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Practical Graph States in Low-Bandwidth, Noisy Quantum Networks

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14. ABSTRACT
The general theme of the work is to advance the use of quantum graph states (a special form of entangled quantum state) for the use of quantum communication, specifically in the context of a Noisy, Intermediate-Scale Quantum Internet (NISQI). Our charter
includes the use of graph states for a quantum link (connecting two neighboring nodes in a network through a quantum channel), as a switching method within a quantum repeater node, and as a wide-area, multi-party quantum state useful for a variety of applications. In the October 2020-September 2021 time frame, the AQUA (Advancing Quantum Architecture) group headed by Prof. Van Meter has significantly improved its simulation capabilities, published one journal paper, and prepared several more for submission, and contributed to the research and development community through leadership of the Quantum
Internet Research Group (QIRG) and participation in the Quantum Internet Task Force. A the new web browser-based version of the simulator was built using WebAssembly (Wasm).

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"Practical Graph States in Low-Bandwidth, Noisy Quantum Networks"

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Abstract: The general theme of our work is to advance the use of quantum *graph states* (a special form of entangled quantum state) for the use of quantum communication, specifically in the context of a Noisy, Intermediate-Scale Quantum Internet (NISQI). Our charter includes the use of graph states for a *quantum link* (connecting two neighboring nodes in a network through a quantum channel), as a switching method within a *quantum repeater node*, and as a *wide-area, multi-party quantum state* useful for a variety of applications.

In the October 2020-September 2021 time frame, the AQUA (Advancing Quantum Architecture) group headed by Prof. Van Meter has significantly improved its simulation capabilities, published one journal paper, and prepared several more for submission, and contributed to the research and development community through leadership of the Quantum Internet Research Group (QIRG) and participation in the Quantum Internet Task Force. We are particularly proud of the new web browser-based version of our simulator, built using WebAssembly (Wasm).

Summary

1. Key design and implementation goals for graph states in repeater networks
    a. Simulation of multi-party graph state creation was nearing completion (joint project with Sorbonne U.), but now needs to be re-implemented for the current structure of our open-source Quantum Internet Simulation Package (QuISP).
    b. Implementation of simulation of RGS (repeater graph state) is essentially complete.
2. Additional technical goals and achievements
    a. We have proposed a Quantum Internet architecture.
    b. Simulation of midpoint source (MSM) links is nearing completion.
    c. Simulation of 2G (quantum error correction-based) repeaters (joint project with Mahidol U.).
    d. Flexible traffic generation model for testing behavior under different conditions nearing completion.
    e. Community uptake for QuISP.
3. Improvements to the QuISP simulator infrastructure
    a. A web browser-based (web assembly, or WASM) version of the latest simulator is now available.
    https://aqua.sfc.wide.ad.jp/quisp-online/master/
    b. Dramatic improvements in code quality and maintainability.
    c. Increase in automated software testing.
    d. Improved availability and robustness on various platforms, including improved installation.
    e. Reorganization of user and programmer documentation, including a shift to wiki-based documentation.
4. Experimental work
    a. Due to COVID-19 restrictions and the loss of two students who were expected to conduct the work, no experimental work was conducted.
5. Publications, drafts, preprints and theses (in chronological order)
    a. P Pathumsoot, T Matsuo, T Satoh, M Hajdušek, S Suwanna, R Van Meter, "Modelling of Measurement-based Quantum Network Coding on IBM Q Experience Devices",
    Physical Review A 101, 052301 (2020). (peer reviewed)
    https://journals.aps.org/pra/abstract/10.1103/PhysRevA.101.052301
    Network coding is a technique for using multiple communication links, at least one of which calculates a function of data intended to transit a bottleneck output link, rather than simply forwarding the data. The quantum version of network coding builds on graph states or similar structures; in this case, we use Bell pairs to emulate similar behavior. This paper was one of the world's first papers to use a *quantum computer* to simulate a *quantum network*. This work was conducted while the first author was an undergraduate summer

intern at Keio, and led to him joining Keio as a Ph.D. student after his master's degree.

