Scalable and Robust Integrated Quantum Communication System

Shota Nagayama
Keio University
Mercari, Inc.

Table of Contents

- Introduction of the group
- Distributed quantum computing and Quantum Networks
- Subfields of Quantum Network systems
- Milestone
- R&D Themes in Nagayama PJ (including Background Results/Achievements)
  - Optical technologies
  - Quantum memory
  - Architecture & protocol
  - Application
  - Prototype at Testbed
- Summary

Shota Nagayama

Roughly speaking:

Quantum information processing system researcher,
based on classical Internet technology

mercari R4D

Keio University

- Ph.D. in Media and Governance
- Motivation: Realization of quantum technology as an information system
- Research Subjects: **Distributed Quantum Computers, Quantum Internet**
- Affiliation
  - Senior Researcher at R4D (R&D Division) of Mercari Inc.
  - Project Associate Professor, Graduate School of Media and Governance, Keio Univ.
- Co-innovation activities

Quantum Computing — Internet — Quantum Internet

"Scalable and Robust Integrated Quantum Communication System" Project (Project Manager) Underneath JST Moonshot Target 6
※ started from 2022

MOONSHOT

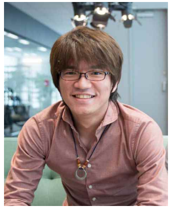
WIDE PROJECT

A consortium that started the Japan Internet by connecting 3 univ. (the Univ. of Tokyo/Keio Univ. / Tokyo Tech) and the U.S. in 1980s. (Board Member)

QITF QUANTUM INTERNET TASK FORCE

Multi-Organization Consortium for the Quantum Internet (Founder and Director)

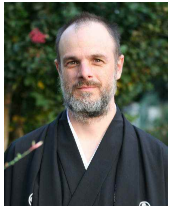
List of PIs

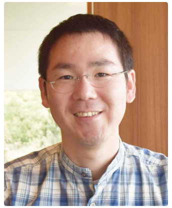

S. Nagayama
Keio U.
Mercari, Inc.

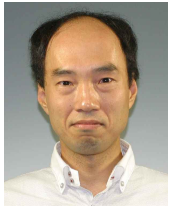

H. Ohno
Kanazawa U.

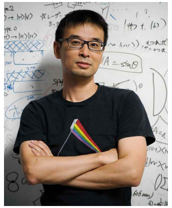

T. Sasaki
U. of Tokyo

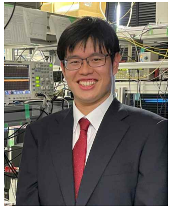

K. Nemoto
OIST


R. Van Meter
Keio U.


R. Ikuta
Osaka U.


M. Takeoka
Keio U.


D. Akamatsu
Yokohama
National U.


K. Niizeki
LQUOM Corp.


T. Horikiri
Yokohama
National U.


H. F. Lei
Yokohama
National U.


H. Tanji
UEC


R. Yamazaki
ICU


Y Yamaguchi
NICT


R. Sasaki
RIKEN


A. Soeda
NII


T. Satoh
Keio U.


Y. Matsuzaki
Chuo U.

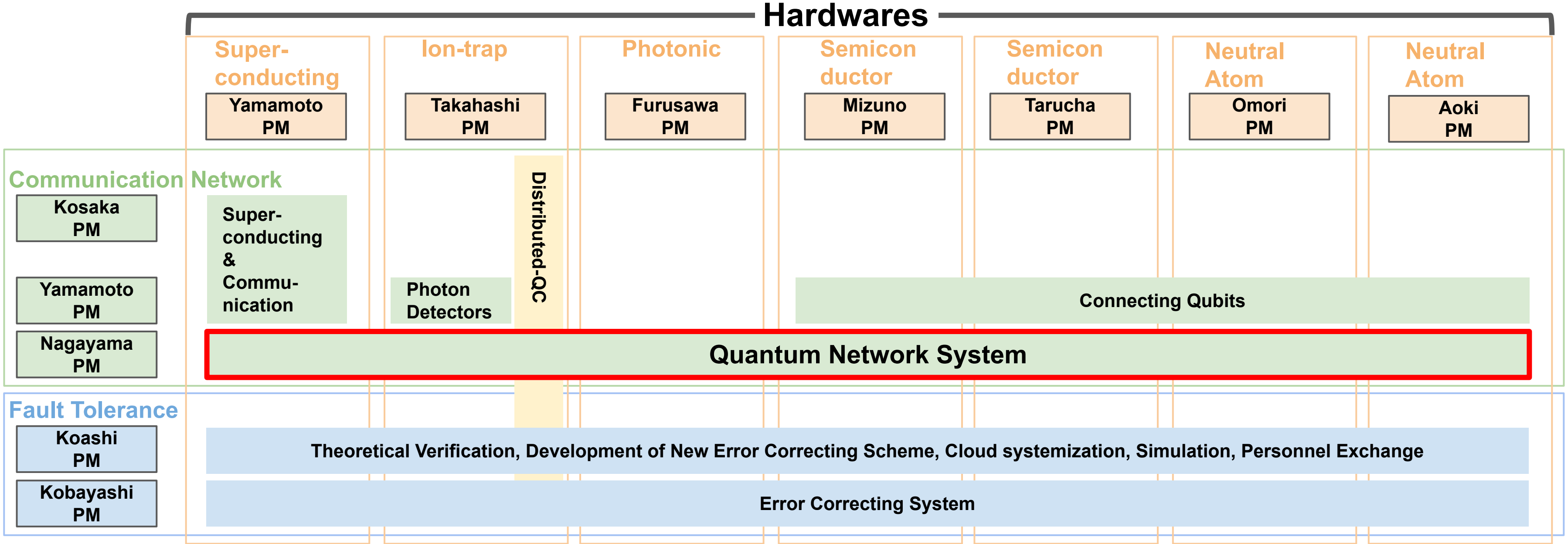

A. Osada
U. of Tokyo

Nagayama PJ's Contribution to Moonshot Goal 6

MOONSHOT RESEARCH & DEVELOPMENT PROGRAM

Three Elements of Large-Scale Distributed Quantum Computers

- Quantum computers themselves
- Quantum Communication Interface
- [main topic] Quantum network that enables free connection between quantum computers



In particular, demonstration of **integrated quantum network system & architecture** that combines **quantum/classical**, **hardware/software**

Distributed Quantum Computer and Quantum Network

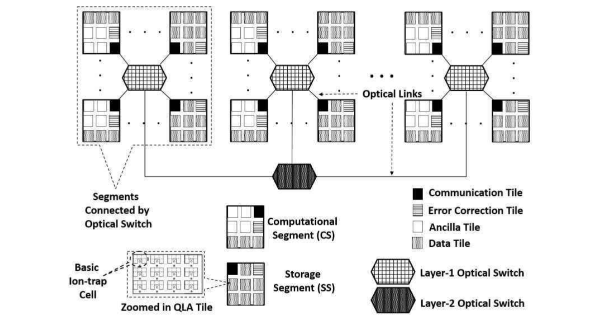


Fig. 3. Overview of the reconfigurable quantum computer architecture analyzed in our performance simulation tool.

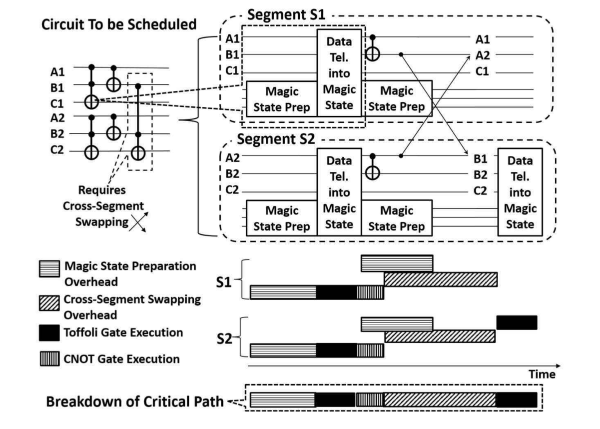


Fig. 6. An example shows tracking of latency overheads comprising critical path of the circuit.

Designing a Million-Qubit Quantum Computer Using a Resource Performance Simulator

- Steane code
- Ion trap
- Optical interconnect
- Multi-level optical interconnect for Steane code ion trap affects possible operation scheduling.

Ahsan, Van Meter, Kim.
ACM JETC 12(4) No.39, July 2016

Application qubit assignment and network topology affect teleportation requirements.

Van Meter, Munro, Nemoto, Itoh.
ACM JETC 3(4) No.2, Jan. 2008

Linear network is best for Ripple adders.

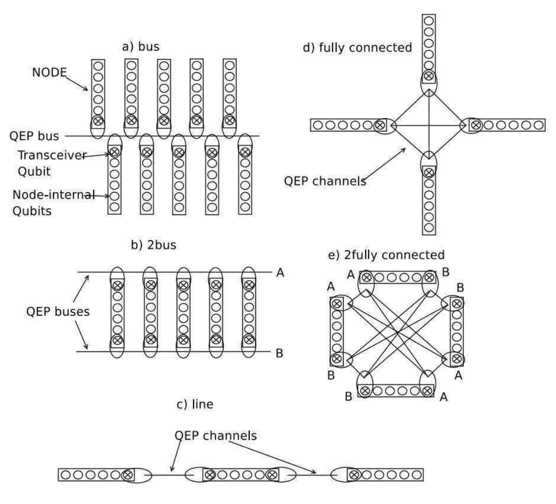
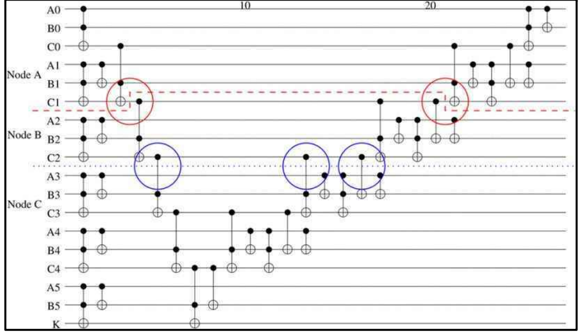
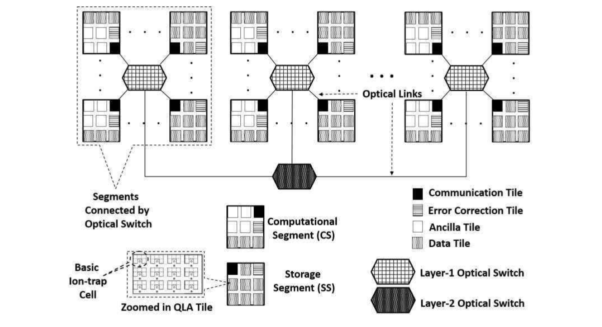


Fig. 4. The five physical topologies analyzed in this paper.



