# 第３部

# 特集3 Quantum Internet

Rodney Van Meter、永山 翔太


## Abstract

AQUA (Advancing Quantum Architecture) working group members coauthored the world's first RFC on Quantum Internet and established a testbed network focusing on architecture, protocols and distributed control for data center-scale parallel/distributed computation and wide-area Quantum Internet. We released an online course titled "Quantum Internet", released a Creative Commons-licensed book *Quantum Communications*, and recruited and began developing a new cohort of quantum native network engineers literate in both quantum and classical engineering. We continued leadership of the IRTF Quantum Internet Research Group (QIRG). We continued various quantum computing research projects.


## 第１章　Networking

### 1.1　経緯

WIDEプロジェクトでは，AQUAワーキンググループの立ち上げ以来，量子コンピューティングシステムのアーキテクチャの研究開発に取り組んでいる．近年の量子コンピュータ技術への注目を受けて，AQUAの活動は拡大している．AQUAチェアのVan Meterとコチェアの永山は，2019年に，量子インターネットに取り組む全国の研究者らとともに，産学官連携で量子インターネットの実現を目指す量子インターネットタスクフォース[*1]を立ち上げた．2023年には，産学官連携の量子インターネットタスクフォースとの連携のもと，国プロであるJSTムーンショット型研究開発プロジェクト目標6におけるプロジェクト「スケーラブルで強靭な統合的量子通信システム」や，文科省光・量子飛躍フラッグシッププログラム（Q-LEAP）人材育成プログラム「量子技術高等教育拠点標準プログラムの開発」に取り組んだ．本稿では，上記の取り組みを含む，AQUAワーキンググループが貢献する最新の成果について報告する．

### 1.2　IETF 116 Yokohama

IETF116はWIDEプロジェクトがホストし，2024年3月25日から31日まで，横浜で開催した[*2]．IETF116では，量子インターネット関連の活動として，Quantum Internet Research Groupの通常BoFの開催のほか，Host Speaker Seriesにおいて，量子インターネットの概要の説明と，WIDEプロジェクトや量子インターネットタスクフォースでの取り組みについての講演を行った．また，量子インターネットタスクフォースのメンバーである横浜国立大学堀切研究室へのラボツアーを実施した．

#### 1.2.1　Host Speaker Series

開催概要は下記の通りである．

- タイトル：ホスト・スピーカー・シリーズ量子インターネット
- 時間：3月30日11時45分から12時45まで．
- 会場：パシフィコ横浜3F G303
- 講演者：
  - Rodney Van Meter（WIDEプロジェクトボードメンバー /慶應義塾大学）
  - 永山翔太（WIDEプロジェクトボードメンバー / QITF代表/慶應義塾大学/メルカリ株式会社）

＊1　https://qitf.org/
＊2　https://ietf116.jp/

この講演では，まず，量子インターネットの概要を説明した．その後，我々が行っている，量子インターネットアーキテクチャ（本稿第1.4章)や，量子インターネットテストベッドの方針や進捗状況(本稿第1.5)，量子インターネットシミュレータ(本稿第1.6)，オンライン量子教育(本稿第2)について共有した．

### 1.2.2 Quantum Internet Research Group

The Quantum Internet Research Group (QIRG) is a research group of the Internet Research Task Force (IRTF). WIDE Board Member Van Meter is co-chair of QIRG. In Yokohama, the main theme testbed networks around the world and a presentation about the network stack used in the Netherlands testbed:

- Jesse Robbers, Quantum Network Testbed Developments in NL
- Joaquin Chung, Design and Implementation of the Illinois Express Quantum Metropolitan Area Network
- Shota Nagayama, Quantum Internet Task Force (Japan)
- Carlo Delle Donne, Experimental demonstration of entanglement delivery using a quantum network stack

### 1.2.3 ラボツアー

開催概要は下記の通りである．ホスト・スピーカー・シリーズの講演に続き、3月31日の金曜日の午後に、横浜国立大学の量子インターネット実験室を見学する機会を参加者に提供した[*3]。パシフィコ横浜ノースと，横浜国立大学間の無料バスを提供した。ツアーは3月31日の金曜日、14:00-17:30に実施され、参加者は40名に限定された．この40人の枠はすぐに埋まり，キャンセル待ちも出た．

## 1.3 RFC 9340: Architectural Principles for a Quantum Internet

QIRGにおいて，初のRFCとなるRFC9340[34][*4]が発行された．本節ではRFC9340が出版された背景や問題意識などについて概説する．

RFC9340は、量子インターネット研究グループ(QIRG)によって作成され、量子ネットワークを紹介し、そのようなネットワークの設計と構築のための一般的なガイドラインを提示している。全体として、ネットワークエンジニアや研究者向けの，量子インターネットへの導入として意図されている。RFC9340は，量子ネットワークがどのように実装されるべきか、または実装されるだろうかについての決定的な声明として考えるべきではない。あくまで量子インターネットが持つ基本的な概念(principles)を論じているのみであり，このprinciplesにしても，今日のインターネットにおけるBest Effort principle やEnd-to-End principleのような，抽象化されたprinciplesに昇華されてはいない．RFC9340はQIRGメーリングリストやいくつかのIETFミーティングで議論された。これは、量子およびネットワーキングのドメインからの主題の専門家と、ターゲットとなる新参者の両方のQIRGメンバーの合意を代表している。

量子ネットワークは、重ね合わせ、量子もつれ、量子測定などの基本的な量子力学現象を利用する量子デバイスの分散システムであり、非量子(古典的)ネットワークでは実現できない能力を達成することが可能である。量子ネットワークの段階に応じて、これらのデバイスは、一度に1つの量子ビット(キュービット)のみを準備し測定できる単純な光子デバイスから、将来の大規模量子コンピューターに至るまで様々である。量子ネットワークは古典的ネットワークを置き換えることを意図しているわけではなく、古典的ネットワークでは実現不可能な新しい機能をサポートする全体的な古典-量子ハイブリッ

*3　https://ietf116.jp/tour/

*4　RFC (Request for Comments)は、インターネット技術に関する標準化文書の一種であり、インターネットプロトコルや関連技術についての仕様、概念、手順、およびその他の情報を提供するものである。これらの文書は、インターネットエンジニアリングタスクフォース(IETF)によって管理され、RFCエディタによって公開される。RFCはインターネットの基盤となる技術やプロトコルの標準化を目指す文書であり、インターネットアーキテクチャの重要な部分を形成する。例えば、TCP/IPプロトコルスイートやHTTP、SMTPなど、インターネットで広く使用されている技術の仕様がRFCとして公開されている。RFCには、提案された標準(Proposed Standard)、インターネット標準(Internet Standard)など、さまざまな成熟度レベルが存在する。新しい技術や概念がRFCとして提出された後、コミュニティによるレビューと実装を経て、インターネットの標準技術として採用されることがある。RFC文書は、誰でも自由にアクセスして閲覧できるようになっており、インターネット技術の開発と普及において重要な役割を果たしている。