b. Angela Sara Cacciapuoti, Marcello Caleffi, Rodney Van Meter, Lajos Hanzo, "When entanglement meets classical communications: Quantum teleportation for the quantum internet",
IEEE Transactions on Communications 68, 6, June 2020 (peer reviewed)
DOI: 10.1109/TCOMM.2020.2978071
https://ieeexplore.ieee.org/abstract/document/9023997
This peer-reviewed tutorial paper presents the key quantum networking concepts of teleportation and decoherence to a classical communications audience. This paper has been well received, and is already highly cited.

c. Ryosuke Satoh, Michal Hajdušek, Rodney Van Meter,
"Federated Graph State Preparation on Noisy, Distributed Quantum Computers",
IPSJ Quantum Software Kenykuukai, Sept. 2020,
IPSJ Technical Reports, (not peer reviewed)
http://id.nii.ac.jp/1001/00207190/
This paper directly addressed the issue of creation of multi-party graph state creation, one of the two main areas of this project. It proposes a framework for subdividing graph state and assigning them to separate nodes, based on a noise model that captures the behavior of independent physical components.

d. Wojciech Kozlowski, Rodney Van Meter,
"Schrödinger's Internet at the IRTF",
IEEE Communications Standards Magazine, 4(3), pp. 4-6, Sept. 2020
DOI: 10.1109/MCOMSTD.2020.9204590 (not peer reviewed)
https://ieeexplore.ieee.org/document/9204590
This article describes the work of the Quantum Internet Research Group, of which Prof. Van Meter is the co-chair.

e. A Chia, M Hajdušek, R Nair, R Fazio, L-C Kwek, V Vedral,
"Phase-preserving linear amplifiers not simulable by the parametric amplifier",
Physical Review Letters 125, 163603 (2020). (peer reviewed)
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.125.163603
This work addresses issues with amplifiers needed in quantum optical systems, and includes a study of two-photon effects.

f. Ryosuke Satoh,
Resource Allocation Policy for Noisy Distributed Quantum Computing,
Bachelor's thesis for Environment and Information Studies, Keio University
March 2021 (faculty reviewed)
https://aqua.sfc.wide.ad.jp/publications/cocori_GP_final_compressed.pdf
This thesis builds on the earlier workshop paper and examines three algorithms for assigning variables in a distributed computation to various nodes on the network.

g. Takahiko Satoh, Shota Nagayama, Shigeya Suzuki, Takaaki Matsuo, Michal Hajdušek, Rodney Van Meter,
"Attacking the Quantum Internet",
IEEE Transactions on Quantum Engineering, 2, 4102617, July 2021. (peer reviewed)
DOI: 10.1109/TQE.2021.3094983
https://ieeexplore.ieee.org/document/9477172
This paper follows on from an earlier AOARD-supported project. It represents one of the first peer-reviewed papers on the issue of securing operation of the Quantum Internet. The types of potential attacks on hardware and software both are examined. In particular, we found that the tomography (or other state characterization method) necessary for tracking the fidelity of states being created can be fooled by a malicious party, and ultimately can be manipulated to cause network management protocols to declare certain repeaters down, partitioning the network. Secure, cryptographic selection of the states used for tomography can solve this problem.

h. P Pathumsoot, N Benchasattabuse, R Satoh, M Hajdušek, R Van Meter, S Suwanna,
"Optimizing Link-Level Entanglement Generation in Quantum Networks with Unequal Link Lengths",
(2021) 25th International Computer Science and Engineering Conference (ICSEC) Jan 2022 (peer reviewed)
DOI: 10.1109/ICSEC53205.2021.9684634
https://ieeexplore.ieee.org/abstract/document/9684634
A phenomenon that was noted some years ago is that unidirectional quantum links make most effective use of memory qubits when unbalanced, with more at the transmitting end than the receiving end. This paper examines this impact of this phenomenon on second generation (2G) quantum networks.