Distributed Quantum Computer and Quantum Network



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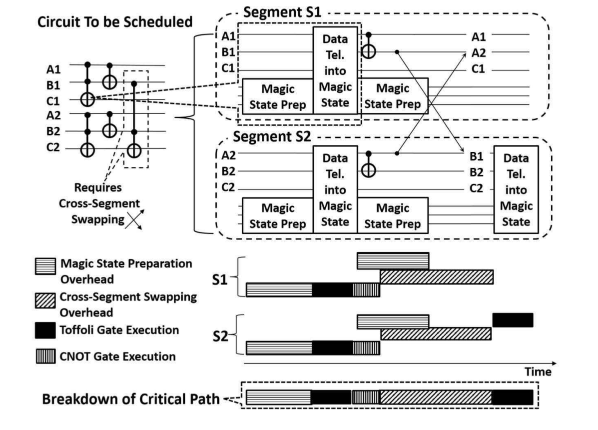

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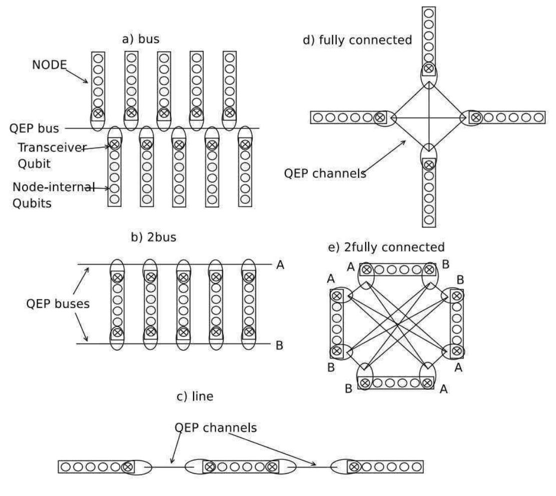

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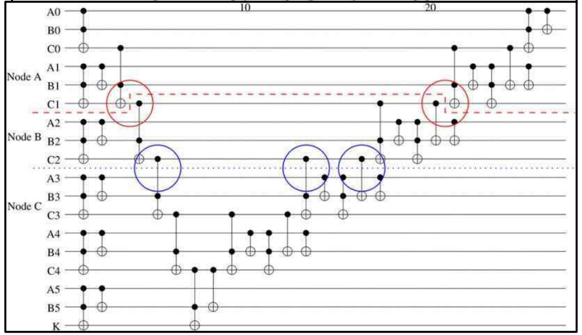


Application qubit assignment and network topology affect teleportation requirements.

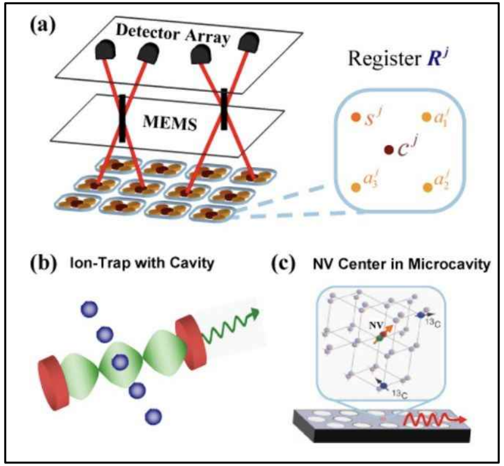
Van Meter, Munro, Nemoto, Itoh.
ACM JETC 3(4) No.2, Jan. 2008

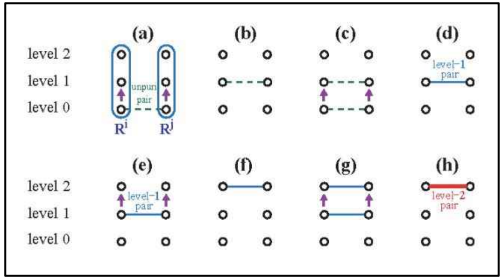
Linear network is best for Ripple adders.

Any distributed computation is based on networking systems!

Distributed Quantum Computer Architecture Work

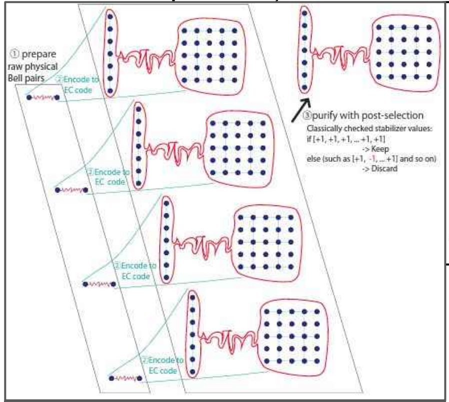
Jiang *et al.* Phys. Rev. A **76**, 062323 (2007)

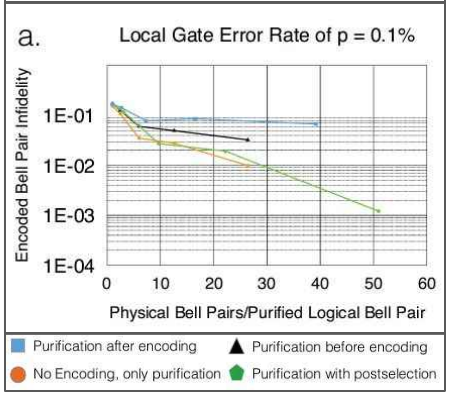


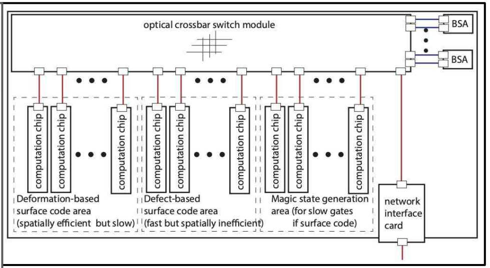


- computation qubits and comm. qubits
- distributed quantum computation depends only on fidelity of computation qubits because of distillation on comp. qubits

- An conceptual architecture that combines multiple codes and physical systems by networking them.
- network interface module for external communication for distributed computing
- High efficiency to first encode raw entanglements and then post-select during the entanglement distillation process, for code conversion.







Nagayama *et al.*
Phys. Rev. A 93, 042338.
Ph.D thesis (2017)

Monroe, .., Brown, et al.
Phys. Rev. A 89, 022317.
2013)

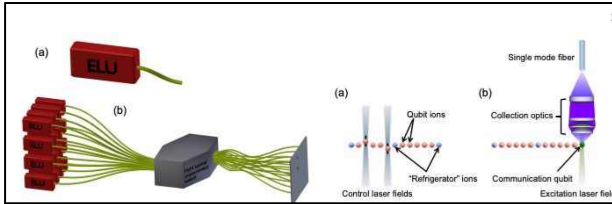


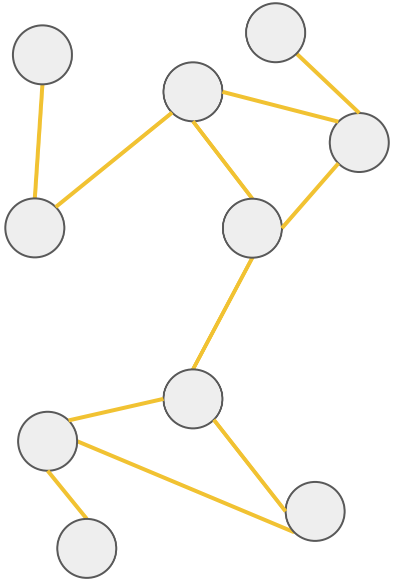
Table III: Estimated execution time and physical qubits necessary to complete Shor algorithm of a given size. The numbers on top (bottom) correspond to MUSIQC (QLA) architecture.

Performance Metrics		$n = 32$	$n = 512$	$n = 4,096$
Code Level		1	2	3
# Physical Qubits	MUSIQC	4.7×10^4	9.2×10^7	4.1×10^{10}
	QLA	3.7×10^5	7.2×10^8	3.2×10^{11}
Execution Time	MUSIQC	2.5 min	2.1 days	650 days
	QLA	2.2 min	1.5 days	520 days

Computer Network

: Classical node

: Classical Channel(e.g. optical fiber)



Deployment

Usecase

ELSI (Ethical, Legal, Social Issues)

Informatics (science, engineering)

Distributed Algorithms

Applications

Computer Engineering

Software Engineering
- System Software
- Distributed Systems
- Security

Network theory
- Graph theory

Communication theory/enginnering
- encoding

Network Engineering
- Protocol Stack

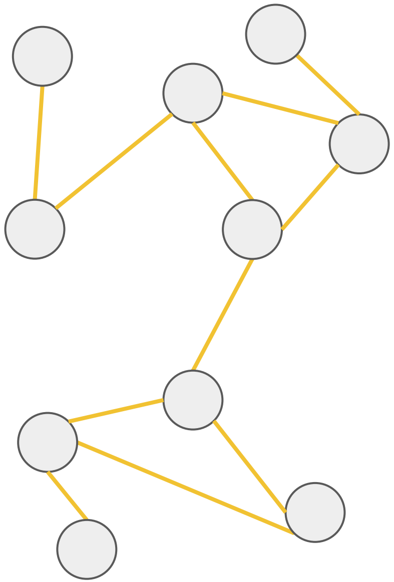
Classical Physics

Electronics
Optics
Control Engineering
Physical Properties etc.

Quantum Computer Network

: Quantum node

: Quantum Channel(e.g. optical fiber)



Deployment

Usecase

ELSI (Ethical, Legal, Social Issues)

Quantum Informatics (science, engineering)

Di… …ithms

Applications

Network theory
・Graph theory

Communication theory/enginnering
・encoding

Network Engineering
・Protocol Stack

Everything changes

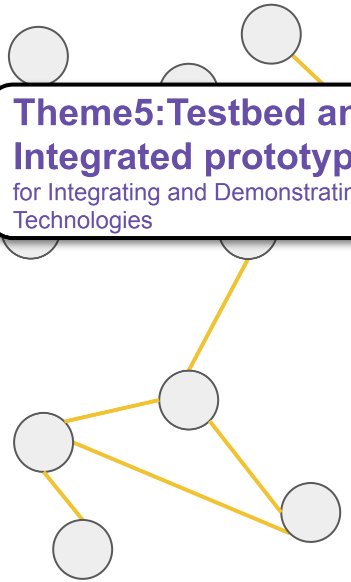
Quantum Physics

Quantum Electronics, Quantum Devices, Quantum Optics, Optical Properties, Non-liner optics, Quantum Controll Engineering, etc.

Quantum Computer Network

: Quantum node

: Quantum Channel(e.g



Theme5:Testbed and Integrated prototype for Integrating and Demonstrating Technologies

Theme4:Distributed Quantum Applications
Enabled by Distributed Environments for Quantum Information

Theme1:new network architectures and protocols to realize robust and large-scale communication networks

Theme2:Quantum optical technology
enabling precise control of quantum light

Theme3:Quantum memory and quantum repeating for repeating and converting quantum signals

Deployment

- Usecase
- ELSI (Ethical, Legal, Social Issues)

Quantum Informatics (science, engineering)

- Distributed Algorithms
- Applications
- Computer Engineering
- Software Engineering
  - System Software
  - Distributed Systems
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- Network theory
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Quantum Physics

Quantum Electronics, Quantum Devices, Quantum Optics, Optical Properties, Non-liner optics, Quantum Controll Engineering, etc.

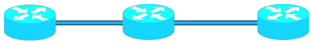
Long-term milestones for quantum computer networks

Current Key Issues

(a)Overall picture of Q Network System with Optical techs.

