Center for Quantum Networks

# Quantum Networks and the Role of Classical Networks

**Dan Kilper**

**University of Arizona**

**November 13, 2020**

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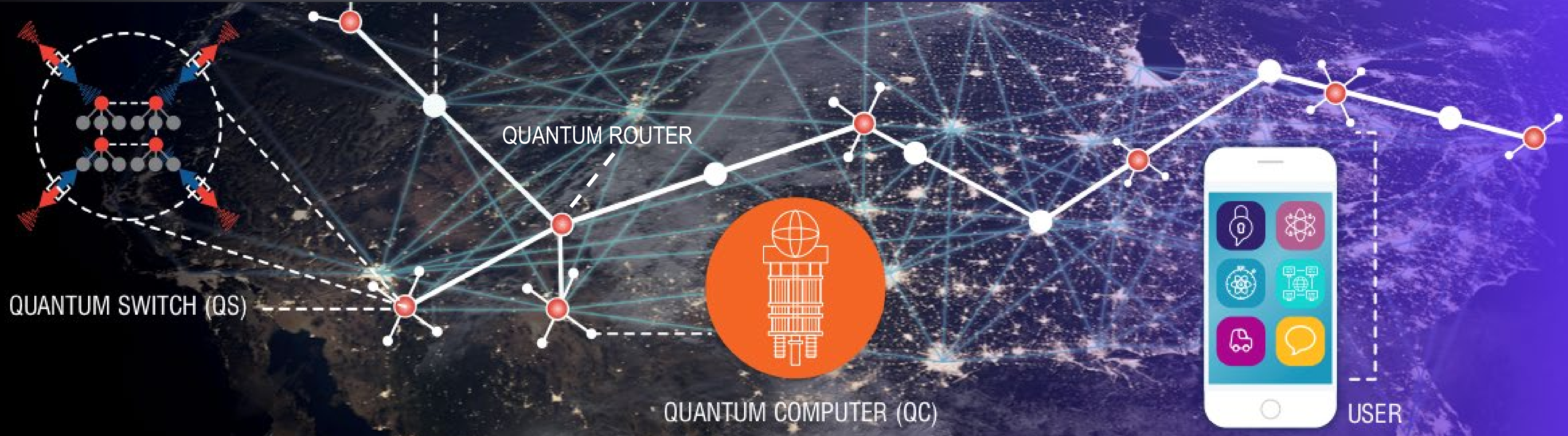
# The Quantum Internet

**Vision:** **The foundation for a socially responsible quantum internet which will spur new technology industries and a competitive marketplace of quantum service providers and application developers for the benefit of all**

**Mission:** **Develop the first quantum network enabling fully error-corrected, high-speed and long-range quantum connectivity between multiple user groups enabled by quantum repeaters, education pathways for a large and diverse workforce, and a roadmap for the just and equitable deployment of quantum internet technology and its transformative applications**

Saikat Guha
Director

## Universities

- The University of Arizona
- MIT
- Harvard
- Yale
- NAU Northern Arizona University
- University of Massachusetts Amherst BE REVOLUTIONARY
- Howard University
- University of Oregon
- The University of Chicago
- BYU

## Industry

- General Dynamics
- Lockheed Martin
- Raytheon BBN Technologies
- Xanadu
- Applied Materials
- FT
- Corning
- OSAGE University Partners
- KCK
- Flybridge Capital Partners

## FFRDCs

- NIST National Institute of Standards and Technology U.S. Department of Commerce
- Sandia National Laboratories

## International Partners

- IQC Institute for Quantum Computing
- Canada NRC·CNRC
- uOttawa
- Imperial College London
- TU Delft
- LKB
- University of Warsaw

## Incubators

- The University of Arizona Eller College of Management McGuire Center for Entrepreneurship
- Yale Center for Business and the Environment
- Martin Trust Center for MIT Entrepreneurship
- Technology & Entrepreneurship Center at Harvard

## Education Partners

- Pueblo Warriors
- Gallup McKinley County Schools
- Sunnyside Unified School District
- Flagstaff Unified School District

# Why a Quantum Internet?

- **[fundamentally-powerful] computing**
- **[provably-secure] communications**
- **[high-resolution] sensing**

- **Quantum-enabled applications that we cannot imagine today**

# Key Societal Impacts

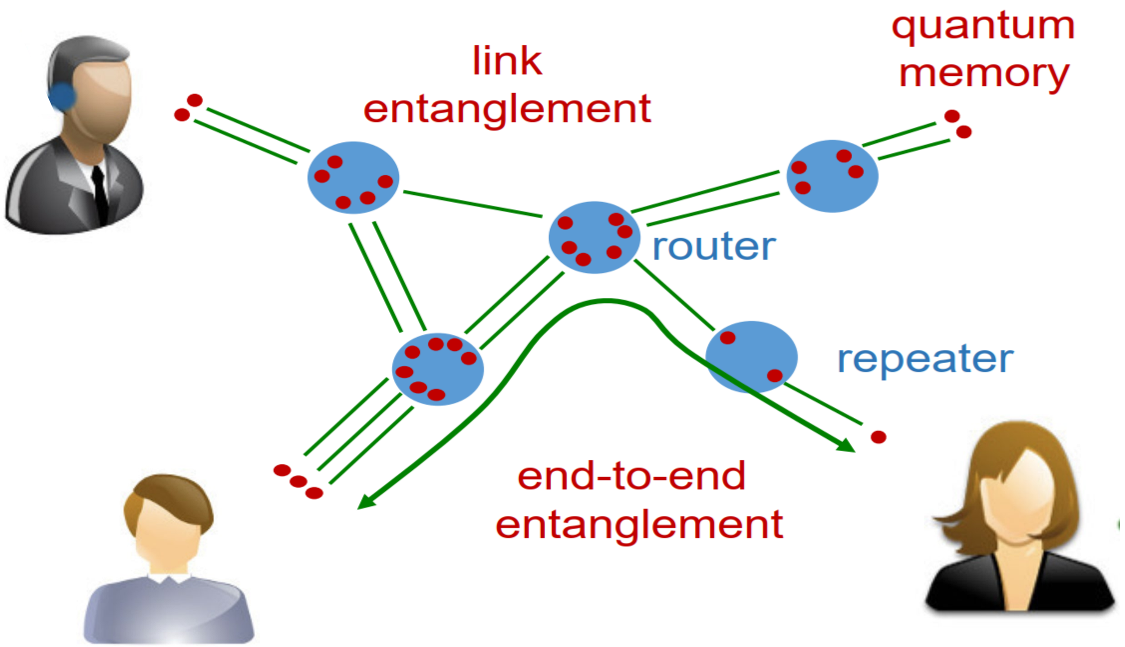
- Data security and privacy that is “future proof”
  - Promotes national security, personal finance, electronic medical records