i. Makoto Nakai,
Qubit Allocation For Distributed Quantum Computing,
Bachelor's thesis, Keio University, Faculty of Environment and Information Studies, Mar. 2022. (faculty reviewed)
https://aqua.sfc.wide.ad.jp/publications/dave_bthesis.pdf
This thesis proposed a heuristic for splitting a single computation into two parts suitable for execution in a distributed manner.

j. David D Awschalom, Hannes Bernien, Rex Brown, Aashish Clerk, Eric Chitambar, Alan Dibos, Jennifer Dionne, Mark Eriksson, Bill Fefferman, Greg David Fuchs, Jay Gambetta, Elizabeth Goldschmidt, Supratik Guha, F Joseph Heremans, Kent David Irwin, Ania Bleszynski Jayich, Liang Jiang, Jonathan Karsch, Mark Kasevich, Shimon Kolkowitz, Paul G Kwiat, Thaddeus Ladd, Jay Lowell, Dmitri Maslov, Nadya Mason, Anne Y Matsuura, Robert McDermott, Rod van Meter, Aaron Miller, Jason Orcutt, Mark Saffman, Monika Schleier-Smith, Manish Kumar Singh, Phil Smith, Martin Suchara, Farzam Goudeh-Fallah, Matt Turlington, Benjamin Woods, Tian Zhong,

"A Roadmap for Quantum Interconnects",
Argonne National Laboratory technical report ANL-22/83, July 1, 2022. (not peer-reviewed)
https://www.osti.gov/biblio/1900586
Quoting the description, "Created by Q-NEXT, a U.S. Department of Energy (DOE) National Quantum Information Science Research Center, this document is a roadmap for quantum interconnects research and its impact for quantum information science and technology. It is the outcome of the collective work of a large team of Q-NEXT members and participants from academia, industry and DOE national laboratories. The roadmap addresses the role of quantum interconnects in three emerging areas of quantum information: computing, communication and sensing. It reviews the materials, components and systems used for these purposes; summarizes relevant scientific questions and issues; and addresses the most pressing research needs. The document then distills these considerations into recommendations for strategic science and technology research imperatives for the next decade. In addition to informing Q-NEXT's internal activities, the roadmap has also been created with a broader objective of developing a guide for key issues and research needed over the next decade for the worldwide scientific and engineering community interested in quantum information." Prof. Van Meter participated as an outside voice in this work, and in particular contributed to the definition of network types and network nodes, helping to create a roadmap for quantum network architecture and protocol research and development.

k. Rodney Van Meter, Ryosuke Satoh, Naphan Benchasattabuse, Takaaki Matsuo, Michal Hajdušek, Takahiko Satoh, Shota Nagayama, Shigeya Suzuki, "A Quantum Internet Architecture",
2022 IEEE International Conference on Quantum Computing and Engineering (QCE), pp. 341-352 Sep 2022 (peer reviewed)
https://arxiv.org/abs/2112.07092.
This paper is one of our principal outputs of this project. It is a fairly complete vision for not only a quantum network architecture, but a Quantum Internet architecture. It is also the first public summary of the icon set discussed below. This paper presents the RuleSet construction for managing individual connections, as well as the current conception of QRNA, the Quantum Recursive Network Architecture. QRNA achieves global scalability and autonomy of network operations by allowing individual networks to appear as single nodes in the network topology, much as Autonomous Systems (ASes) are treated as single hops in the Internet's Border Gateway Protocol (BGP). In contrast to the Internet, which has several separate layers of network and topology management, QRNA unifies them into a single system. The RuleSets discussed here were initially presented in an earlier paper, but are more fully developed here.

l. Ryosuke Satoh, Michal Hajdušek, Naphan Benchasattabuse, Shota Nagayama, Kentaro Teramoto, Takaaki Matsuo, Sara Ayman Metwalli, Takahiko Satoh, Shigeya Suzuki, Rodney Van Meter,
"QuISP: a Quantum Internet Simulation Package",
2022 IEEE International Conference on Quantum Computing and Engineering (QCE), pp. 353-364 Sep 2022 (peer reviewed)
https://arxiv.org/abs/2112.07093.
Awarded Best Paper.
This paper is one of our principal outputs from this project. It describes our error basis quantum Internet simulator, designs for network protocol development and scalability testing as we look for emergent behavior in large-scale systems. This paper and our participation in the Workshop for Quantum Repeaters and Networks have resulted in new international collaborations, especially with Argonne National Laboratory.