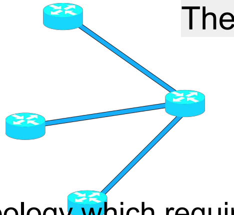
Theme 1, 2

(a)①



- Demonstration of quantum link system between nodes
- assuming a memory with zero memory time

(a)②

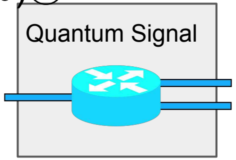


- smallest topology which requires QN sys.
  ○Routing is required!
- Multiplexing (not only wavelength division multiplexing, but as system to deal with many communication)

(b) Quantum Memory･Quantum Comm. I/F

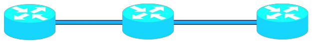
Theme 3

(b)①



Demonstration of Proof of Concept Quantum Repeating with memory

(b)②



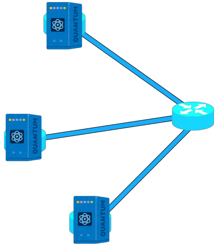
- Memory provides buffering which provides flexible and highly efficient-use of communication resource (C.F. classical communication)
- Improving "quantum efficiency" (Reducing the number of simultaneous probabilistic events)

Theme 5

Key Issue to 2030

Scalable and robust integrated Quantum Communication System

③



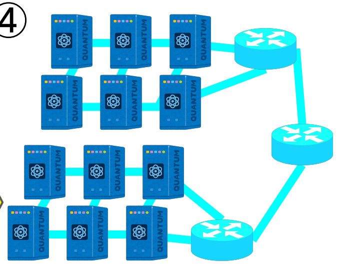
Complete Demonstration of systems and protocols in a small-scale configuration that evolve into large-scale networks, and **verify scalability through simulation.**

small-scale distributed QC

Theme 1, 4

2040s and later

④



to large-scale Quantum Computer Networks

Large-scale distributed QC

Deployment

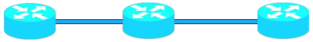
Long-term milestones for quantum computer networks

Current Key Issues

(a)Overall picture of Q Network System with Optical techs.

Theme 1, 2

(a)①



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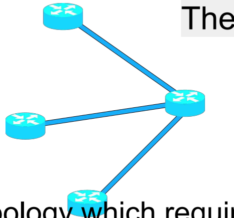

- smallest topology which requires QN sys.
  ○Routing is required!
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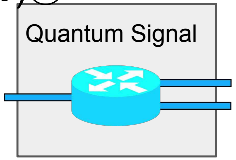
(b) Quantum Memory･Quantum Comm. I/F

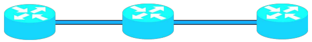
Theme 3

(b)①



Demonstration of Proof of Concept Quantum Repeating with memory

(b)②



- Memory provides buffering which provides flexible and highly efficient-use of communication resource (C.F. classical communication)
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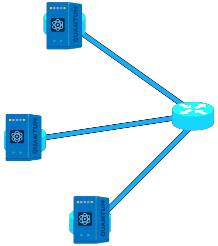
Theme 5

Key Issue to 2030

Scalable and robust integrated Quantum Communication System

③



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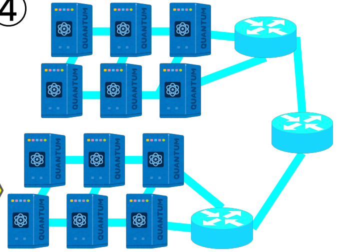
Theme 1, 4

2040s and later

④



to large-scale Quantum Computer Networks

small-scale distributed QC **Large-scale distributed QC**

Deployment

R&D with "Trial and error", two pillars

Real Testbed

- **Implementation**, but small-scale

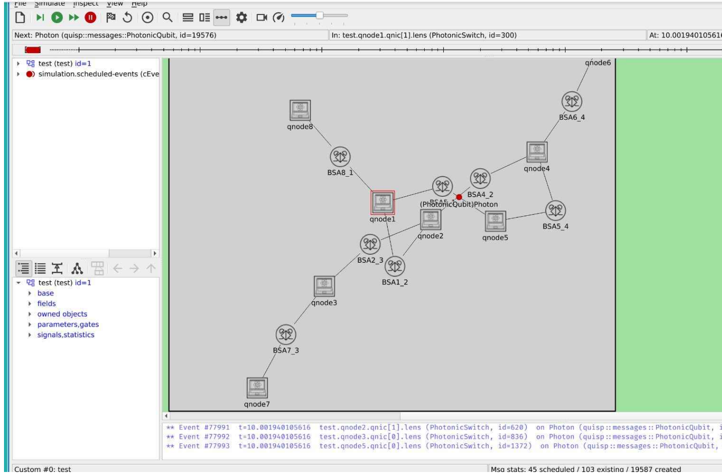
  to confirm practical working

Simulation

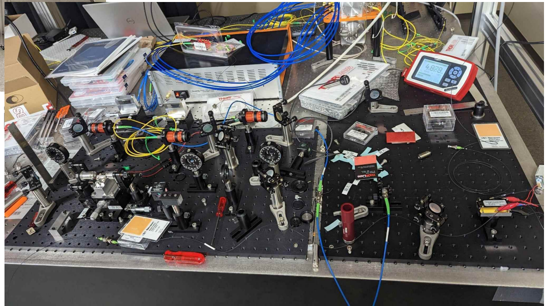
- **Large-scale**, but virtual

  to confirm working in large-scale

working on both &
going back and forth



Transform such physical experiments "quantum network **systems**"→



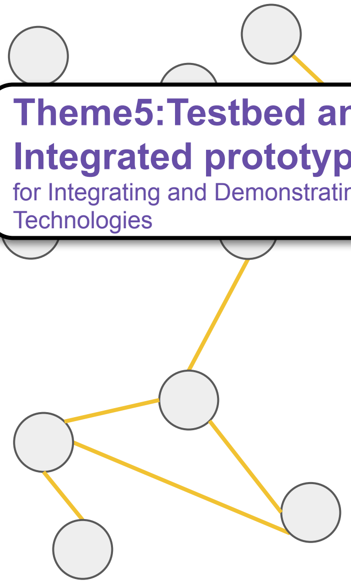
@shin-kawasaki, next to U. of Tokyo's IBM quantum computer

Those two pillars together provides confirmed system for large-scale Q Network.

Quantum Computer Network

: Quantum node

: Quantum Channel(e.g



Theme5:Testbed and Integrated prototype for Integrating and Demonstrating Technologies

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Theme1:new network architectures and protocols to realize robust and large-scale communication networks

Theme2:Quantum optical technology enabling precise control of quantum light

Theme3:Quantum memory and quantum repeating for repeating and converting quantum signals

Deployment

- Usecase
- ELSI (Ethical, Legal, Social Issues)

Informatics (science, engineering)

- Distributed Algorithms
- Applications
- Computer Engineering
- Software Engineering
  - System Software
  - Distributed Systems
  - Security
- Network theory
  - Graph theory
- Communication theory/enginnering
  - encoding
- Network Engineering
  - Protocol Stack

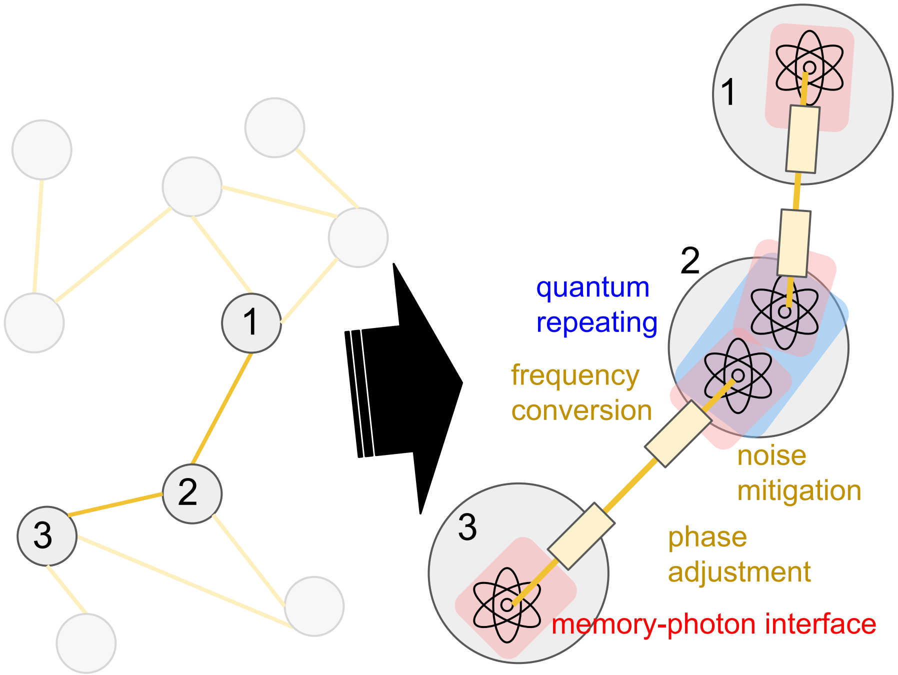
Quantum Physics

Quantum Electronics, Quantum Devices, Quantum Optics, Optical Properties, Non-liner optics, Quantum Controll Engineering, etc.

Quantum Computer Network

: Quantum node

: Quantum Channel(e.g. optical fiber)



Deployment

Usecase

ELSI (Ethical, Legal, Social Issues)

Informatics (science, engineering)

Distributed Algorithms

Applications

Computer Engineering

Software Engineering
・System Software
・Distributed Systems
・Security

Network theory
・Graph theory

Communication theory/enginnering
・encoding

Network Engineering
・Protocol Stack

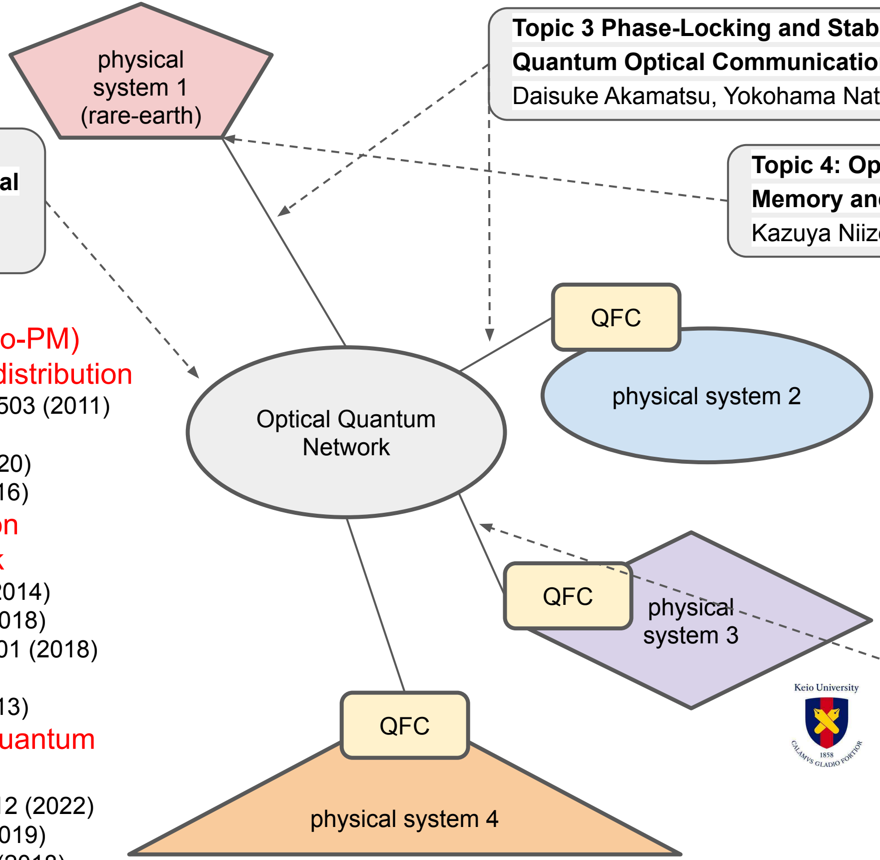
Quantum Physics

Quantum Electronics, Quantum Devices, Quantum Optics, Optical Properties, Non-liner optics, Quantum Controll Engineering, etc.