- Pattern search and decision making on large distributed data
  - Enables personalized medicine, self-driving cars, accurate weather and financial modeling

- Bringing the power of quantum computing to the masses
  - Democratization of access

# Quantum Networks

- Quantum Network that provides shared entanglement, and quantum information transfer to (many) users that is robust to noise, workload dynamics, eavesdroppers, and failures
- Quantum memories or registers are NICs for quantum networks

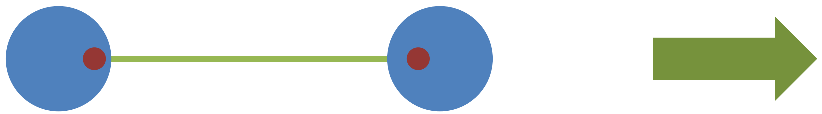


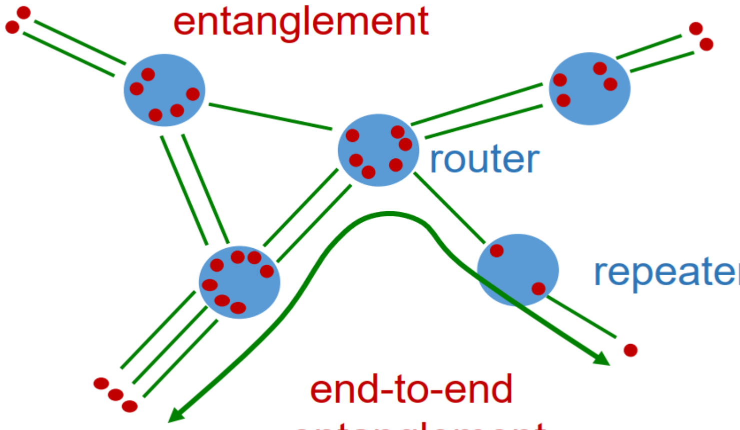
# State of the Art

- Two-party entanglement across a single point to point, loss limited connection

# Challenges

- Quantum network design entirely different from classical counterpart
- Loss & noise kill quantum entanglement
- Single photons with no equivalent to an amplifier in quantum networks

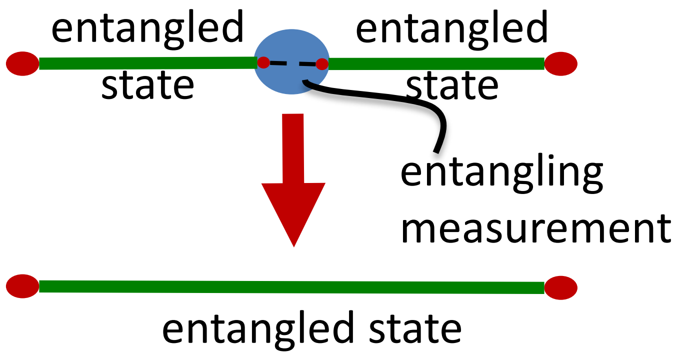




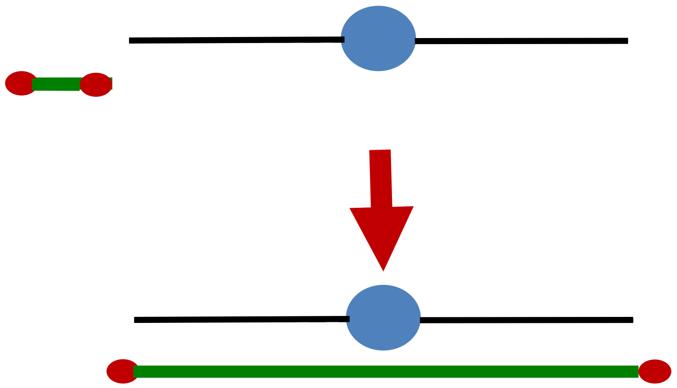
# Quantum Network Services

- Two quantum network services:
  - creation of entanglement
  - transfer of quantum information

Create entanglement




Transfer quantum information



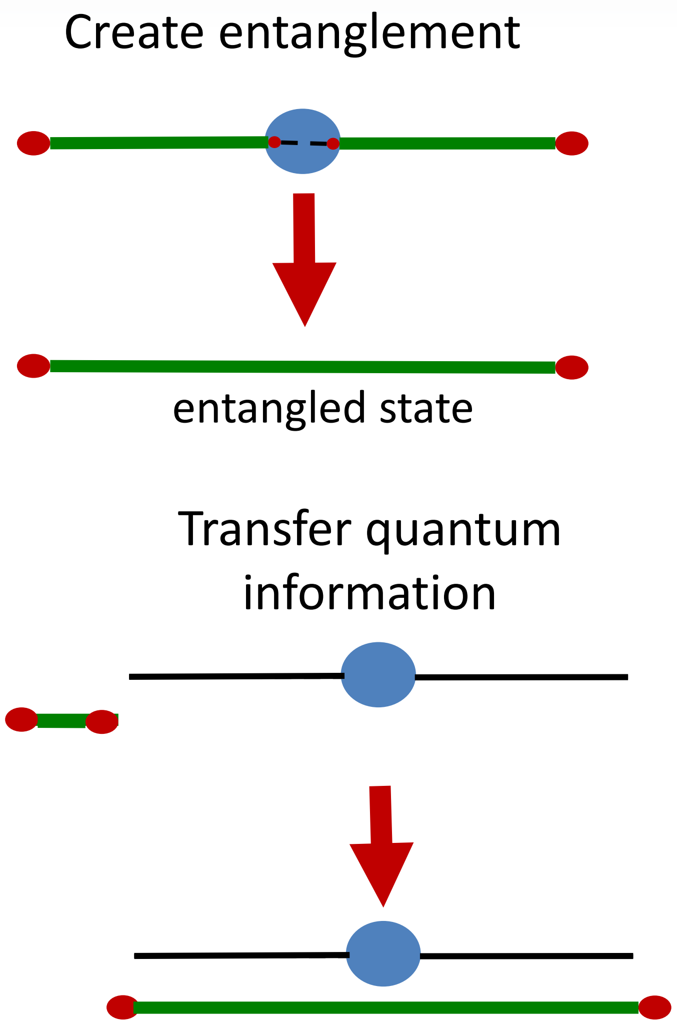
Vardoyan, Guha, Nain, Towsley *Qcrypt'19*