ドネットワークを形成することを目的としている。例えば、量子通信の最もよく知られた応用である量子鍵配送(Quantum Key Distribution; QKD)は、物理法則に基づいて数学的に証明された秘匿性を持っており、特定の数学的問題の難解性に依存しない方法で、対称暗号鍵のペアを作成し配布することができる。QKDネットワークは、すでに短距離(約100キロメートル)で展開されている。

量子ネットワーキングの有用性は、量子鍵配送の秘匿性にとどまらず, 新しいアプリケーション領域でも約束されている。例えば、分散量子計算、クラウド内の安全な量子計算、量子強化測定ネットワーク、より高精度な長基線望遠鏡などがある。これらのアプリケーションはQKDよりもはるかに要求が厳しく、それらを実行できる量子もつれネットワークの実現への道のりはまだ長い。量子情報を送受信し、分散的に量子情報を操作できる最初の量子マルチノードネットワークが最近になって原理実証されたばかりである。

量子ネットワークや分散量子情報処理を可能にするデバイスを物理的に実現し、接続し、速度とエラー許容度を改善するために多大な努力が払われているが、これらのネットワークをどのように運用するかに関する提案は、RFC9340の執筆時点でまだ策定されていない。古典的なネットワークとの類似で言うと、デバイスを物理的に接続し、信号を送信する段階には到達しているが、データの送信、受信、バッファ管理、接続同期などはすべて、便利な高レベルインターフェイス(例えばソケット)を提供するネットワークスタックによってではなく、低レベル、カスタムビルド、ハードウェア固有のインターフェイスを直接使用してアプリケーションによって直接管理されなければならない。このようなネットワークスタックを試みる最初の実験が、最近になって実験室設定で示された。さらに、量子情報を伝送するための物理的メカニズムが存在する一方で、そのような伝送を管理するためのロバストなプロトコルは存在しない。

このような状況下で，量子ネットワークを紹介し、そのようなネットワークの設計と構築のための一般的なガイドラインを提示するものとして，RFC9340が出版された．ネットワークエンジニアや研究者向けの，量子インターネットへの導入とすることで，量子インターネットの実現に向けたより高度な議論や研究協力の実現を助ける意図がある．詳細についてはRFC9340[34]を参照して欲しい．

### 1.4 Protocols & Architecture Advances

We made significant strides in network architecture, working to make systems more complete and realizable. Here, we

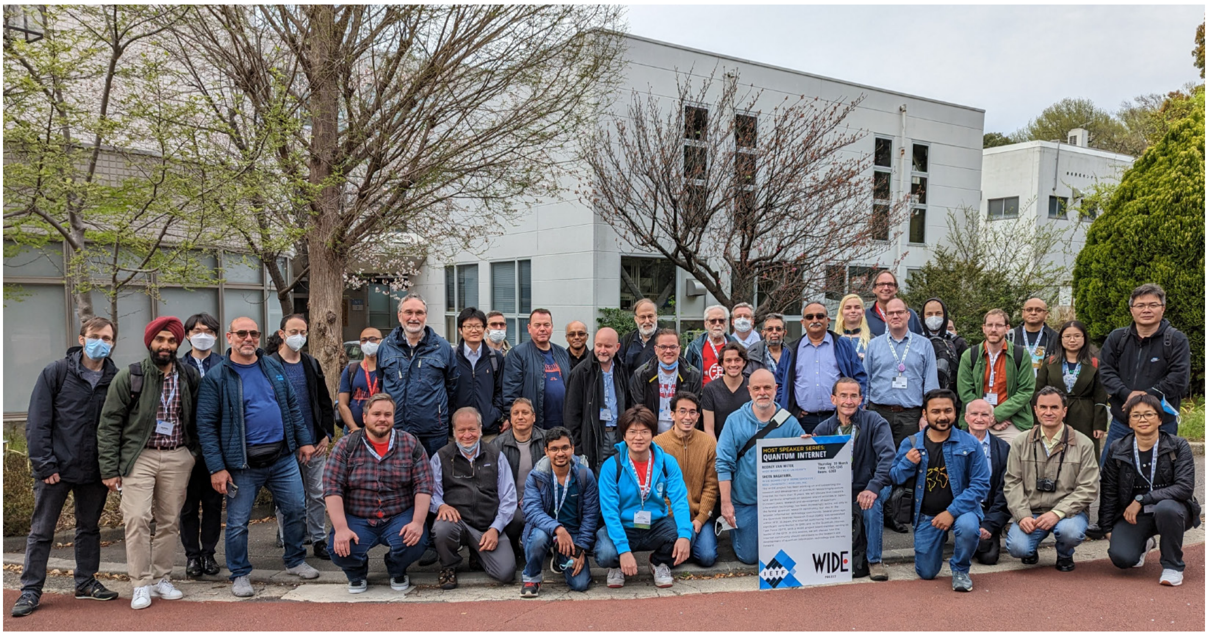


Figure 1: The IETF 116 lab tour at Yokohama National University.

highlight several advances. All show the WIDE emphasis on practicality in networking, filling in the protocol and engineering details for ideas that have been proposed either by ourselves or others.

### 1.4.1 Internetworking: QRNA

A decade ago, Van Meter, Horsman and Touch defined QRNA, the Quantum Recursive Network Architecture, as the first architecture for internetworking of quantum networks. Much as the classical Internet has routing and forwarding at the LAN level, network level, and internetwork level, we expect the Quantum Internet to be a multi-tiered scheme. QRNA unifies the mechanisms for operational rules for a connection into a recursive scheme that allows entanglement swapping, purification, and delivery of entangled states to end nodes and applications to all proceed in a scalable fashion. QRNA allows individual networks to operate autonomously and without sharing information about network internal topology and operations, much as BGP does for routing in the Internet.

A key architectural decision in recursive networking is whether to recurse on nodes or on links, as shown in Fig. 2. Both forms are possible, with different tradeoffs, making the appropriate choice context dependent.

### 1.4.2 Data Center and Metro/Wide Area Networking

Both the WIDE Project and more broadly the quantum computing and networking community have recognized the important differences in the goal, scale and performance requirements for data centers and wider-area networks.

Data center networks, or system area networks (SANs) when more tightly coupled, can be used to scale solving a single problem. This idea formed the basis of Van Meter's 2006 Ph.D. thesis [50]. Similar systems appeared on the roadmap published by IBM in 2023[*5]. Data centers have high performance demands, but present a clear use case. The current QITF testbed is primarily aimed at prototyping interconnects for multicomputer architectures.

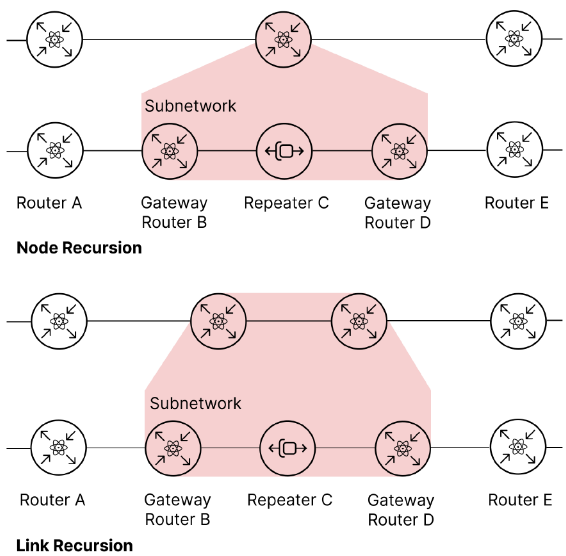


Figure 2: An important decision is whether to perform recursion on links or nodes. The "correct" answer depends on several factors in the design of the network. The physical set of nodes of course does not change; each layer is a separate logical view of the network, with separate addressing. This provides scale and autonomy to networks, much like the IGP/EGP distinction the Internet.