R&D Theme2: Optical Quantum Technologies

大阪大学
OSAKA UNIVERSITY

Topic 1:
High-performance quantum optical communication technology
Rikizo Ikuta, Osaka Univ.



Topic 3 Phase-Locking and Stabilization Techniques for Quantum Optical Communication
Daisuke Akamatsu, Yokohama National Univ.

Topic 4: Optical Interface between Rare-Earth Quantum Memory and Quantum Optical Communication
Kazuya Niizeki, LQUOM Corporation

Topic 2: Loss-Tolerant Quantum Optical Communication Technology
Masahiro Takeoka, Keio Univ.

Background results

(Prof. Ikuta, also with Yamamoto-PM)

High-fidelity entangled photon distribution

Physical Review Letters 106 (11), 110503 (2011)
Scientific Reports 7 (1), 4819 (2017)
npj Quantum Information 6 (1), 44 (2020)
Physical Review A 93 (5), 052307 (2016)

Quantum Frequency Conversion theoretical & experimental work

Optics express 22 (9), 11205-11214 (2014)
Nature communications 9 (1), 1997 (2018)
Physical review letters 120 (20), 203601 (2018)
Nature Communications 2, 537 (2011)
Physical Review A 87 (1), 010301 (2013)

Fundamental and Functional Quantum Routing experiments

Physical Review Applied 17 (3), 034012 (2022)
Nature communications 10 (1), 378 (2019)
Optics express 25 (11), 12069-12080 (2018)
New Journal of Physics 16 (2), 023005 (2014)

Rare-earth memory related optical I/F work

Japanese Journal of Applied Physics 61 (8) 088003 (2022)
Optics Express 29 (25), 41522-41533 (2021)
Japanese Journal of Applied Physics 60, 122001 (2021)
Communications Physics.,**3**, 138 (2020)
Journal of the Optical Society of America B **35**, 2023,(2018)
Applied Optics **57** (20) 5628-5634,(2018)
Japanese Journal of Applied Physics **57**, 062801,(2018)

Theory on Capacity calculation and tradeoff

Phys. Rev. Lett., 119, 150501 (2017).
Nat. Commun. 5: 5235 (2014).

Fast HOM effect for raw Bell pair generation

Opt. Express, 29, 37150 (2021).

1st year achievement in Optical Quantum Technologies

MOONSHOT

Efficient Dicke state distribution in a network of lossy channels

W state – single photon state

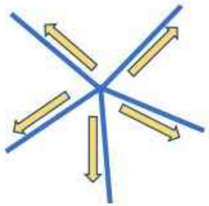
$$|W_3\rangle = \frac{1}{\sqrt{3}}(|100\rangle + |010\rangle + |001\rangle)$$

- W and Dicke states can be a convenient resource for quantum networks
- photons suffer from losses, not only in fibers, but in nodes
- distributing multi-qubit state in different nodes may fail exponentially to the number of nodes
- This work proposes to use 1-photon interference in repeater-like method to distribute multi-qubit state.
- squeezed vacuum for the input state: less effects from losses.

Direct transmission method

Polarization states W

$$|W_3\rangle = \frac{1}{\sqrt{3}}(|hvv\rangle + |vhv\rangle + |vvh\rangle)$$



N links

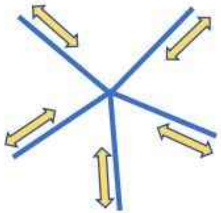
Generation rate $\sim T^N$

T – power transmittance of one link

Repeater-like method

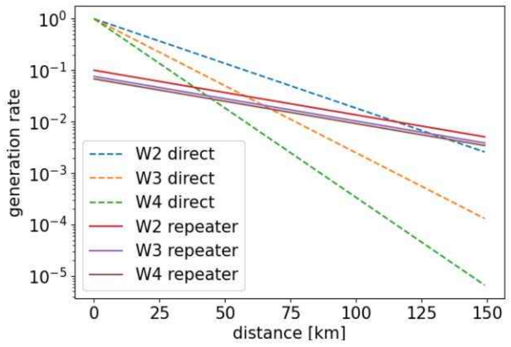
$$|\psi\rangle_{X_i X_i'} = a|00\rangle_{X_i X_i'} + b|11\rangle_{X_i X_i'}$$

$$a \gg b$$



Generation rate $\sim T$

W states in a star network with loss

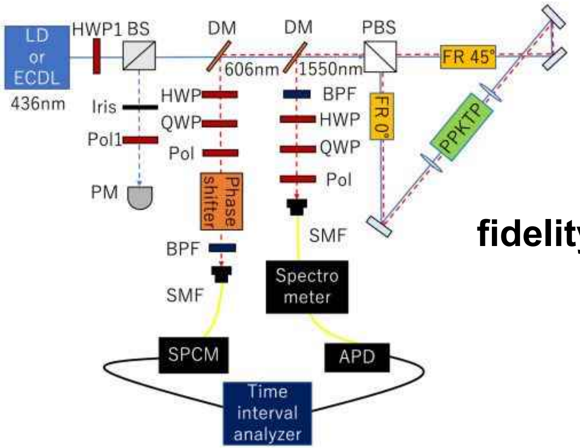


Comparison repeater-like scheme with the direct method

Efficient Dicke-state distribution in a network of lossy channels. W. Roga, R. Ikuta, T. Horikiri, M. Takeoka. Phys. Rev. A 108, 012612

1st year achievement in Optical Quantum Technologies

606nm-1550nm entanglement generation



fidelity=94.4%

- Entanglement generation between different wavelength
- 1550: telecom wavelength
- 606: Pr:YSO (rare-earth quantum memory) wavelength
- this result achieves efficient connection of Pr:YSO memory to telecom wavelength

Sagnac interferometer-type nondegenerate polarization entangled two-photon source with a Fresnel rhomb.
Aizawa, Niizeki, .., Horikiri, *et al.* Applied Optics 62 (9) 2273-2277 (2023)

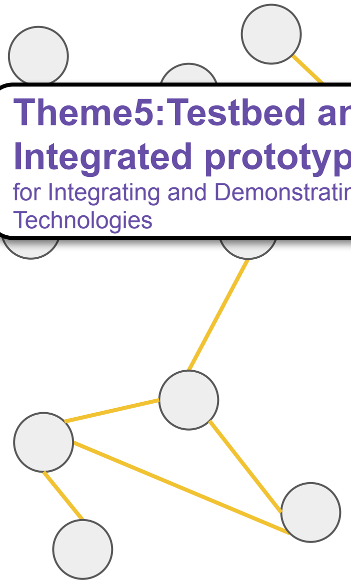
Comparison of the Current Study with Previous Studies

Year	Reference	Photon Wave Length (nm)	Fidelity	Visibility
2008	[16]	810,1550	–	91%
2009	[14]	810,1550	98.2%	–
2013	[15]	810,1550	96.5%[a]	–
2016	[10]	894,1313	75.3%	70.2%
2022	This work	606,1550	94.4%	–

Quantum Computer Network

: Quantum node

: Quantum Channel(e.g



Theme4:Distributed Quantum Applications Enabled by Distributed Environments for Quantum Information

Theme5:Testbed and Integrated prototype for Integrating and Demonstrating Technologies

Theme1:new network architectures and protocols to realize robust and large-scale communication networks

Theme2:Quantum optical technology enabling precise control of quantum ligh

Theme3:Quantum memory and quantum repeating for repeating and converting quantum signals

Deployment

- Usecase
- ELSI (Ethical, Legal, Social Issues)

Informatics (science, engineering)

- Distributed Algorithms
- Applications
- Computer Engineering
- Software Engineering
  - System Software
  - Distributed Systems
  - Security
- Network theory
  - Graph theory
- Communication theory/enginnering
  - encoding
- Network Engineering
  - Protocol Stack

Quantum Physics

Quantum Electronics, Quantum Devices, Quantum Optics, Optical Properties, Non-liner optics, Quantum Controll Engineering, etc.

R&D Theme3: Quantum Memory

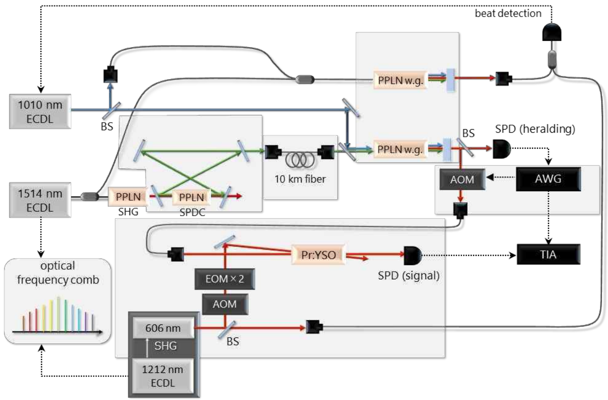
Theme3 Topic 1: Multiplexed quantum memory for quantum memory networks
Tomoyuki Horikiri, Yokohama National Univ.

Background results

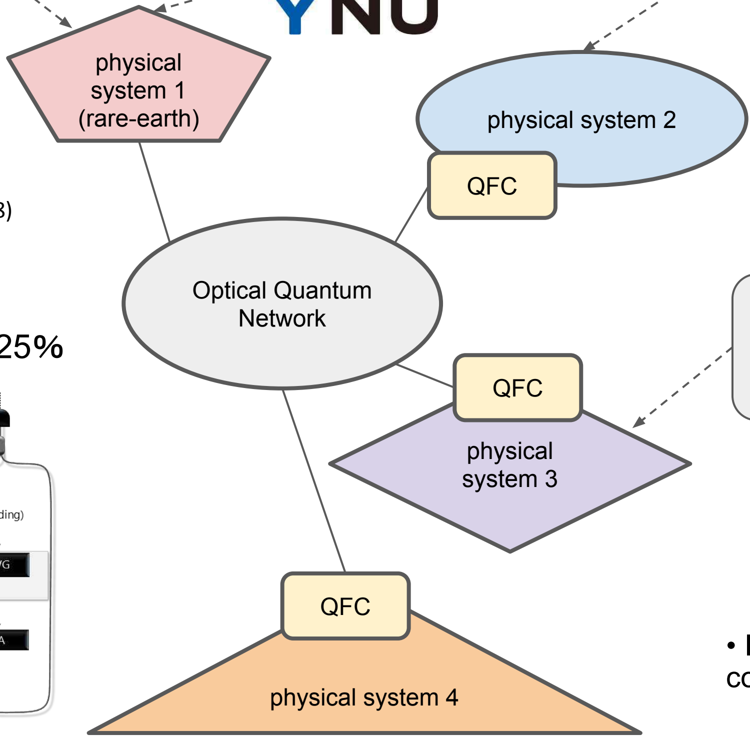
Rare-earth memory work

Japanese Journal of Applied Physics 61 (8) 088003 (2022)
Optics Express 29 (25), 41522-41533 (2021)
Japanese Journal of Applied Physics 60, 122001 (2021)
Communications Physics.,**3**, 138 (2020)
Journal of the Optical Society of America B **35**, 2023,(2018)
Applied Optics **57** (20) 5628-5634,(2018)
Japanese Journal of Applied Physics **57**, 062801,(2018)

Our lifetime for now: 50μs
store/load quantum efficiency: about 25%



Theme 3 Topic 2 light source stabilization technology for quantum memory for repeating
Hong Feng Lei, Yokohama National Univ.