# Quantum Network Services

- Two quantum network services:
  - creation of entanglement
  - transfer of quantum information

Challenges

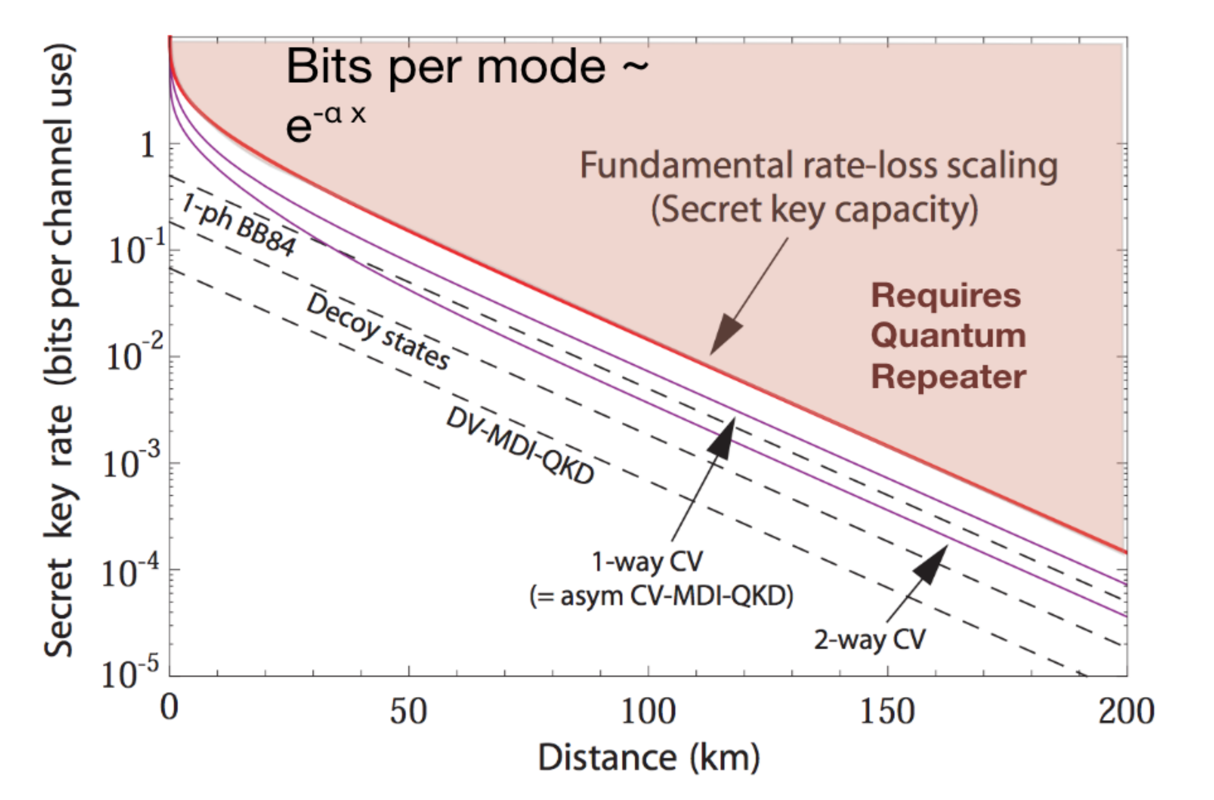
- complexity, resource usage, performance
- key factor: how to overcome effects of noise
  - quantum state purification & error correction




Vardoyan, Guha, Nain, Towsley *Qcrypt'19*

# Quantum Repeater

The repeaterless bound: rate falls off exponentially with photon transmission probability p~$e^{-kL}$




M. K. Bhaskar, R. Riedinger, B. Machielse, D. S. Levonian, C. T. Nguyen, E. N. Knall, H. Park, D. Englund, M. Lončar, D. D. Sukachev & M. D. Lukin Nature volume 580, pages 60–64 (2020)
M. Takeoka, S. Guha & M. Wilde, Nature Communications 5 (2014)

Boston
p~1%
~1 Mqubit/sec*

p~$10^{-6}$
<100 qubits/hour

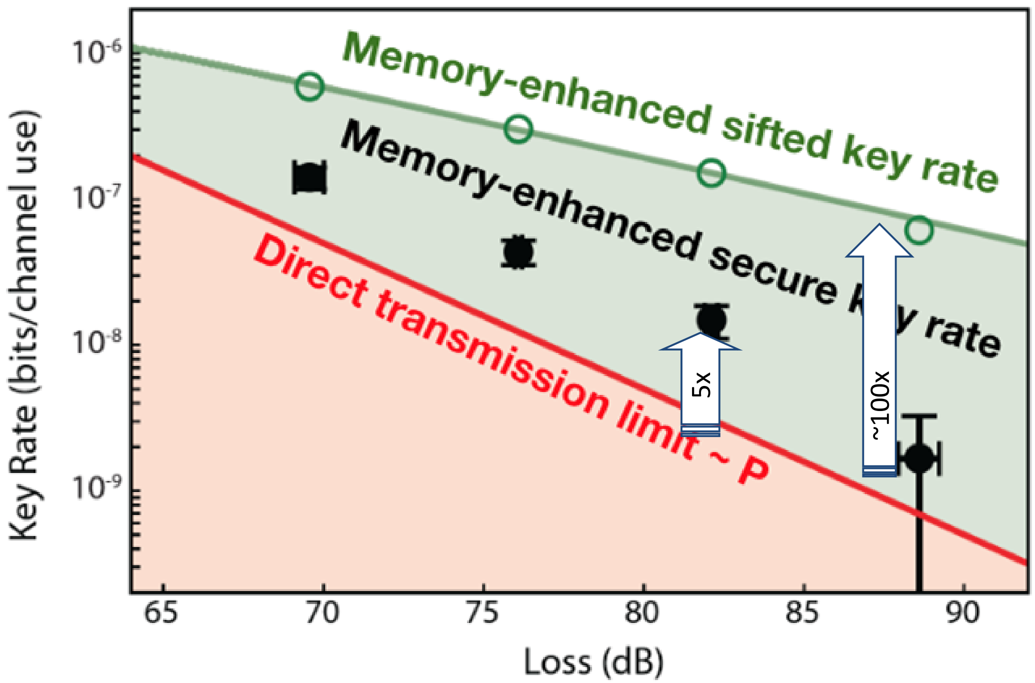
New York
Providence
Albany
Atlantic City