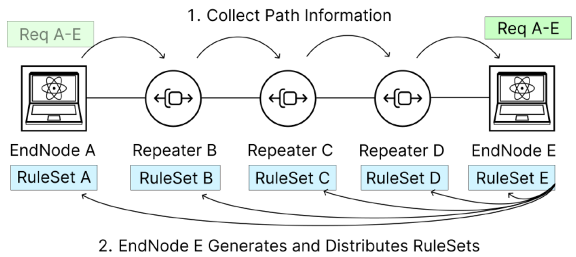


Figure 3: Two-pass connection setup in an individual network.

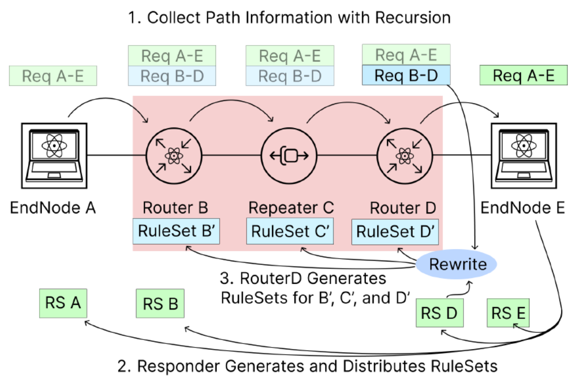


Figure 4: Two-pass connection setup in a recursive network.

*5 https://research.ibm.com/blog/quantum-roadmap-2033

In contrast, wide-area networks have many uses, including cryptographic functions, remote sensing, and blind quantum computation [30, 48, 51].

### 1.4.3 Link Multiplexing

Within a network, the use of a single link must be shared between multiple connections if the network is anything other than full circuit switched. Thus, we need a multiplexing scheme. Earlier work by the WIDE Project demonstrated that statistical multiplexing, akin to packet switching, can be effective in a quantum network [25]. However, on a link, it is crucial that the distribution of entanglement be coordinated properly between the link end points.

Therefore, we have established the concept of a *link allocation policy*. The policy is distributed on the classical control channel for the link via a LINK ALLOCATION UPDATE message (LAU). Each end of the link transmits an LAU to the opposite end of the link based on a change in the set of connections passing through it. After both ends agree on the new policy, then next step is to activate the policy. This is accomplished using a BARRIER message, indicating the first sequence number to be assigned using the new policy. The sequence message established for link update is shown in Fig. 5, and the detailed specification is publicly available in our GitHub repository*6.

The LAU and Barrier are currently designed for repeaters with memory at opposite ends of a single channel. In 2024, the mechanisms will be extended to a switched, multidrop link and to EPPS-based links with no memory.

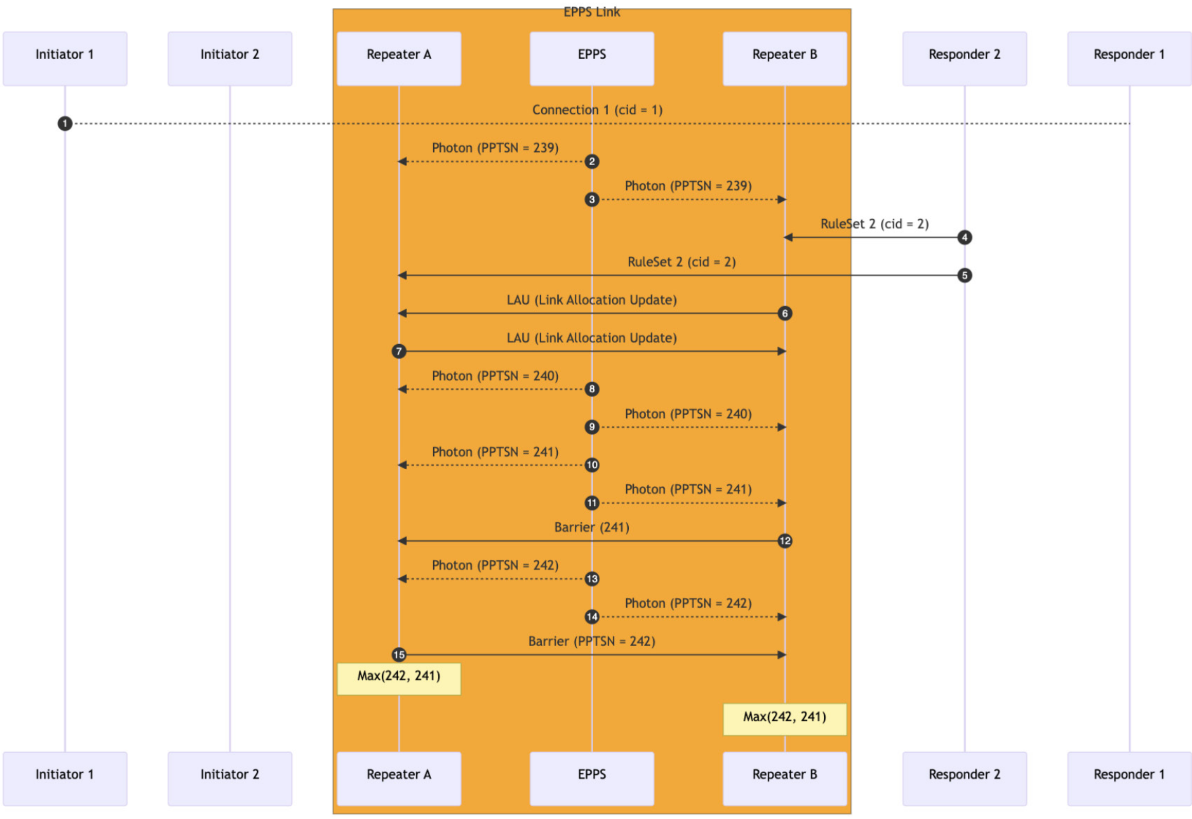


Figure 5: The message and event sequence for link allocation update. Note that the entangled photons are illustrated as being transmitted at different times, but are in fact generated simultaneously. The nodes at each end of the link issue an LAU when triggered by a change to the set of connections passing through the link, as at events 4 and 5. After the node has accepted an LAU from its partner, it issues a BARRIER message to negotiate when the new link allocation policy takes effect.