Theme 3 Topic 3: Improvement of Reliability of Entangled Photon Generation by Spin Waves
Haruka Tanji, The Univ. of Electro-Communications

Highly reliable entanglement buffer

Applied Physics B 116, 821 (2014)
Science 341, 768 (2013)
Science 333, 1266 (2011)

Theme 3 Topic 4: Quantum Mechanical Memory
Rekishu Yamazaki, International Christian Univ.
Yuya Yamaguchi,NICT
Ryo Sasaki, RIKEN

Quantum Optomechanical memory

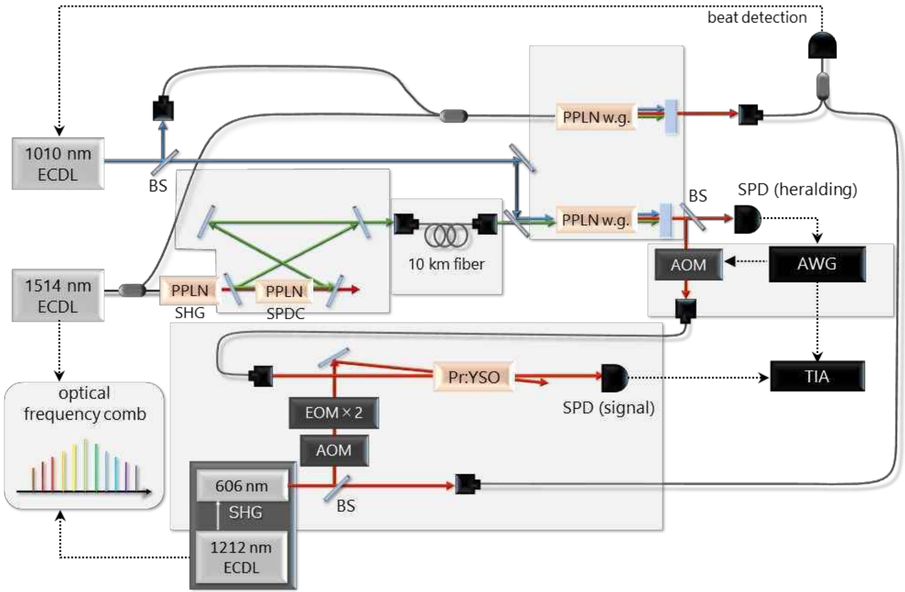
RY et al., Phys. Rev. A 101, 053839 (2020)
K. Takeda, RY et al., Optica 5, 152 (2018)
A. Noguchi, R.Y. et al., Nat. Comm. 11, 1183 (2020)

$$\hat{\mathcal{H}} = \hbar g_0 \left(\hat{a}\hat{a}^\dagger \hat{b} + \hat{a}\hat{a}^\dagger \hat{b}^\dagger \right)$$

- Interaction is parametric = wavelength conversion is inherent
  → Wide frequency range
  <u>Memory frequency, write/read frequency</u>

1st year Achievements in Rare-earth Quantum memory

Reliable quantum memory system

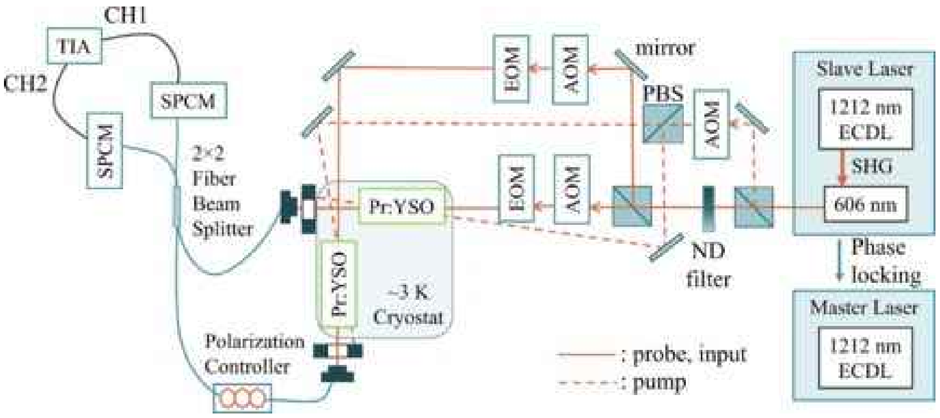


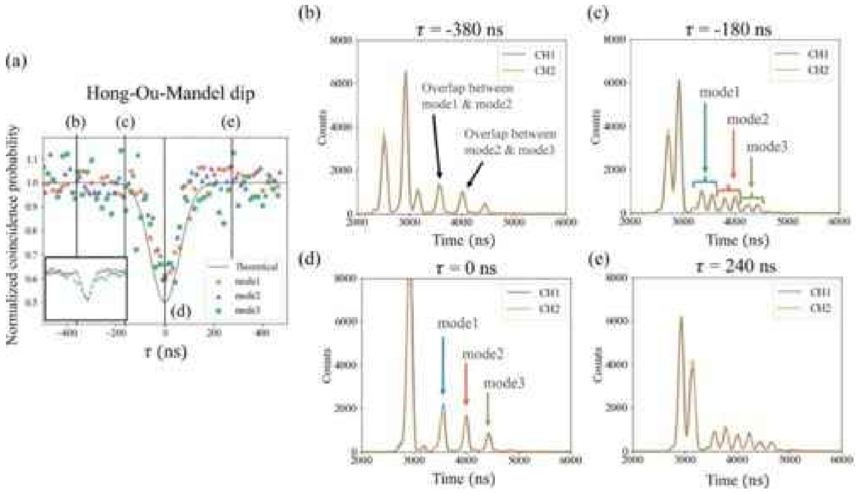
- The atomic frequency comb(AFC), in which an inhomogeneous broadening of rare-earth-doped material is controlled to provide a memory function, has the advantage of being multimode storage.
- This work confirmed stability that photons can be stored in the memory even after 10km fiber drum.
- Furthermore, working time is over 42h
  - important for actual operation of quantum network

Frequency-multiplexed storage and distribution of narrowband telecom photon pairs over a 10-km fiber link with long-term system stability.
Ito, .., Niizeki, .., Hong, Horikiri *et al.* Phys. Rev. Applied 19, 024070 (2023)

1st year Achievements in Rare-earth Quantum memory

Frequency-multiplexed Hong-Ou-Mandel interference, after store-and-load in rare-earth quantum memory





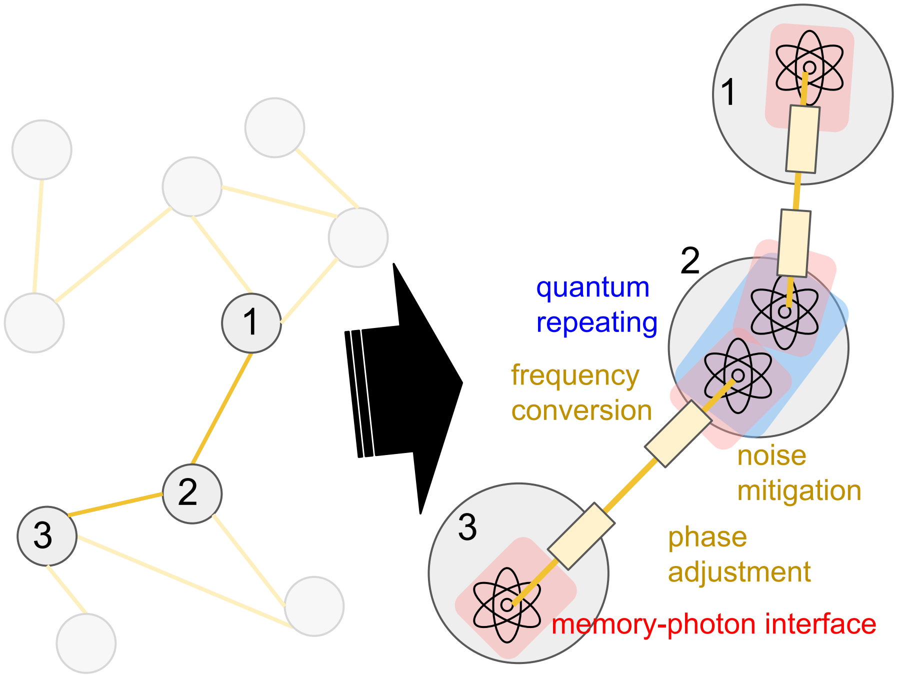
- The setting has two Pr:YSO quantum memories.
- Optical store-and-load operation with three modes (mode 1, 2, 3) at each memory.
- Photon echoes (loaded) moved to Hong-Ou-Mandel interferer and measured.
- Interference between corresponding mode is observed and confirmed.
- **visibility 40%–42%** (theoretically up to 50%)

Frequency-multiplexed Hong-Ou-Mandel interference.
Ichihara, .., Hong, Horikiri *et al.* Phys. Rev. A **107**, 032608 (2023)

Quantum Computer Network

: Quantum node

: Quantum Channel(e.g. optical fiber)



Deployment

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- ELSI (Ethical, Legal, Social Issues)

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- Applications
- Computer Engineering
- Software Engineering
  - ・System Software
  - ・Distributed Systems
  - ・Security
- Network theory
  - ・Graph theory
- Communication theory/enginnering
  - ・encoding
- Network Engineering
  - ・Protocol Stack

In a sense, technology for connecting several nodes

※ Of course, indispensable

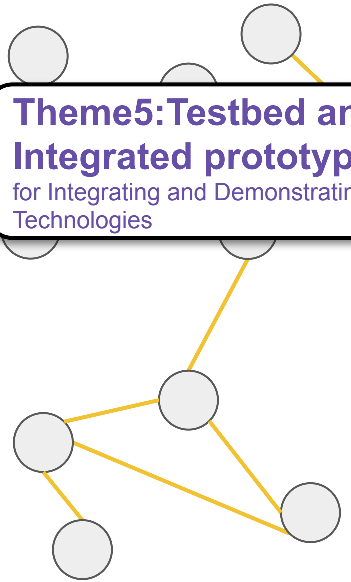
Quantum Physics

Quantum Electronics, Quantum Devices, Quantum Optics, Optical Properties, Non-liner optics, Quantum Controll Engineering, etc.