Rate scales exponentially with distance

# Experimental demonstration of memory-enhanced quantum communication


M. K. Bhaskar,[1,*] R. Riedinger,[1,*] B. Machielse,[1,*] D. S. Levonian,[1,*] C. T. Nguyen,[1,*] E. N. Knall,[2] H. Park,[1,3] D. Englund,[4] M. Lončar,[2] D. D. Sukachev,[1] and M. D. Lukin[1,†]

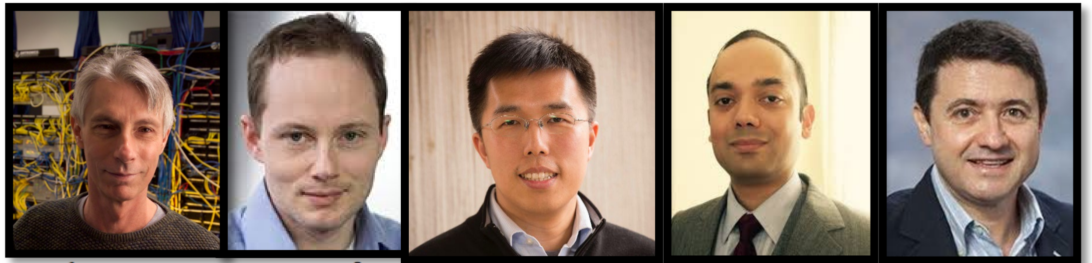
[1] *Department of Physics, Harvard University, Cambridge, MA 02138*
[2] *John A. Paulson School of Engineering and Applied Sciences, Cambridge, MA 02138*
[3] *Department of Chemistry and Chemical Biology, Harvard University, Cambridge, MA 02138, USA*
[4] *Research Laboratory of Electronics, MIT, Cambridge, MA 02139, USA*



npj | Quantum Information

www.nature.com/npjqi

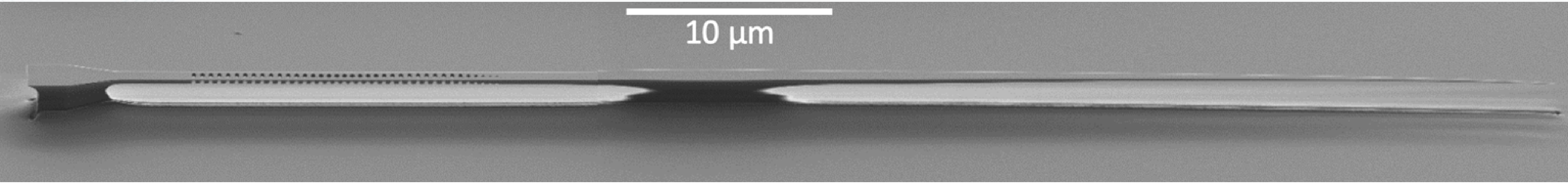



**ARTICLE** **OPEN**

# Routing entanglement in the quantum internet


Mihir Pant[1,2], Hari Krovi[2], Don Towsley[3], Leandros Tassiulas[4], Liang Jiang[5,6], Prithwish Basu[7], Dirk Englund[1] and Saikat Guha[2,8]

# Diamond Color Center Based Memories



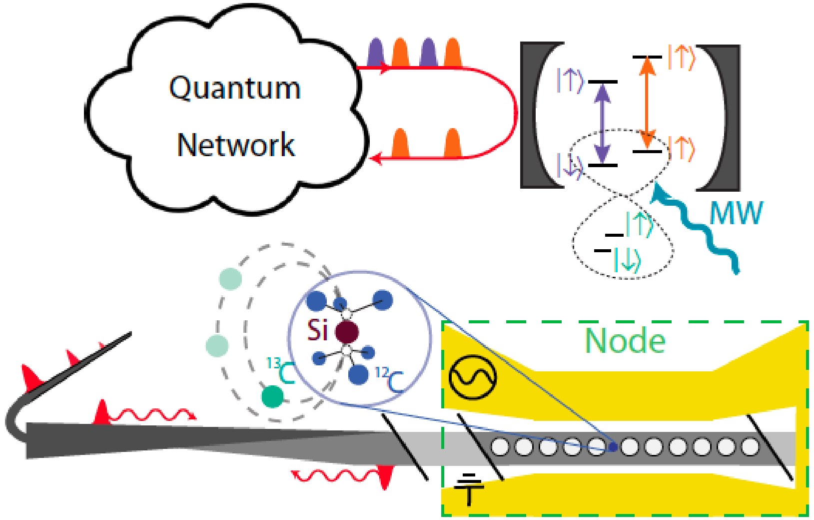

Silicon-Vacancy (SiV): good emitter & long spin spin coherence time (~ 10 ms @ 100 mK)

Fiber coupled photonic crystal cavity in diamond: high co-operativity ($C=4g^2/\kappa\gamma$) spin-photon interface, essential for efficient repeater realization;

**Co-operativity**
2016: C ~1
2017: C ~ 5
2018: C ~ 20
2019: C ~ 130

Using this platform, we demonstrated:

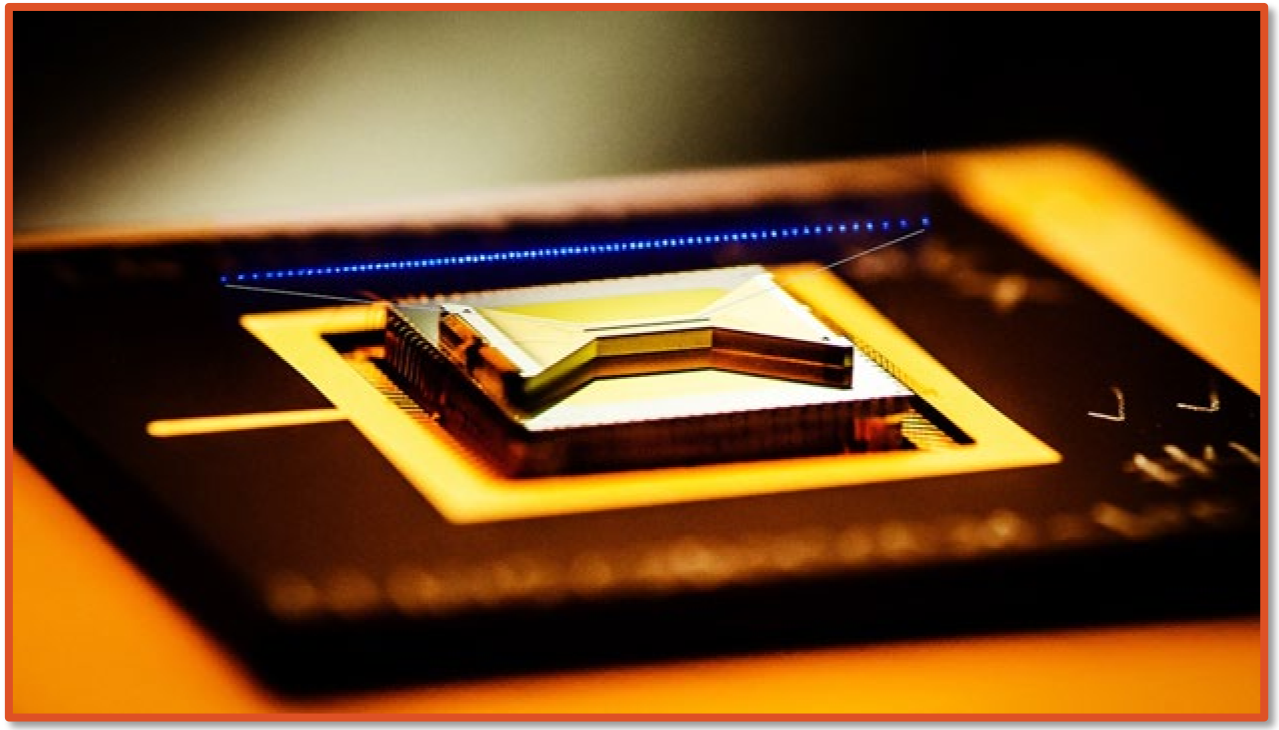
- Photon number router & single photon switch
  A. Sipahigil, et al, *Science*, **354**, 847 (2016)
- Cavity mediated Interactions between spins
  R. Evans, et al, *Science,* **362**, 662 (2018)
- Quantum network node
  C. Nguyen, et al, *arXiv: 1907.13199* (*to appear in PRL*) (2019)
- Memory enhanced quantum communication
  M. Bhaskar, et al, arXiv: 1909.01323 (in review in Nature)




Lukin, Loncar & Englund collaboration

# Many Repeater Technologies

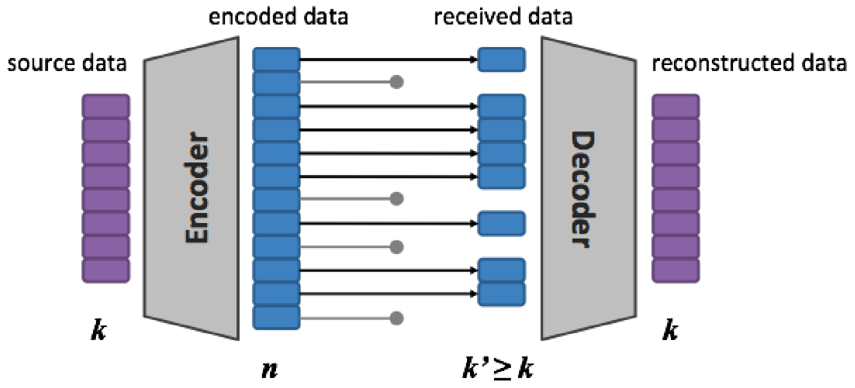
- Superconducting Qubits
- Trapped Ions
- Color Centers
- Neutral Atoms
- All-Photonic
- Others…



Jungsang Kim, Duke, IonQ

# Extensible quantum networks require error mitigation

Error correction in today's internet



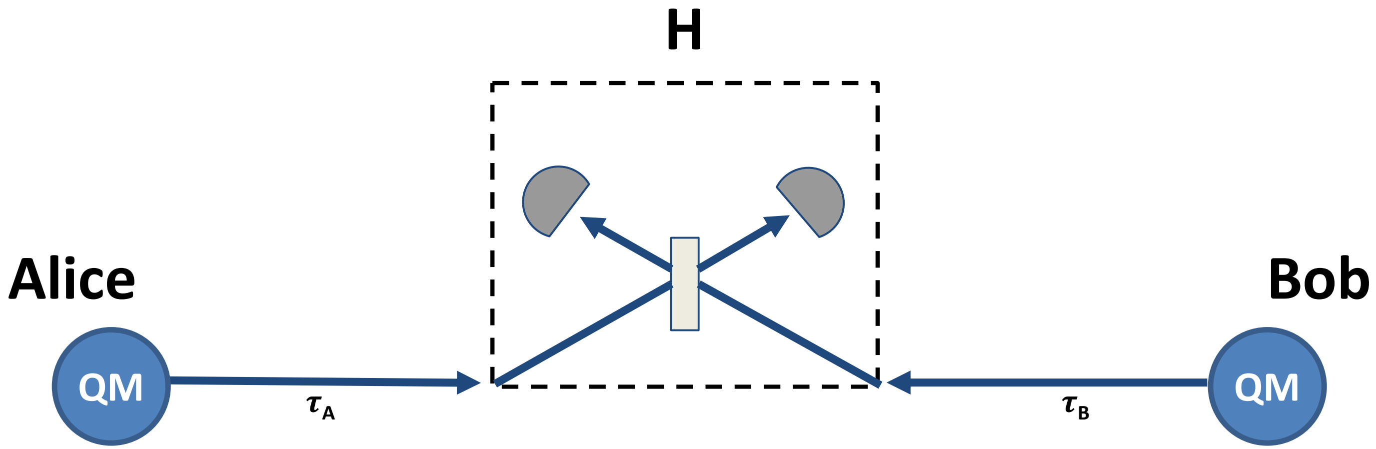

quantum internet

Approaches to be explored for the NSF CQN:

- Entanglement purification
- Quantum error correction

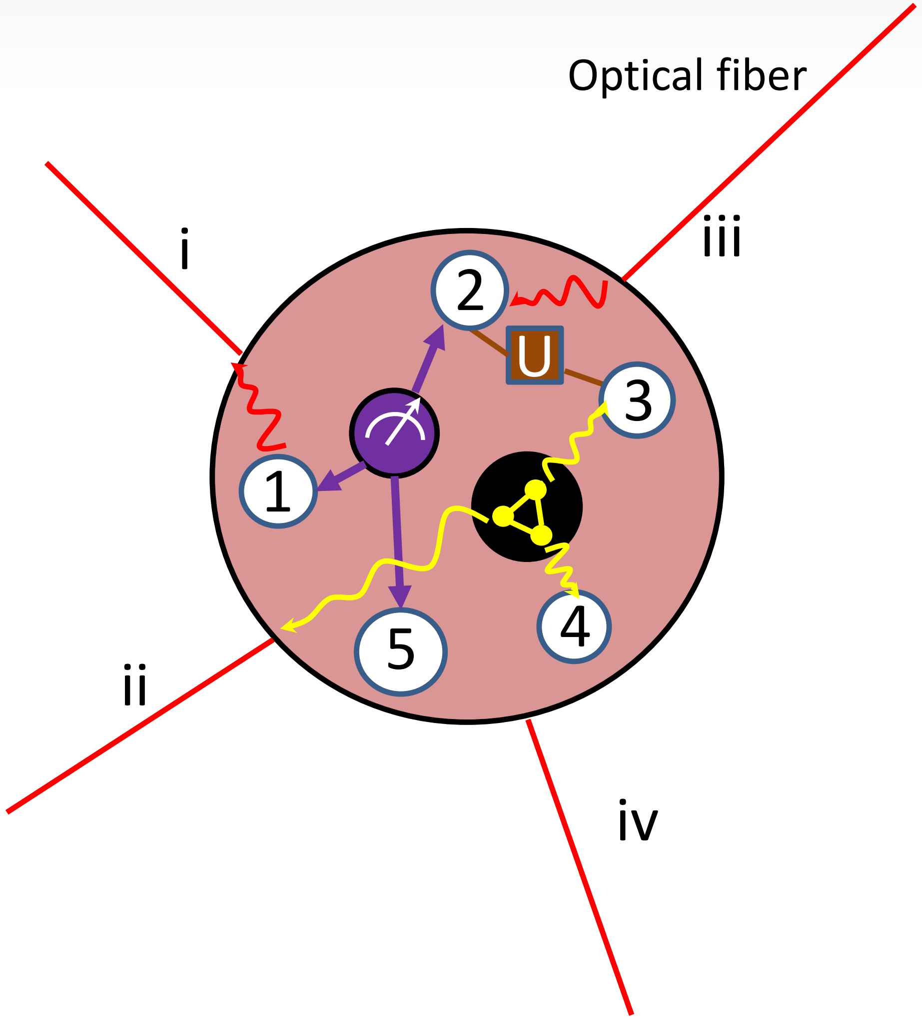
# Basic Repeater Link Unit

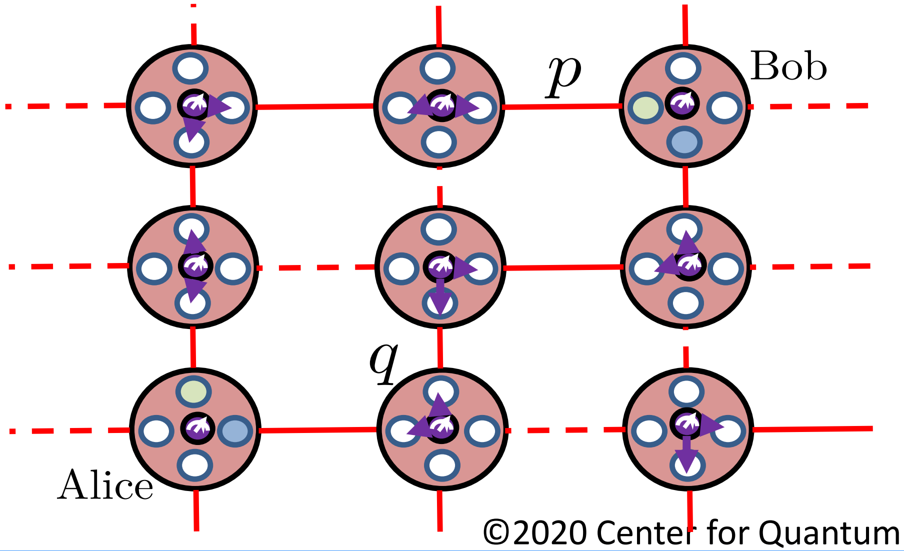
- Single hop link, QM's are essentially small quantum computers
- Need to maintain equal propagation times to interfere photons at Heralding node
- Need ns speed clocking across all nodes
- Single photon, polarization sensitive
  - Many schemes require phase stability/locking
- Fidelity of entanglement depends on losses, memory life, qubits



# Building a Quantum Network

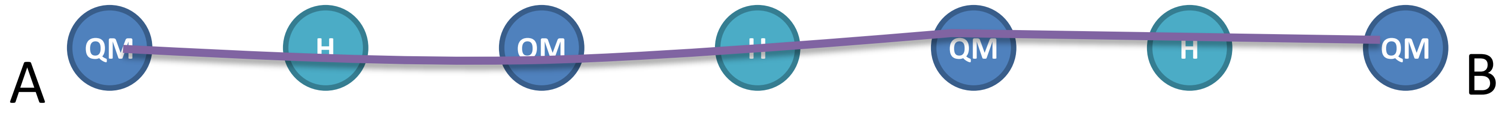
- Quantum memories and interface to photon
- Quantum measurements
- Quantum logic on qubits held in memories
- Multi-photon entanglement sources
- Classical computing and communications