*6 https://github.com/sfcaqua/RuleSetSpec/blob/main/2.1.ConnectionSetupSpec.md

### 1.4.4 Using Entangled Photon Pair Sources

One important approach to distributing entanglement is to use a device that emits pairs of entangled photons; when this device is packaged as a node, it is known as an *entangled photon pair source* (EPPS). These nodes are useful both in data center networks and using satellites [33, 53]. Our testbed network will use EPPS nodes, and therefore it is critical to complete the protocol design. One method for utilizing an EPPS is what is known as a memory-source-memory, or MSM, link, where photons are distributed from the midpoint of the link and their entanglement is transferred to memory qubits at each end, e.g. via Bell state analysis near the memory qubits (Fig. 6). Our analysis (Fig. 7 shows that performance is limited by the amount of time that memory qubits are occupied, and indeed that there are "livelock" conditions in which memories at the two ends succeed in local operations at disparate points in the sequence. The system appears to be working, but the qubit memories are busy with qubit values that are never successfully entangled with the far end, time out and are discarded in a sequence that results in no entanglement being delivered to applications.

### 1.4.5 All-Photonic Links

As noted, a significant constraint on quantum network performance is the dwell time of memories, much of it spent waiting for confirmation of events from elsewhere in the network. This contrasts significantly with the classical Internet,

where packet forwarding is fire-and-forget, and each node makes decisions fully independently (based on information exchanged in the background, such as routing tables). Thus, a potential system improvement is to utilize photonic states that allow for similarly independent processing. One such approach is known as 3G networks, in which full error correcting codes are applied to photonic states, using many photons and a wellunderstand code [41]. Another is to use photonic states known as *graph states* that are robust against loss, in a form known as *all-photonic quantum repeaters* [26]. The initial proposal for all-photonic repeaters, from NTT, was impractical for a number of reasons. The group of Prof. Sophia Economou at Virginia Tech has substantially improved the protocols, but still with many engineering details left unresolved [31].

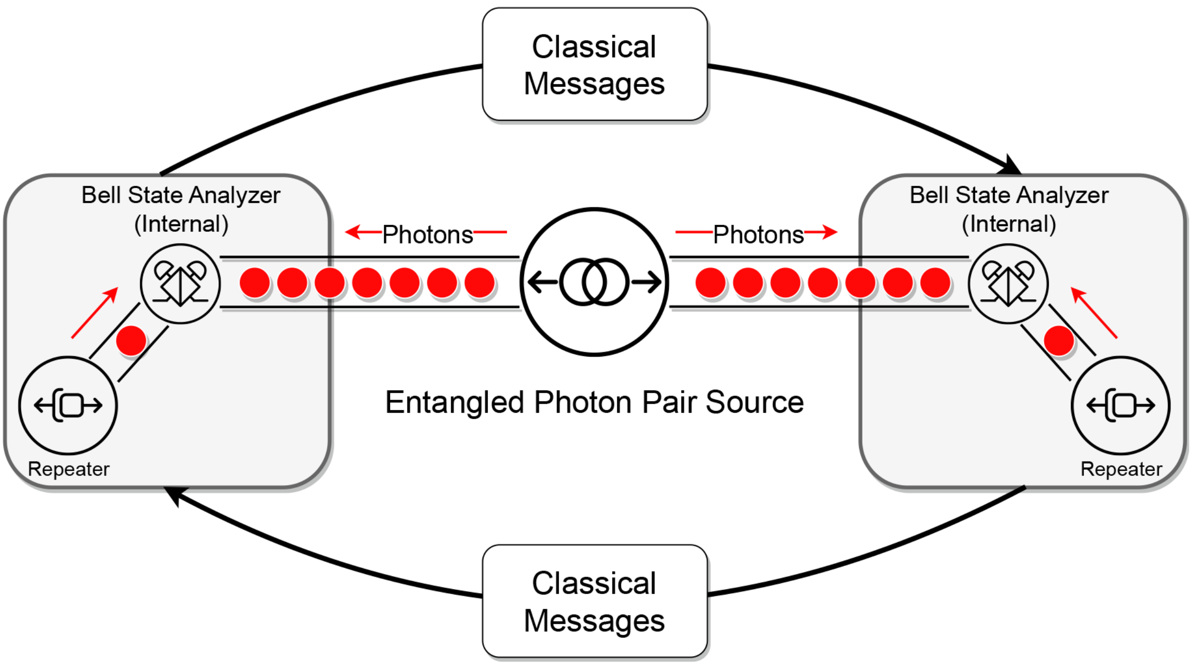


Figure 6: Memory-source-memory (MSM) link architecture. Ideally, this link architecture results in a lower entanglement success probability but orders of magnitude higher attempt rate due to less need to hold a memory and wait for ACK/NAK over the link latency. Our analysis details a more complex performance profile.

Recently, AQUA has worked to resolve some of these remaining issues [27]. Earlier proposals, for example, required buffering of photons to reorder transmission or reception, and while further decisions were being made about the disposition of following photons (particularly the choice of measurement basis for the photons, which depends on success or failure of measurement of prior photons in the graph state). We have determined how to order the creation of the graph state so that measurement can be conducted more simply, and how to effectively work with a small number of memories at the sources. We have also advanced the termination of connections at end nodes with memories and interoperability with networks using different types of links, topics heretofore not addressed.

The overall construction of an all-photonic link is somewhat similar to an MSM link (Sec. 1.4.4), but is perhaps best understood as a time-reversed version of the standard memory-interference-memory (MIM) link. The EPPS is replaced with a *repeater graph state source* (RGSS) node, and the BSA is replaced with an *advanced Bell state analyzer* (ABSA). We are continuing to work on the engineering of these two node types.

### 1.4.6 Error Management

Quantum networks depend upon two major forms of error management (error detection and error correction) and a form of error monitoring for links and end-to-end connections. Error detection is often done via a technique known as *purification*, which, when successful, improves our confidence that the state we are holding matches our expectation. When an error is detected, the quantum state is discarded; because the service of the network is delivering specific, generic entangled states known as *Bell pairs*, discarding the state results only in a performance penalty and does not result in the loss of important data. Quantum error correction (QEC), on the other hand, can be used on any quantum state. Its disadvantage is that it requires more physical resources and higher initial fidelity.