Quantum Computer Network

: Quantum node

: Quantum Channel(e.g



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Quantum Physics

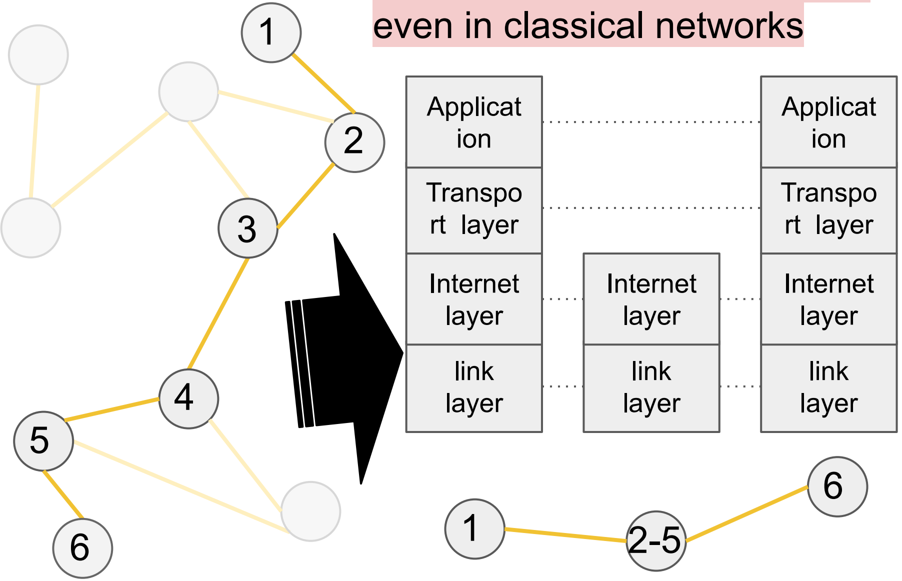
Quantum Electronics, Quantum Devices, Quantum Optics, Optical Properties, Non-liner optics, Quantum Controll Engineering, etc.

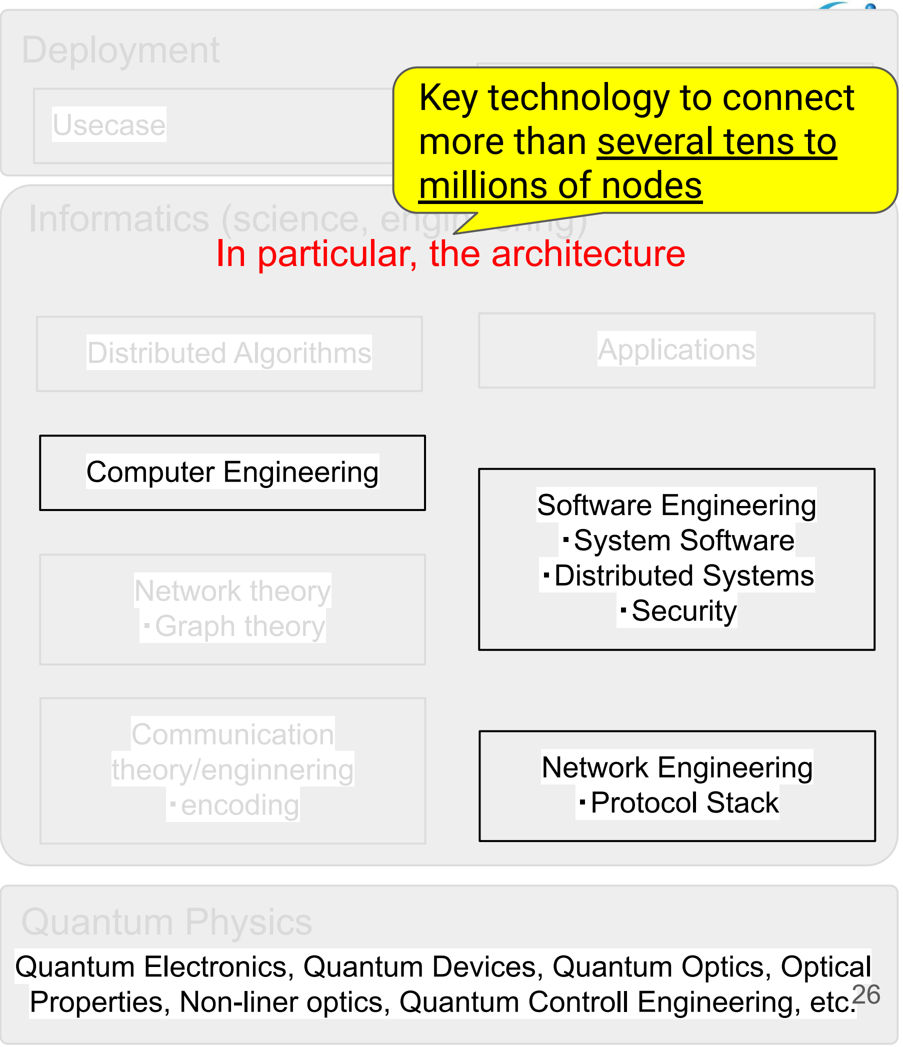
Quantum Computer Network

: Quantum node

: Quantum Channel(e.g. optical fiber)

A field that has taken decades even in classical networks



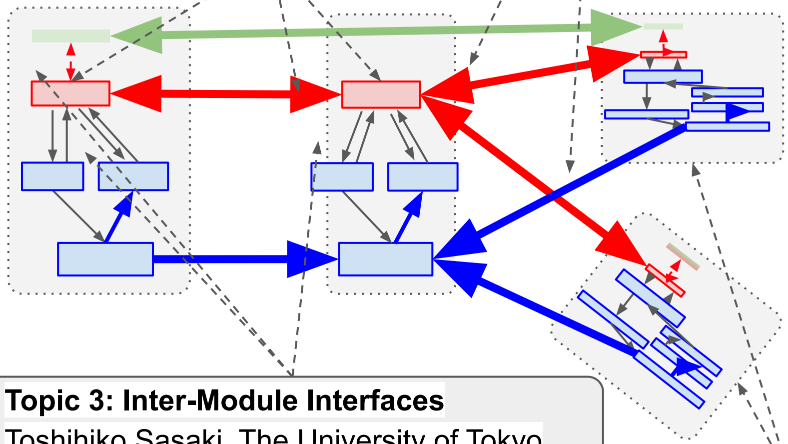


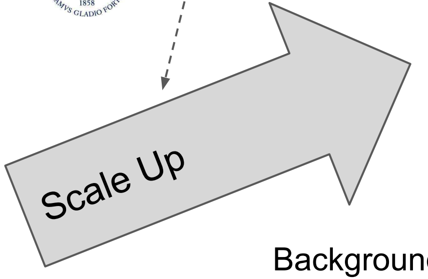
R&D Theme1: Architecture & Protocol

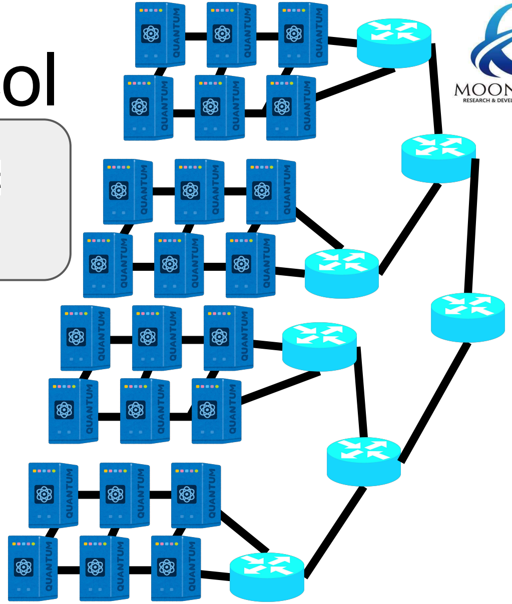
Topic 1:Quantum Communication Architectures and Protocols
Shota Nagayama, R4D, Mercari, Inc.

Topic 2: Classical Systems and Protocols
Hiroyuki Ohno, Kanazawa Univ.

Topic 4: Protocol Operation Methodology for a 1000-unit Data Center Network
Rodney Van Meter, Keio Univ.







Topic 3: Inter-Module Interfaces
Toshihiko Sasaki, The University of Tokyo

Topic 5: Scalable Quantum Communication Network Edge Architecture
Kae Nemoto, OIST

Background results

Quantum Network Architecture.
IEEE QCE2022. 10.1109/QCE53715.2022.00055 (2022)
IEEE QCE2022. 10.1109/QCE53715.2022.00056 (2022)
arXiv:1701.04586 (2017)
Nature Photonics volume 4, pages792–796 (2010)
Nature Photonics volume 6, pages777–781 (2012)

Quantum and Classical protocols.
Internet Draft. draft-nagayama-ipsecme-ipsec-with-qkd-01. (2015)
RFC 9340. (2023)
Physical Review A 93 (3), 032302.

QEC for practical systems.
New Journal of Physics 19 (2), 023050 (2017)
Physical Review A 93 (4), 042338 (2016) etc.

Another emerging movement
(also our background results)

RFC9340!!!

This first document took four years.
(not even standards track)

- RFCs are documents admitted by IETF/IRTF.
- IETF is the standardizing organization for the classical Internet, such as TCP/IP, ssl/tls, http, etc.
- IRTF is co-organization for research that holds quantum internet research group (QIRG).
- RFC9340 is the first RFC on quantum network, and a informational document on architectural design principles.

Stream: Internet Research Task Force (IRTF)
RFC: 9340
Category: Informational
Published: January 2023
ISSN: 2070-1721

Authors: W. Kozlowski, *QuTech*; S. Wehner, *QuTech*; R. Van Meter, *Keio University*; B. Rijsman, *Individual*; A. S. Cacciapuoti, *University of Naples Federico II*; M. Caleffi, *University of Naples Federico II*; S. Nagayama, *Mercari, Inc.*

RFC 9340
Architectural Principles for a Quantum Internet

Abstract

The vision of a quantum internet is to enhance existing Internet technology by enabling quantum communication between any two points on Earth. To achieve this goal, a quantum network stack should be built from the ground up to account for the fundamentally new properties of quantum entanglement. The first quantum entanglement networks have been realised, but there is no practical proposal for how to organise, utilise, and manage such networks. In this document, we attempt to lay down the framework and introduce some basic architectural principles for a quantum internet. This is intended for general guidance and general interest. It is also intended to provide a foundation for discussion between physicists and network specialists. This document is a product of the Quantum Internet Research Group (QIRG).

Status of This Memo

This document is not an Internet Standards Track specification; it is published for informational purposes.