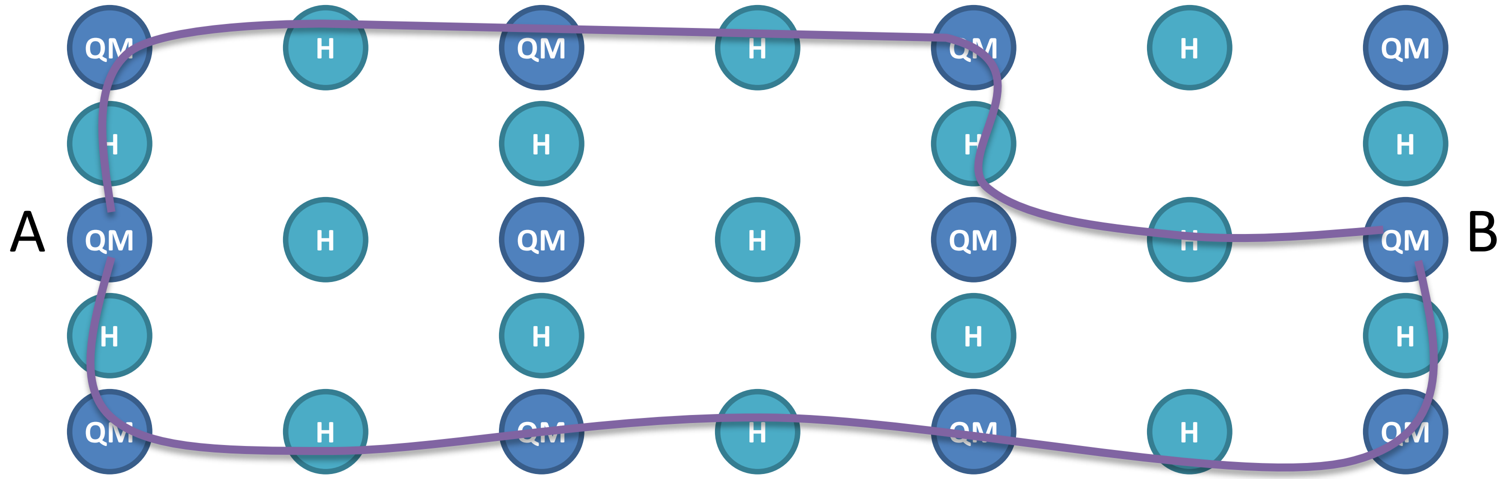


# Repeater Links

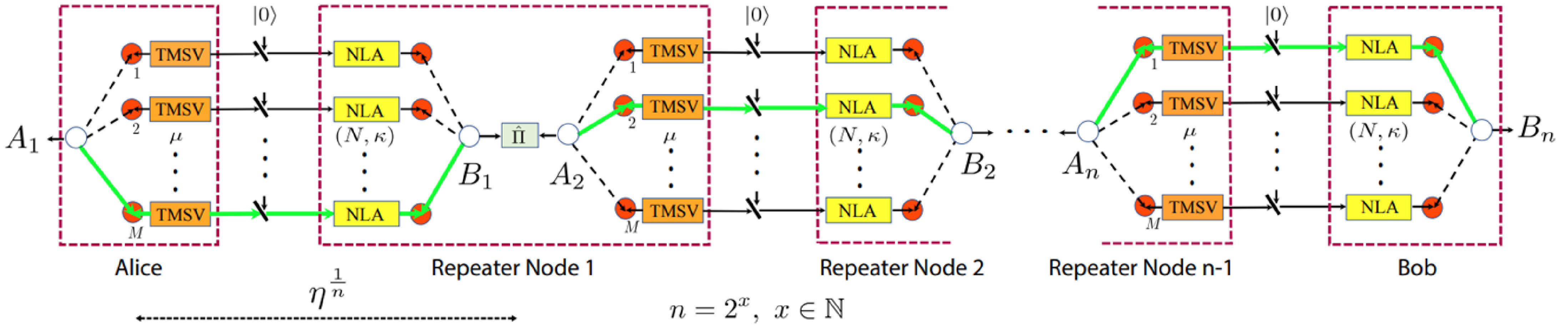
- Single links have low probabilities of success
- Multi-path or cluster states increase success rates




M. Pant, et. al. arXiv:1708.07142v2 2017

# Multiplexed Repeaters

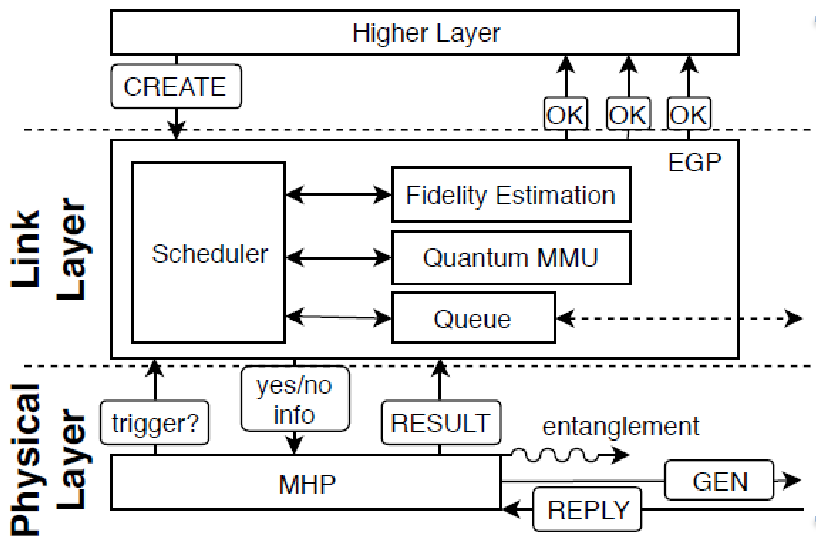



Seshadreesan et al., "A continuous-variable quantum repeater based on quantum scissors and mode multiplexing", Phys. Rev. Research 2, 013310 , March 2020

- Create entanglement between Alice A1 and Bob Bn
- Generate two mode squeezed vacuum states at each node
- Attempt to entangle M states between neighboring nodes
- Use switches to create end to end channel during given clock cycle
  - Nanosecond speeds