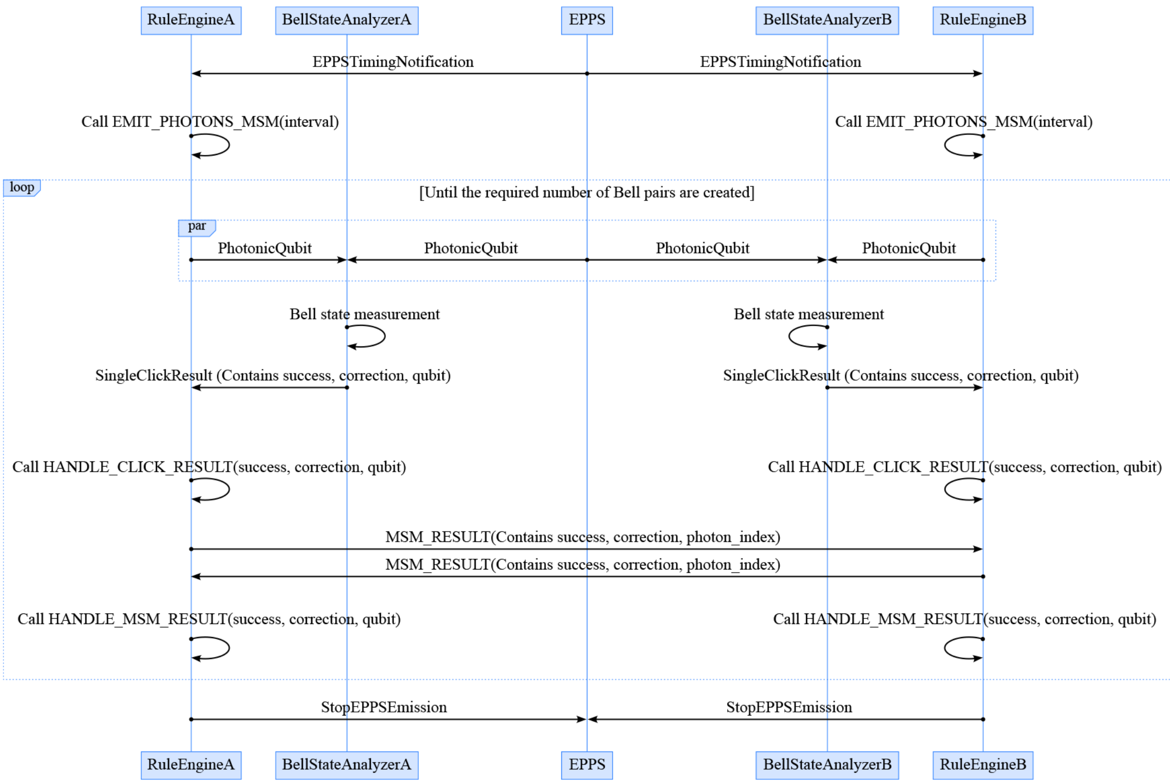


Figure 7: The messaging sequence for MSM (memory-source-memory) link control. Performance here is limited by classical messaging and by “dwell time” on memories, where memories are locked awaiting another event or condition, or are busy executing actions.

We have investigated combining QEC *with* purification in the operation of a single connection. We found that, under certain circumstances, either alone cannot achieve sufficient end-to-end fidelity of quantum states, but used correctly together, they can [44].

A link, and a connection, must be monitored to assess the fidelity of the quantum states being generated [29]. A common, but expensive, technique for full characterization of a quantum state is known as *quantum state tomography*. In the past, we have proposed a distributed network protocol for executing tomography [42]. Now, we propose a mechanism that uses information gained from the purification process, not for a complete characterization of the quantum state, but to learn enough *actionable* information to make online, real-time decisions about the next step for each quantum state [37].

## 1.5 Testbed

As a result of Shota Nagayama being chosen as a Program Manager for Moonshot Goal 6, QITF has established a laboratory at KBIC (Kawasaki Business Incubation Center)[*7]. The goal of this laboratory is to support the development of a large-scale, fault-tolerant quantum computer. The natural architecture is a multicomputer, or a data center network. Although most of the physical elements must still be hand-built, the focus is on advancing the *architecture* and *engineering* of a network, rather than to test new physical concepts. As such, we are emphasizing true distributed control and aiming for complete, online, real-time control systems and protocols.

WIDE members Shota Nagayama, Rodney Van Meter, Toshihiko Sasaki, Takahiko Satoh, Michal Hajdušek and Hiroyuki Ohno and their students are among the contributors to the testbed. Including PIs, students and staff, this multi-institutional effort includes about one hundred people.

### 1.5.1 Physical Implementation

Each node in Fig. 8 is controlled by a RaspberryPi microcontroller. In contrast to many testbed networks, we are establishing fully distributed control of the network from the beginning. Each controller consists of several software modules:

- CM: the connection manager, responsible for receiving and negotiating RuleSets that govern each connection;
- RE: the RuleEngine, responsible for determining the next action for each quantum state;
- RD: the routing daemon, which will run a distributed variant of Dijkstra's algorithm similar to OSPF [49];
- HM: the hardware monitor, responsible for monitoring the link's performance; and
- RT: the real-time device drivers for controlling hardware.

The physical elements are constructed in an optics laboratory, on a vibration-suppressing optical table, as shown in Fig. 10. To generate entangled photon pairs, we use a technique known as *spontaneous parametric down conversion* (SPDC), in which single photons from a strong laser beam are converted into entangled pairs of photons, with low probability. The entangled photons each have twice the wavelength (half the energy) of the input photons. As of the end of 2023, the optical components are partially in place, but entanglement has not been demonstrated.

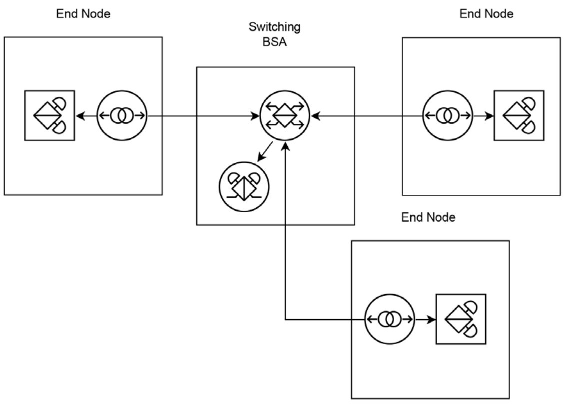


Figure 8: The network diagram for the planned first phase of the testbed network. The switching Bell State Analyzer in the middle includes mechanisms to support timing alignment of arriving photons. End nodes incorporate both EPPS devices and measurement stations.

*7 https://qitf.org/en/moonshotnagayama/

### 1.5.2 Timing Regimes

Quantum networks that distribute end-to-end entanglement involve a number of tasks with varying demands on timing precision and jitter. The design of a quantum network will involve a layered protocol architecture where different layers take responsibility for meeting these differing constraints. To build a robust network, we must understand these constraints; as part of the Moonshot testbed network we have begun developing a document detailing them. This section describes the various timing regimes, from most to least stringent, in order to assist the process of making key design decisions, including establishing which protocol layer or network subsystem is responsible for meeting each constraint.

Summary of timing regimes:

A. interferometric stabilization: need for sub-wavelength stability is photonic qubit representation-dependent

B. photon wave packet overlap: technologydependent photon wave packet length, but roughly nanoseconds

C. opening and closing of detector timing windows, detector recovery time: nanoseconds to microseconds

D. measurement basis selection (if required in BSA): performance will constrain entanglement attempt rate

E. optical switch control: switching of trains of wave packets

F. pre-configured event-driven tasks such as timing-triggered or measurement-triggered execution of quantum circuits: microseconds

G. urgent but not synchronization-critical tasks (e.g. execution of classical code that processes RuleSet messages and selects or creates new quantum circuits for execution): milliseconds

H. host-side application-level tasks (e.g. postmeasurement operations): milliseconds

I. background tasks (link tomography calculations, routing table updates): seconds to minutes

Some of these can only be achieved using high-quality hardware, while others are software tasks. Detailed analysis of these regimes will affect core software design in each network node type.