Architectural Principles for a Quantum Internet
draft-irtf-qirg-principles-11

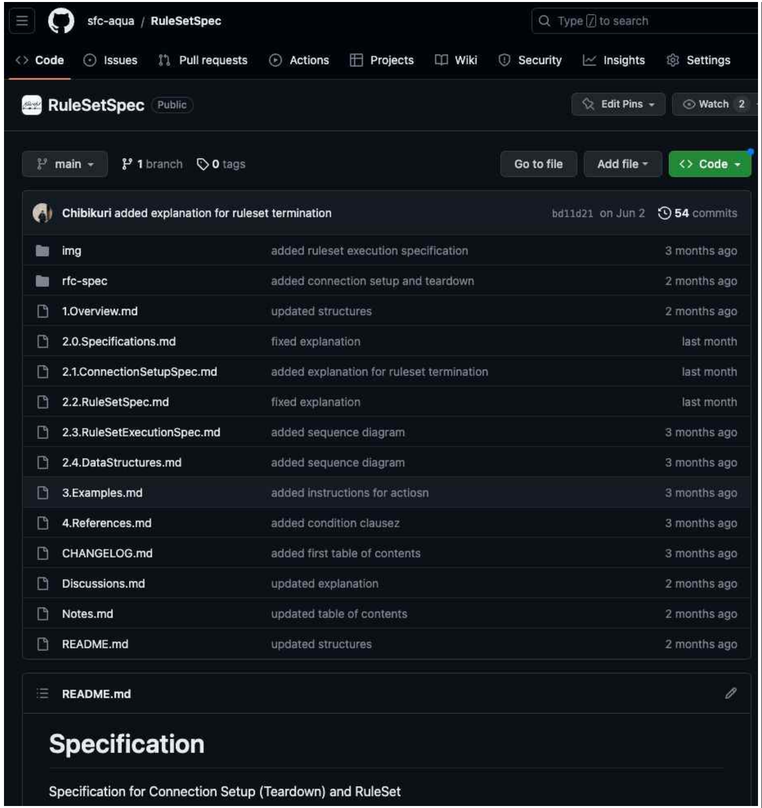
Status | IRSG evaluation record | IESG evaluation record | IESG writeups | Email expansions | History

Versions: 00 01 02 03 04 05 06 07 08 09 10 11

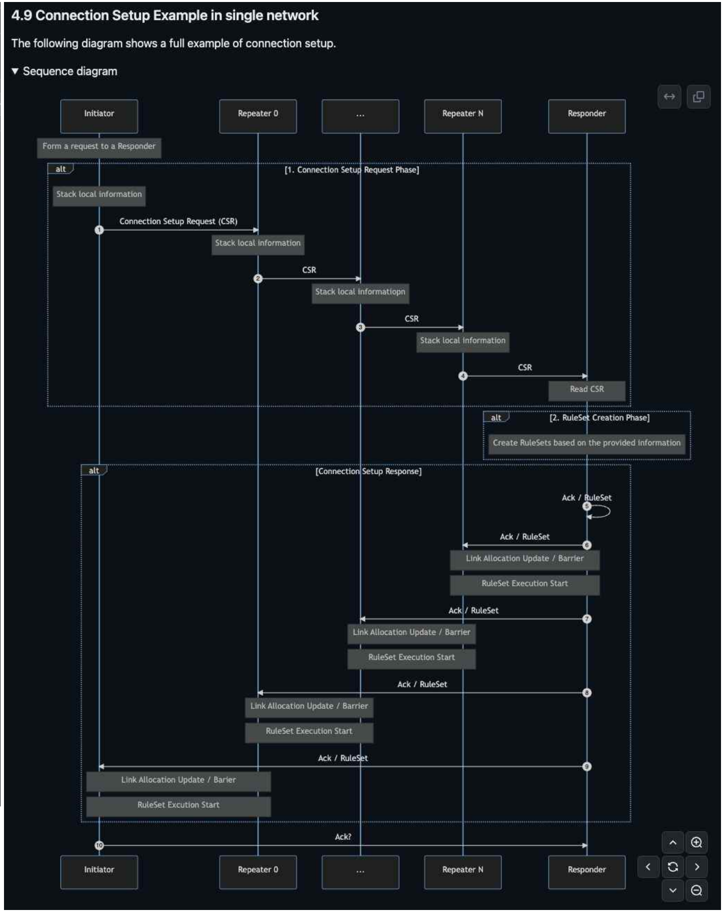
Another our background: Activities at IETF/IRTF

- **IETF**: Standardization organization for the Internet (TCP/IP, http, etc.)
- **IRTF**: Corresponding research organization
- 116th meeting 2023/3/27-31 @Yokohama, Japan
  - Quantum Internet Research Group meeting in IRTF
  - Host Speaker Series
    "The Future & Roadmap to the Quantum Internet - Testbed Efforts in Japan -"
    - Shota Nagayama & Rodney Van Meter
    - more than 10% of participants (top classical network specialists) of IETF/IRTF joined the session.
  - Quantum Network Lab Tour to Yokohama National Univ. Horikiri-PI.
  - https://ietf116.jp/tour/

1st year Achievements: Our network protocol design available on Github



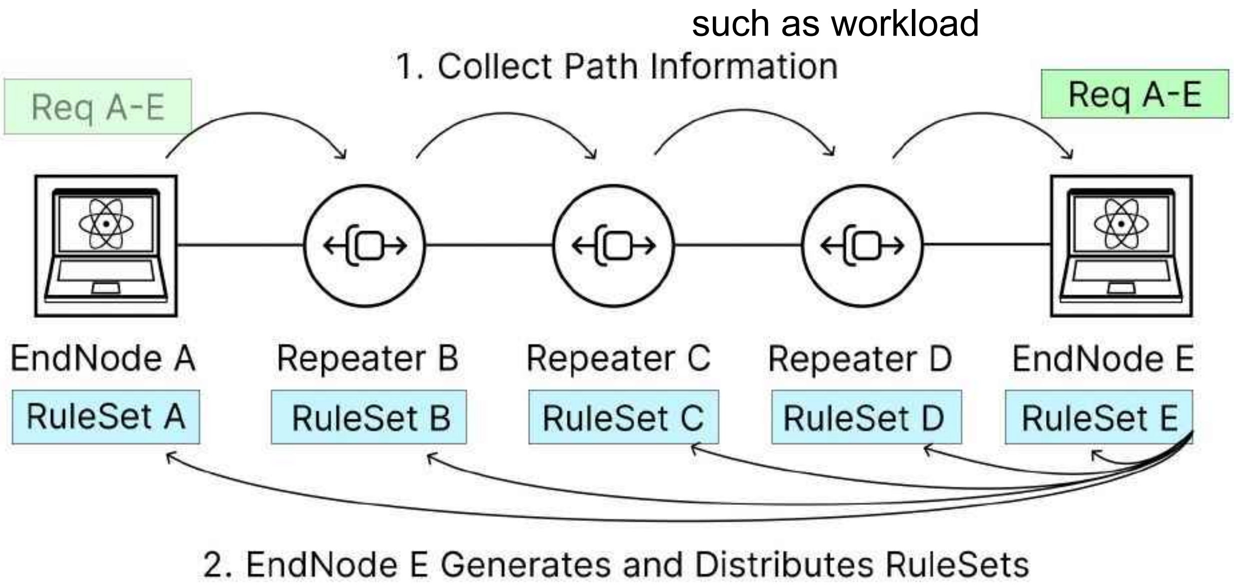
https://github.com/sfc-aqua/RuleSetSpec/



- Computer networking itself is a complex distributed computation, even in classical networks.
- Quantum computer networking is more complex distributed computation crossing quantum and classical computing.
- Key components of distributed computing is complex state machine. Any idea to simplify the state machine?
  →Rule-set based networking !!

RuleSet-based Protocol

RuleSet(RS): a program for each node in a path. RS allows each node to do classical/quantum operations autonomously in a distributed manner.



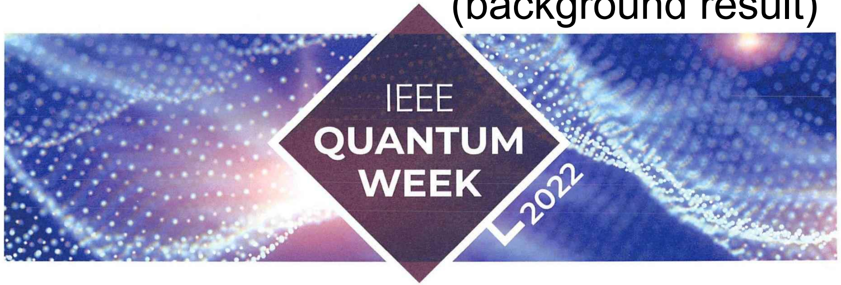
QuNet2023, to appear.
IEEE QCE2022. 10.1109/QCE53715.2022.00055 (2022)
IEEE QCE2022. 10.1109/QCE53715.2022.00056 (2022)

RS can reduce naive state synchronization in distributed network operation, in order not to block distributed quantum computation.

1st year Achievements in Computer Network Engineering

MOONSHOT
RESEARCH & DEVELOPMENT PROGRAM

Awarded in IEEE Quantum Week 2022 (background result)



BEST PAPER AWARD

Presented to

Ryosuke Satoh, Michal Hajdušek, Naphan Benchasattabuse, Shota Nagayama, Kentaro Teramoto, Takaaki Matsuo, Sara Ayman Metwalli, Poramet Pathumsoot, Takahiko Satoh, Shigeya Suzuki, and Rodney Van Meter

Track: Quantum Networking and Communications

Paper Title: QuISP: a Quantum Internet Simulation Package

Greg Byrd
QCE22 General Chair
NC State University

Bert de Jong
QCE22 Program Chair
Lawrence Berkeley National Laboratory

Hausi Müller
QCE22 Finance Chair
QCE22 Workshops Co-Chair
Co-Chair Quantum Initiative

Stephan Eidenbenz
QCE22 Workshops Co-Chair
Los Alamos National Laboratory

https://github.com/sfc-aqua/quisp

Accepted to **SIGCOMM (top-conference in computer networks) 's workshop**, to be held in Sep 2023. to appear.

SIGCOMM
2023 New York City

1st Workshop on Quantum Networks and Distributed Quantum Computing (QuNet)

Call for Papers

RuleSet-based Recursive Quantum Internetworking

Kentaro Teramoto
R4D, Mercari, Inc., Tokyo, Japan
Graduate School of Media and Governance
Keio University, Kanagawa, Japan
zigen@sfc.wide.ad.jp

Michal Hajdušek
Graduate School of Media and Governance
Keio University
Kanagawa, Japan
michal@sfc.wide.ad.jp

Toshihiko Sasaki
Department of Applied Physics, Graduate School of Engineering
The University of Tokyo
Tokyo, Japan
sasaki@qi.t.u-tokyo.ac.jp

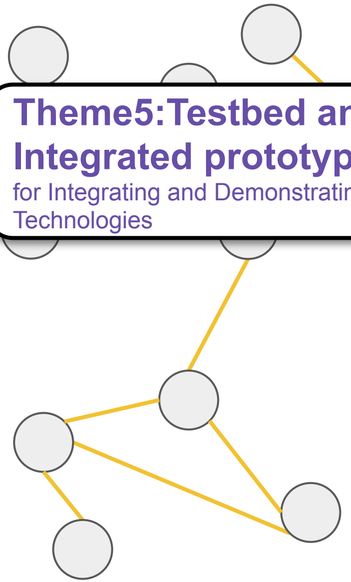
Rodney Van Meter
Faculty of Environment and Information Studies
Keio University
Kanagawa, Japan
rdv@sfc.wide.ad.jp

Shota Nagayama
R4D, Mercari, Inc., Tokyo, Japan
Graduate School of Media and Governance
Keio University, Kanagawa, Japan
shota@qitf.org

Quantum Computer Network

: Quantum node

: Quantum Channel(e



Theme5:Testbed and Integrated prototype for Integrating and Demonstrating Technologies

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nformatics (science, engineering)

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Quantum Physics

Quantum Electronics, Quantum Devices, Quantum Optics, Optical Properties, Non-liner optics, Quantum Controll Engineering, etc.