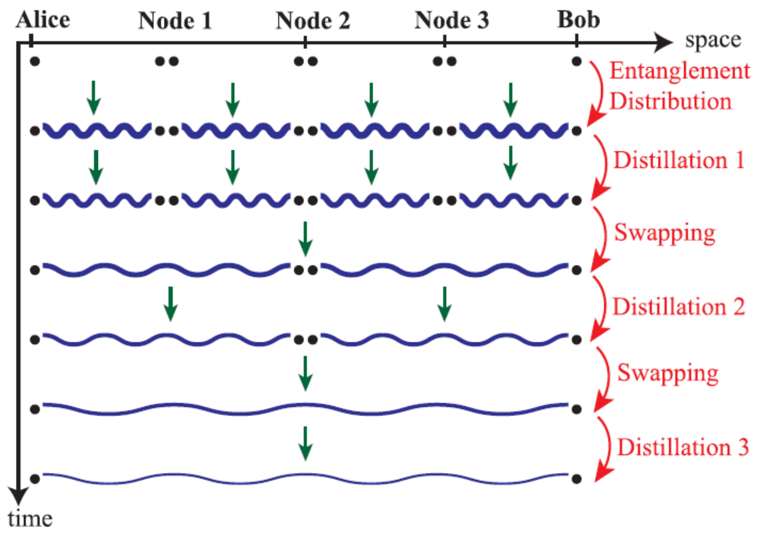
# Quantum Repeater Control Planes

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




All Classical Communication!

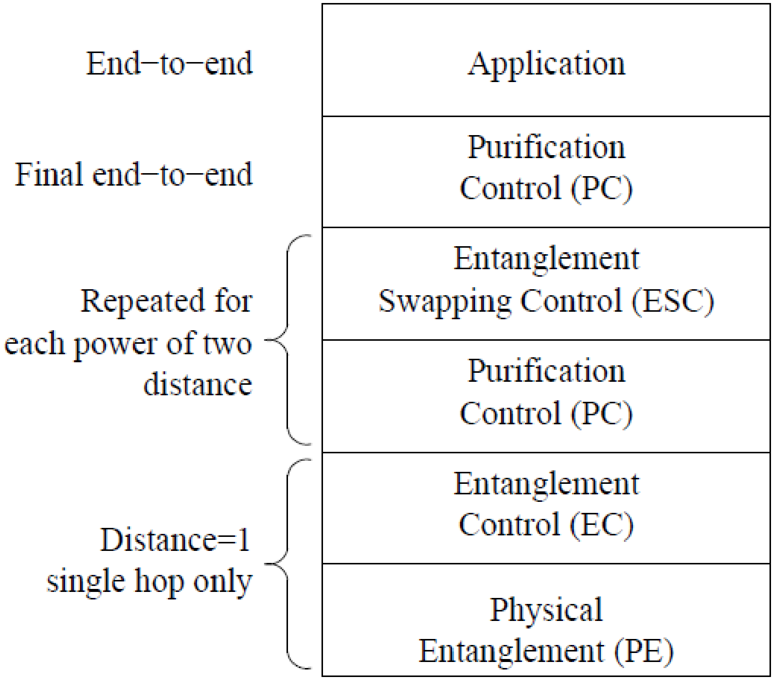
Dahlberg, et. al. ARXIV 1903.09778v1



# Quantum Network Layers

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

Dahlberg, et. al. ARXIV 1903.09778v1

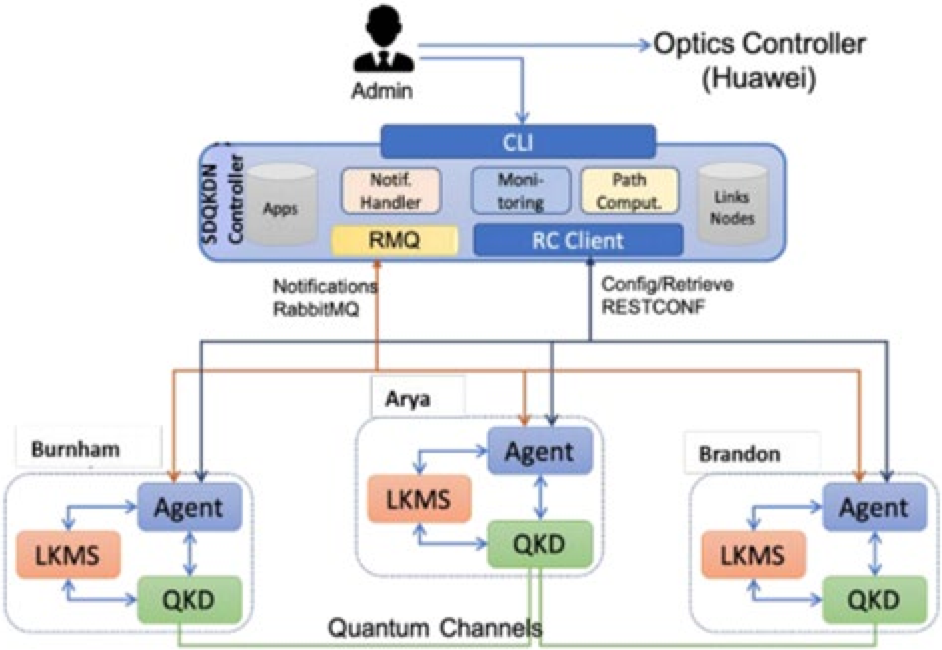



Van Meter, et. al. ARXIV 0705.4128v2

# Quantum-Classical Coexistence

- QKD integrated with classical network using SDN control
  - WDM CV-QKD along with classical signals
  - 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



# Forms of Coexistence

- In-Channel: time multiplexed with classical signals
- In-Band: spectrally muxed in-band (1550 nm) with classical
- Out-of-Band: Separate bands, e.g. 1300nm quantum/1550 nm classical
- Separate fiber: quantum signals in separate fiber
  - Might still share node optical switches and other resources
- Future quantum network coexisting in SCinet?

# Conclusions

- State of quantum networks similar to optical networks in 1980's & early 1990's
  - Pre-SONET, no optical amplifiers, lab based optical devices
- Classical networks are to quantum networks what electronic data networks are to optical networks
  - Woven into all aspects of quantum networks
  - Control & coordinate physical hardware
  - Manage and coordinate 'higher layer' operations
  - But, generally not carried over the quantum channels, parallel instead
- Still uncertain layering & control architecture

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