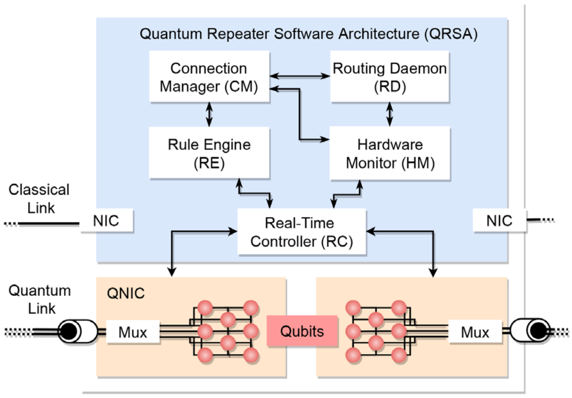


Figure 9: The Quantum Software Repeater Architecture, as defined for repeater nodes that have memory. This architecture is being adapted for memoryless nodes for the current testbed.

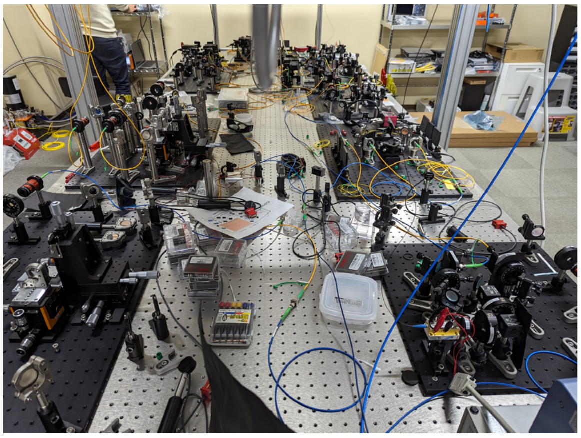

Figure 10: One of the three optical tables in the QITF laboratory at KBIC. The optical table top is silver colored, and each black breadboard holds the components for one major subsystem, such as a source of entangled photon pairs.

*8 https://github.com/sfc-aqua/quisp?tab=readme-ov-file

## 1.6 QuISP

Our quantum Internet simulator, QuISP [46], received continuing development attention in 2023 [*8]. In Sec. 1.4.1, we described the year's developments in quantum internetworking. These developments were prototyped using QuISP, and the results appeared in a SIGCOMM workshop paper [47]. This workshop was the first SIGCOMM workshop on quantum networking. In Sec. 1.4.3, we described link-level multiplexing. This multiplexing is being implemented in both the testbed network and in QuISP. The implementation in QuISP is described in the 2024 master's thesis of Makoto Nakai.

The EPPS and MSM link are actually implemented in two forms: the standard form for fixed, fiber-based networks, by Kento Samuel Soon, and a satellite link version, by collaborator Paolo Fittipaldi. The former is in the main branch of QuISP, and can be used in regular networks with some limitations.

## 1.7 Quantum Internet Task Force

The Quantum Internet Task Force (QITF) [*9] is continuing its technical work on system architecture (including protocol architecture and design), and is advancing toward an experimental metropolitan area testbed. We continue to recruit members for both financial support and technical expertise.

# 第２章 Society & Education

## 2.1 "Quantum Internet" online course

As members of the Q-Leap Education project, WIDE members Michal Hajdušek and Rodney Van Meter created the online course "Quantum Internet", with videos in both English and Japanese, and with quizzes included in the learning management system (LMS). The LMS is open only to learners from member institutions, but the videos are published on YouTube [*10]. All videos have subtitles in the corresponding language, in order to improve accessibility.

This course is the third in our series for QLeap Education, following "Overview of Quantum Communications" (2021) and "From Classical to Quantum Light" (2022). The videos on the YouTube channel we have established (Fig. 11) have been viewed more than 200,000 times to date. The videos have been viewed in more than 90 countries and territories; the top three are India, U.S. and Japan (Fig. 12).

The content of the "Quantum Internet" course is as follows:

- I Errors: Purification and Quantum Error Correction
- 1 Error Management Generations
- 1-1 Module overview
- 1-2 Introduction to QuISP
- 1-3 Types of errors
- 1-4 State tomography
- 1-5 Repeater generations
- 2 Purification
- 2-1 Detecting X and Z Errors
- 2-2 Multiple purification rounds
- 2-3 Scheduling
- 2-4 Reality
- 2-5 Purification demo
- 3 Quantum Error Corrected Repeaters
- 3-1 Introduction to QEC
- 3-2 Repeaters with encoding
- 3-3 3G repeaters
- 3-4 Quiz
- II Hardware
- 4 Flying qubits and stationary memories
- 4-1 Photonic qubit representation
- 4-2 Nitrogen vacancy center in diamond
- 4-3 Ion Trap
- 4-4 Wavelength conversion
- 5 Link Architectures
- 5-1 Meet-in-the-middle (MIM)
- 5-2 Memory-memory (MM)
- 5-3 Memory-source-memory (MSM)
- 5-4 Repeater Graph States (RGS)

*9 https://qitf.org/.
*10 https://www.youtube.com/@QuantumCommEdu/playlists

- 5-5 Sneakernet
- 6 Types of Network Nodes
- 6-1 Classification of network node
- 6-2 End nodes
- 6-3 Repeater nodes
- 6-4 Support nodes - creating and measuring
- 6-5 Support nodes - optical switching
- 6-6 Quiz
- III Networks
- 7 Types of Networks
- 7-1 Organizations and requirements
- 7-2 Topology and Traffic
- 7-3 SAN / multicomputer interconnect
- 7-4 Data center (DC)
- 7-5 LAN, MAN, WAN
- 8 Connections
- 8-1 Naming
- 8-2 Rules and RuleSets
- 8-3 Condition and action clauses
- 8-4 Two-pass setup
- 9 Routing and Multiplexing
- 9-1 Routing concepts
- 9-2 Routing Algorithms & Protocols
- 9-3 qDijkstra
- 9-4 Multiplexing concepts
- 10 Quantum Recursive Network Architecture

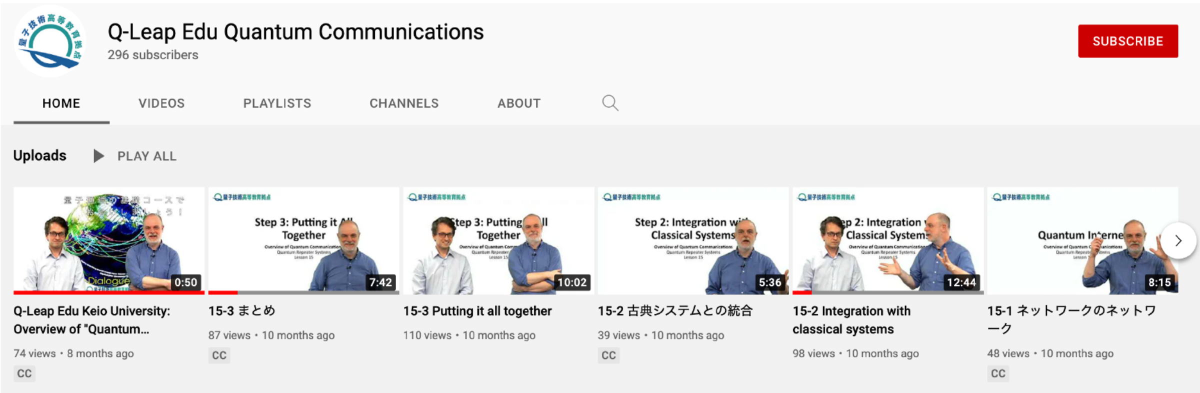


Figure 11: The Q-Leap Edu Quantum Communications YouTube channel. Videos are available in both English and in Japanese.