R&D Theme4: Application

Background results

Quantum Applications & Programming

Physical Review A 101 (5), 052301

IEEE Transactions on Quantum Engineering 1, 1-15

Quantum Network Coding

Physical Review A 93 (3), 032302

Physical Review A 97 (6), 062328

Topic 3: Theoretical Proposal for Quantum Applications Using Distributed Environment

Yuichiro Matsuzaki, Chuo Univ.

Direct use of Quantum properties of the distributed computing enviroment

Background results

Computation after sensing and blind QC applications

PHYSICAL REVIEW A 99(2) 1-14 2019

JPSJ 91(7) 1-12 (2022)

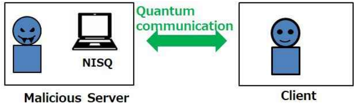
Physical Review A 105(2) 1-10 (2022)

Topic 2: Distributed Processing Protocols and Use Cases

Takahiko Satoh, Keio Univ.

Engineering to implement quantum programs on the distributed enviroment

Reduce requirement for hardware



	Qubit number	Security
Conventional QC	N	No security
Blind QC	3N	Almost all information is secured
	N+1	Ansatz parameters and outputs are hidden (ansatz circuit is known)

Topic 1: Quantum properties and its Applications in Distributed Processing Environments

Akihito Soeda, NII

Quantum properties of distributed computing environments

Verification of hardware for application

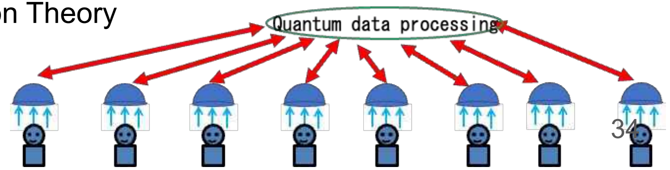
Quantum computation over network

Phys. Rev. A 84, 012333 (2011)

IEEE Trans. on Information Theory 63, 5372 - 5403 (2017)

Evaluation of Quantum Resource

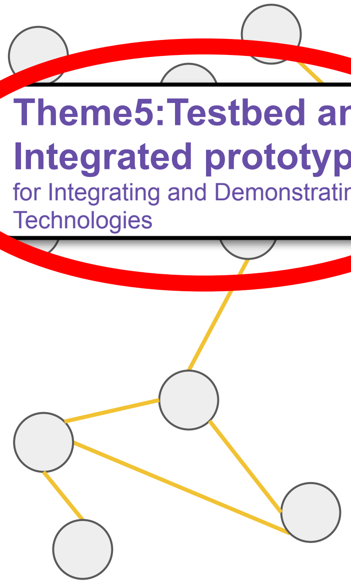
PRL 107, 180501 (2011)



Quantum Computer Network

: Quantum node

: Quantum Channel(e.g



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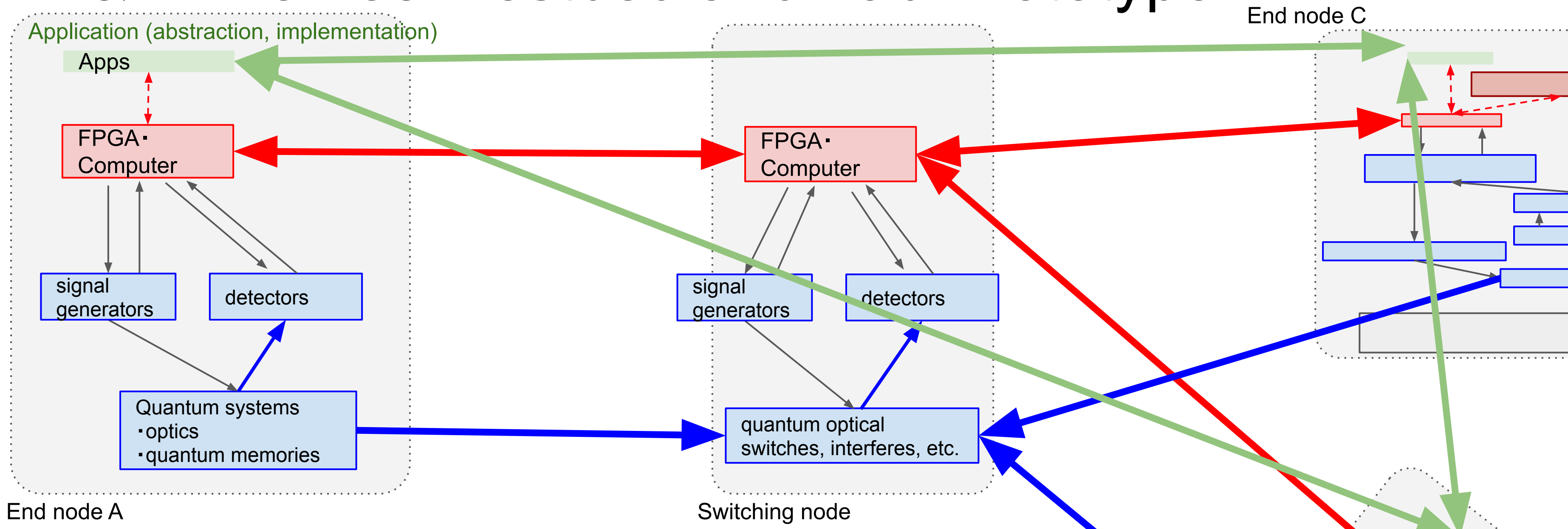
Quantum Electronics, Quantum Devices, Quantum Optics, Optical Properties, Non-liner optics, Quantum Controll Engineering, etc.

R&D Theme5: Testbed and Lab Prototype



Network system software/system hardware (Net systems)

Quantum Hardware/Quantum control equipments (Hardware)

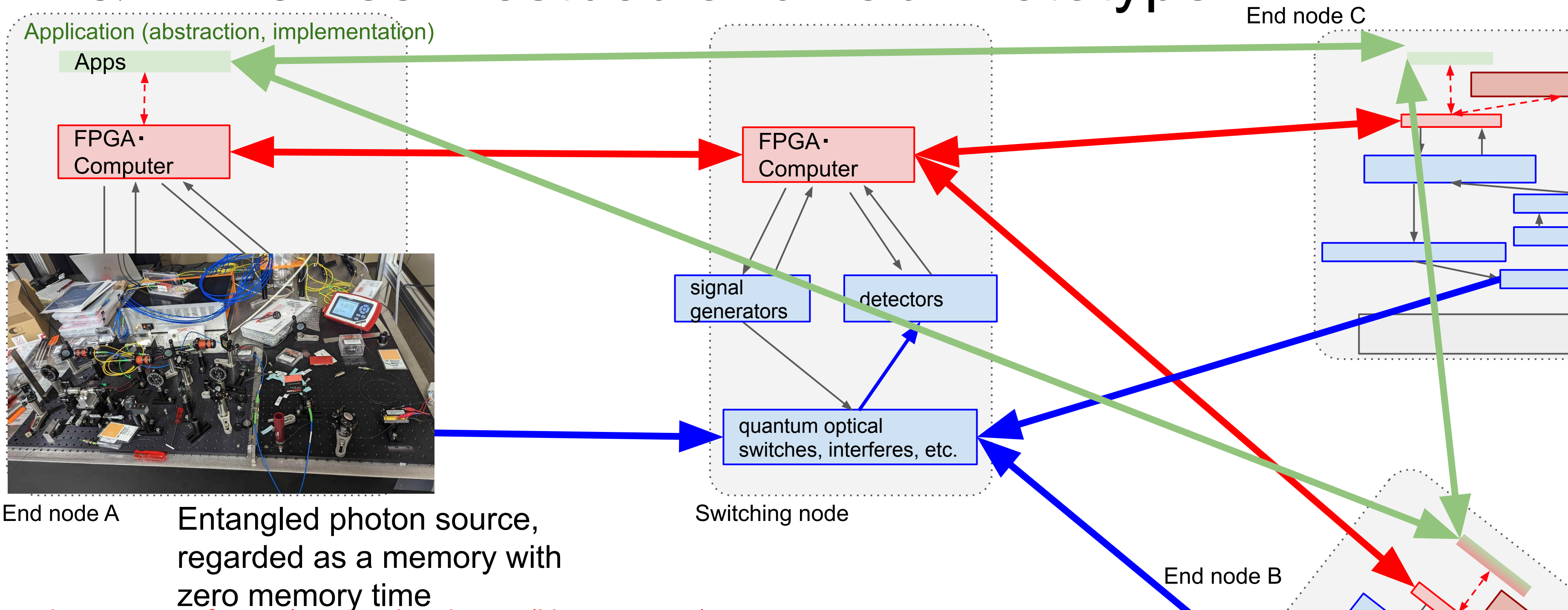
THE UNIVERSITY OF TOKYO

Topic 1: Integrated Demonstration of Quantum Communication Networks Using Optical Tech.
Shota Nagayama, Keio Univ.

Keio University

Topic 2: Ion Trap Quantum Nodes for Demonstration of Quantum Network Systems
Alto Osada, The University of Tokyo

R&D Theme5: Testbed and Lab Prototype



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Keio University

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Alto Osada, The University of Tokyo

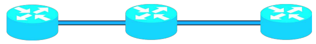
Summary: Scalable Network

Current Key Issues

(a)Overall picture of Q Network System with Optical techs.

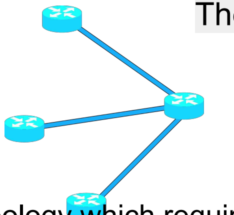
Theme 1, 2

(a)①



- Demonstration of quantum link system between nodes
- assuming a memory with zero memory time

(a)②

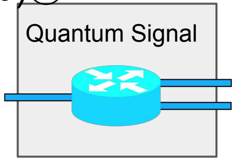


- smallest topology which requires QN sys.
  ○Routing is required!
- Multiplexing (not only wavelength division multiplexing, but as system to deal with many communication)

(b) Quantum Memory･Quantum Comm. I/F

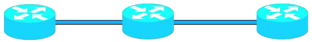
Theme 3

(b)①



Demonstration of Proof of Concept Quantum Repeating with memory

(b)②



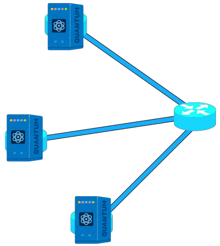
- Memory provides buffering which provides flexible and highly efficient-use of communication resource (C.F. classical communication)
- Improving "quantum efficiency" (Reducing the number of simultaneous probabilistic events; optical techs increase simultaneous events)

Theme 5

Key Issue to 2030

Scalable and robust integrated Quantum Communication System

③



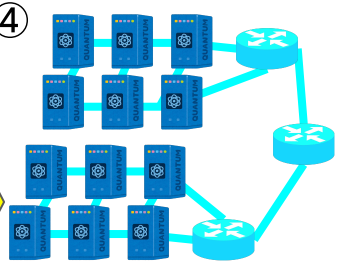
Complete Demonstration of systems and protocols in a small-scale configuration that evolve into large-scale networks, and **verify scalability through simulation.**

small-scale distributed QC

Theme 1,4

2040s and later

④



to large-scale Quantum Computer Networks

Large-scale distributed QC

Deployment