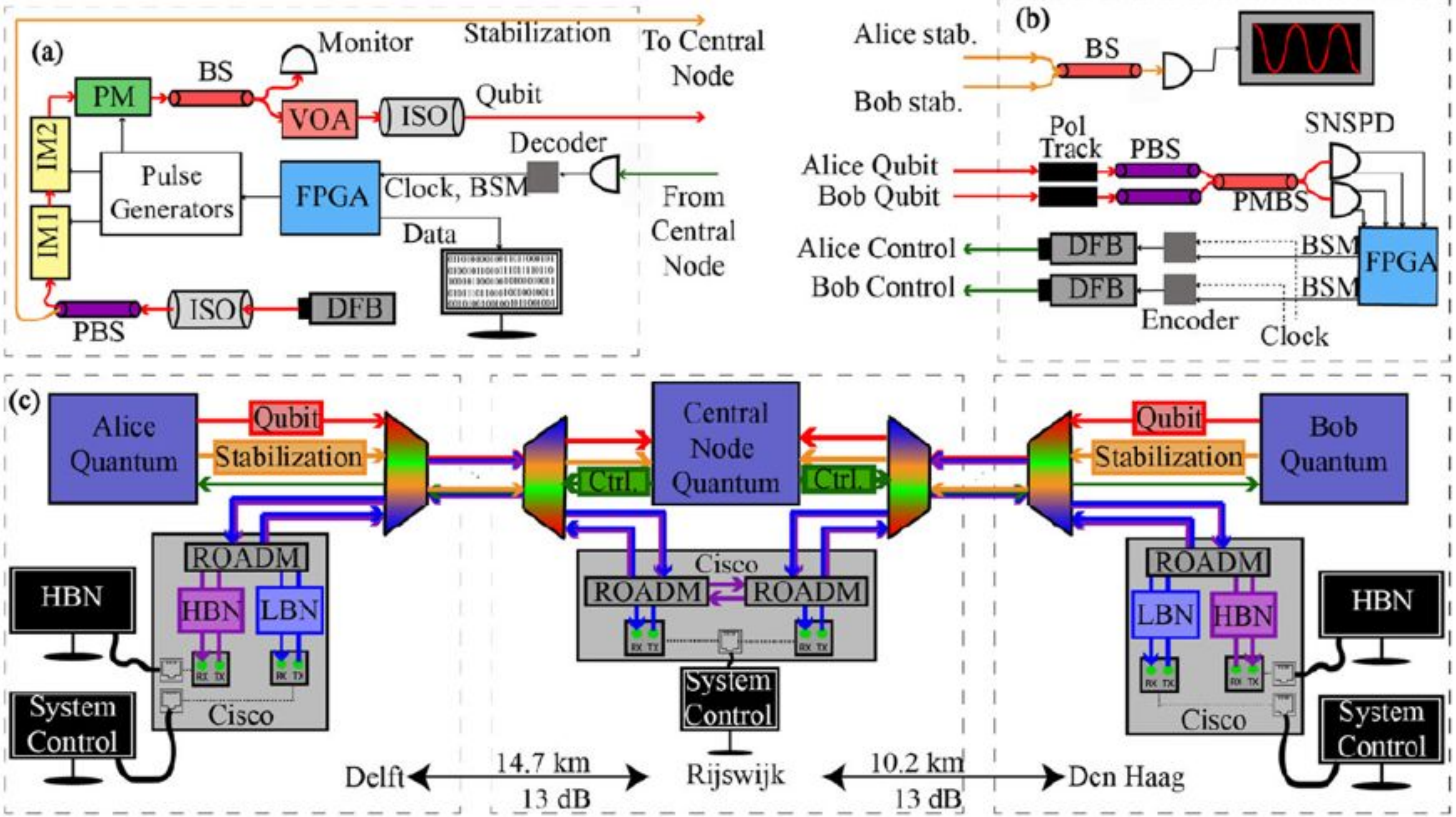
Leakage into central core (- dB)

Core	Forward	Backward
1	56.2	77.8
2	63.8	79.9
3	58.5	83.5

Toshiba & Cambridge: J. F. Dynes et al., Opt. Express 2016

MDI-QKD Field Trial

- Multiplexed with ROADM classical DWDM network
- 1310 nm QKD signals
- 1548 nm classical control channel
  - Clock distribution
- Frequency stabilized
- Polarization tracking



QuTech: R. C. Berrevoets, et. al. Nature Communications 2022

Further Reading

- Optical Fiber Telecommunications Vol. III-VI, Elsevier
  - Kaminow, Koch, Li, Willner, eds., chapters by leading experts on key topics spanning history of optical communications
- B. Mukherjee, I. Tomkos, M. Tornatore, P. Winzer, Y. Zhao, eds., Springer Handbook of Optical Networks, Springer 2020
- Papen, G. C. and Blahut R. E.: Lightwave Communications, Cambridge University Press 2019
- Cvijetic, M., Djordjevic. I. B.: Advanced Optical Communication Systems and Networks, Artech House 2012
- Agrawal, G.: Fiber-Optic Communication Systems, 4th Ed., Wiley 2010

Course Evaluation Survey

Center for Quantum Networks
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We value your feedback on all aspects of this short course. Please go to the link provided in the Zoom Chat or in the email you will soon receive to give your opinions of what worked and what could be improved.

CQN Winter School on Quantum Networks

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