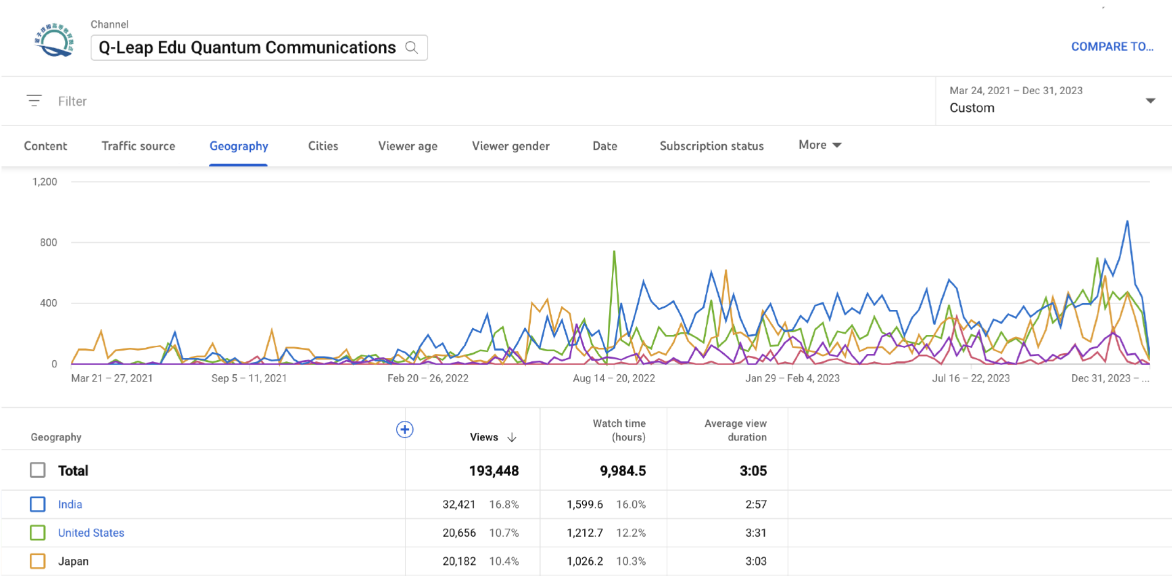


Figure 12: Views on the Q-Leap Edu Quantum Communications YouTube channel. The top three countries are India, U.S. and Japan, each with more than 20,000 views.

## 2.2 *Quantum Communications* Creative Commons-licensed undergraduate textbook

Based on their online couse "Overview of Quantum Communications", Michal Hajdušek and Rodney Van Meter have released their undergraduate textbook *Quantum Communications* under a Creative Commons CC-BY-SA license[*11]. The textbook includes exercises, new figures and improved explanations.

The table of contents of the book is as follows:



*11 https://arxiv.org/abs/2311.02367

- Exercises
- 15 Quantum Internet
- 15.1 Networks of networks
- 15.2 Integration with classical systems
- 15.3 Putting it all together
- Quiz
- Further reading chapters 14-15
- Bibliography
- Index

## 2.3 QIRG activities

QIRG held two face-to-face meetings in 2023, one at IETF 116 in Yokohama and one at IETF 118 in Prague. 120 people attended in Yokohama and 104 in Prague. The content of the IETF 116 meeting was described above.

The agenda for the meeting in Prague was as follows:

- Diego Lopez, A multi-plane architecture for the Quantum Internet, inspired on the lessons learned from QKD deployments
- Martin Stiemerling, DemoQuanDT: Controlling Quantum Key Distribution Networks
- Davide Li Calsi and Paul Kohl, The difficulty of Quantum Cryptography in presence of packet losses
- Marcello Caleffi, Quantum Internet Addressing
- Riccardo Bassoli, Towards the integration of 6G and the Quantum Internet

QIRG activities will continue in 2024.

## 2.4 Quantum native network engineers

An important goal of AQUA, including the QITF/Moonshot testbed, is development and education of the next generation of quantum network engineers, literate in both quantum information and classical network/Internet engineering. We conduct or support the following activities:

- WIDE Camp, WIDE Kenkyuukai and related meetings
- Van Meter's "Quantum Information Processing" course at SFC, taught in Japanese for the first in fall 2023 as「量子情報処理」
- Van Meter's new "Quantum Internet" course at SFC, taught for the first time in fall 2023
- the AQUA 研究会at SFC[*12]
- NICT's Quantum Camp[*13]
- participation in Keio Quantum Computing Center (KQCC) activities such as seminars[*14]
- the Asia-Pacific Internet Engineering program (APIE)[*15]
- the wealth of Internet-oriented classes at SFC, such as "Internet" (Prof. Osamu Nakamura) and "Network Architecture" (Prof. Keisuke Uehara)
- the Q-Leap Education video courses available through the official LMS[*16] (limited to approved students at member universities) or on our YouTube channel[*17] (available to all, of course)
- most importantly, a portion of the effort at KBIC is known as the「**失敗しても大丈夫**」(*"it's okay to fail"*) *testbed;* students are encouraged to build portions of the network even though they have no prior experience with experimental classical optics, let alone quantum optics.

We are encouraging a very hands-on approach to learning under the supervision of a large group of QITF/Moonshot faculty. Students are being exposed to laboratory practices in several research groups across Japan.

The education of quantum network engineers is not limited to Japanese students, and so much of the material above is available in both Japanese and English. The AQUA kenkyuukai at SFC currently consists of about 35 undergraduates, graduate students, staff and faculty from four continents: Asia (Japan,

*12 https://aqua.sfc.wide.ad.jp/
*13 https://nqc.nict.go.jp/
*14 https://quantum.keio.ac.jp/
*15 https://apie.soi.asia/
*16 https://q-leap.lms.nii.ac.jp/auth/shibboleth/login.php
*17 https://www.youtube.com/c/QuantumCommEdu

South Korea, China, Thailand, Indonesia, India, Nepal, Iran, Singapore), Europe (Slovakia, Poland, Netherlands, Sweden), Africa (Egypt, Senegal, Eritrea), and North America (United States, Canada). Some have dual citizenship or were raised in Japan and speak Japanese with native fluency. English is the native language of only a few AQUA members, but is the common language for all. Some Japanese members are initially less comfortable working in English, but with the support of the group grow to speak it well. The AQUA group is shown in Fig. 13.

## 第3章　Computing

The 2023 AQUA quantum computing effort focused on systems-oriented tasks as well as algorithms. We expect quantum software engineering (QSE) to be an important field in the coming decades, able to take advantage of much that has been learned about classical software engineering but with unique challenges. This field offers a true opportunity for students and young researchers to establish key directions for the community and for themselves. Our efforts in QSE and systems work include progressing on methods and tools for debugging quantum software, a compiler for fault-tolerant systems, and error mitigation. Here, we highlight three recent works.

### 3.1　Debugging

We have been working on how to debug quantum programs for a couple of years [38]. In 2023, we improved our understanding of how bugs occur [39] and improved the tools we have created for debugging Qiskit programs [40]. Most importantly, we have categorized bugs into three groups (adapted from a revision of Ref.[40]):

- **Amplitude-Permutation (AP) Blocks** permute the amplitudes of quantum states. These circuits mimic the

Figure 13: About 2/3 of the AQUA group at SFC.

operation of reversible classical logic within the quantum realm. Hence, only rearranging the amplitudes associated with the quantum states without redistributing them or altering their phases. An example is a quantum adder or Grover's oracle. Those blocks are essentially classical reversible logic [28]. Mathematically, for set of states $\alpha_j\, |j\rangle$, an AP block can be defined as

$$\sum_j \alpha_j |j\rangle \rightarrow \sum_j \alpha_{\Pi(j)} |j\rangle. \qquad (1)$$

Where $\Pi(j)$ is a permutation function. A permutation matrix has exactly one 1 in each row and column. An example of a 2- qubit AP block unitary is

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (2)$$

- **Phase-Modulation (PM) Blocks** Quantum circuits that focus exclusively on altering the phases of quantum states without changing their amplitudes. The primary function of these circuits is to introduce phase shifts based on values of certain qubits. Mathematically, for set of states $\alpha_j\, |j\rangle$, a PM block can be defined as

$$\sum_j \alpha_j |j\rangle \rightarrow \sum_j \alpha_j e^{i\pi f(j)} |j\rangle. \qquad (3)$$

where $f(j)$ is a function that calculates the phase shift of a state $\theta_j$ , $f(j) \in$ R. The unitary of a PM block will be a diagonal matrix $D$ with $D_{jj} = e^{i\pi\theta j}$ .

- **Amplitude-Redistribution (AR) Blocks** Unlike the Amplitude-Permutation Circuits, these circuits redistribute the amplitudes across various quantum states, thereby harnessing the full potential of quantum superposition and entanglement. An example of an AR block is the Quantum Fourier Transform (QFT). An AR block contains gates that alter interference patterns and create or destroy superposition. AR blocks can be represented as

$$\sum_j \alpha_j |j\rangle \rightarrow \sum_j \alpha'_j |j\rangle. \qquad (4)$$

Where $\alpha'_j = \Sigma_k\ U_{j,k\alpha k}$. Here, $U$ is a unitary matrix applied to the qubits.

### 3.2 Compilation

Fault-tolerant quantum computation requires new compilation techniques. An international collaboration has been studying the use of specialized *graph states* as intermediate states in executing a quantum circuit [43]. We have joined this collaboration, and contributed one stage of the compiler, focused on mapping graph states onto a particular form of error correction known as *lattice surgery* (originally developed by a collaboration including AQUA members) [32] using the approach known as the *game of surface codes* [35].

Our work involved creating (classical) algorithms for a graph state problem, mapping nodes in the quantum graph state to specific variable locations within the machine. This work was published IEEE Quantum Week [36].

### 3.3 Cosmic Rays

In earlier work, we have participated in an international collaboration proposing a method using quantum error correction as a quantum *erasure* code between nodes, in order to protect against the loss of data when cosmic rays or local high-energy radiation impacts a superconducting quantum chip [52].

That work was a system-level solution to the problem, with a large penalty in the amount of hardware required. Physicists have also proposed hardware solutions for reducing the probabilty of error events, or the range over which such events propagate. In 2023, we added software to this stable of techniques, by proposing and analyzing a method for moving logical qubits around within the machine to avoid “hot” areas that are affected by the radiation event [45].

## 第4章　Publications


1. Michal Hajdušek and Rodney Van Meter, *Quantum Communications*, `https://arxiv.org/abs/2311.02367`

2. W Kozlowski, S Wehner, R Van Meter, B Rijsman, AS Cacciapuoti, M Caleffi, S Nagayama, "Architectural Principles for a Quantum Internet", RFC 9340, March 2023 [34]

3. Sara Ayman Metwalli, Rodney Van Meter, "Cirquo: A Suite For Testing and Debugging Quantum Programs", arXiv preprint arXiv:2311.18202

4. Ananda G Maity, Joshua CA Casapao, Naphan Benchasattabuse, Michal Hajdusek, Rodney Van Meter, David Elkouss, "Noise estimation in an entanglement distillation protocol", ACM SIGMETRICS Performance Evaluation Review, 51(2), Oct. 2023

5. Naphan Benchasattabuse, Michal Hajdušek, Rodney Van Meter, "Protocols for all-photonic quantum repeaters" (poster), 2023 IEEE International Conference on Quantum Computing and Engineering (QCE), Sept. 2023

6. Sara Ayman Metwalli, Rodney Van Meter, "A Categorization of Bugs in Quantum Programs" (poster), 2023 IEEE International Conference on Quantum Computing and Engineering (QCE), Sept. 2023

7. Kentaro Teramoto, Michal Hajdusek, Toshihiko Sasaki, Rodney Van Meter, Shota Nagayama, "RuleSet-based Recursive Quantum Internetworking", Proceedings of the 1st Workshop on Quantum Networks and Distributed Quantum Computing, Sept. 2023

8. Bernard Ousmane Sane, Rodney Van Meter, Michal Hajdušek, "Fight or Flight: Cosmic Ray-Induced Phonons and the Quantum Surface Code", 2023 IEEE International Conference on Quantum Computing and Engineering (QCE), Sept. 2023

9. Sitong Liu, Naphan Benchasattabuse, Darcy QC Morgan, Michal Hajdušek, Simon J Devitt, Rodney Van Meter, "A Substrate Scheduler for Compiling Arbitrary Fault-tolerant Graph States", 2023 IEEE International Conference on Quantum Computing and Engineering (QCE), Sept. 2023

10. Shigetora Miyashita, Takahiko Satoh, Michihiko Sugawara, Naphan Benchasattabuse, Ken M Nakanishi, Michal Hajdušek, Hyensoo Choi, Rodney Van Meter, "Digital quantum simulator for the time-dependent Dirac equation using discrete-time quantum walks", arXiv preprint arXiv:2305.19568

11. Poramet Pathumsoot, Theerapat Tansuwannont, Naphan Benchasattabuse, Ryosuke Satoh, Michal Hajdušek, Poompong Chaiwongkhot, Sujin Suwanna, Rodney Van Meter, "Hybrid Error-Management Strategies in Quantum Repeater Networks", arXiv preprint arXiv:2303.10295

12. Yasuhiro Ohkura, Suguru Endo, Takahiko Satah, Rodney Van Meter, Nobuyuki Yoshioka, "Leveraging hardware-control imperfections for error mitigation via generalized quantum subspace", arXiv preprint arXiv:2303.07660