m. Ryosuke Satoh,
"RuLa: A Programming Language for RuleSet-based Quantum Repeaters",
Master's thesis, Keio University Graduate School of Media and Governance, 2023 (academic year 2022). (faculty reviewed) **Awarded Cyber Informatics Program Research Award.**
One of the challenges with the RuleSet approach to dynamically determining the behavior of the repeaters is that, until now, creating the RuleSets themselves has required direct C++ programming. The programming process involved understanding a great deal about the internals of the simulator in ways that are irrelevant to the RuleSets themselves. Ryosuke took it upon himself to simplify this process, and created an entire domain-specific programming language, with a complete grammar, that is designed for use by researchers and network operators.

n. Wojciech Kozlowski, Stephanie Wehner, Rodney Van Meter, Bruno Rijsman, Angela Cacciapuoti, Marcello Caleffi, Shota Nagayama,
"Architectural Principles for a Quantum Internet",
https://datatracker.ietf.org/doc/draft-irtf-qirg-principles/, accepted by the Internet Research Task Force (IRTF), to be published as Request for Comments (RFC) 9340. Upon completion of final copyediting, will be published at https://www.rfc-editor.org/info/rfc9340. (peer reviewed)
This RFC is the first issued by the Internet Research Task Force on quantum communications. It explains basic quantum concepts and outlines the functions that a quantum network will provide to an integrated quantum-classical communications system, and the roles that quantum repeaters must fill in such a network. Development of this document took four years, and as with all RFCs, was conducted in an open process with extended feedback and criticism from the research community both in person and via the Quantum Internet Research Group (QIRG) mailing list, which consists of over 400 researchers from around the world.

o. 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", in preparation; to be submitted to IoP QST in March, 2023. (draft attached)
   This paper compares 0G (entanglement swapping only, no error management), several forms of 1G (acknowledged link layer, purification for error detection), and 2G (acknowledged link layer, quantum error correction) networks. This paper deepens our understanding of the relative importance of memory lifetime and gate errors in chains of repeaters. This paper was a joint project of Mahidol University and Keio. It originated directly from prior collaborations, and involved biweekly meetings via Zoom. The first author is now a Ph.D. student at Keio.
p. Naphan Benchassatabuse, Michal Hadjušek, Rodney Van Meter,
   "Design and simulation of concrete protocols for graph-based all-photonic quantum repeaters",
   to be submitted to IEEE International Conference on Quantum Computing and Engineering (QCE) in April, 2023. (in preparation)
q. Naphan Benchassatabuse, Michal Hadjušek, Rodney Van Meter,
   "Optimizing graph state logical encoding for connection path in all-photonic quantum repeaters", to be submitted to *Quantum* (in preparation)

6. Talks
   a. Rodney Van Meter and David J. Farber, "The Future of Quantum Computing", KGRI Seminar series, 2019/09/24,
      https://www.youtube.com/watch?v=5pnpkjAL1f8
   b. Rodney Van Meter, "Engineering the Quantum Internet", Caltech INQNET seminar, 2020/10/20
   c. Rodney Van Meter, "Engineering the Quantum Internet", National University of Singapore Center for Quantum Technologies seminar, 2020/10/29
   d. Rodney Van Meter, "Quantum Internet Research Group", panel discussion, National University of Singapore, 2021/2/25
   e. Rodney Van Meter, "QuISP: Quantum Internet Simulation Package," Entanglement-Assisted Communication Networks Workshop (EACN), 2021/3/11
      https://www.mcqst.de/news-and-events/eacn-2021/
   f. Rodney Van Meter, "Operational Security for the Quantum Internet," NIST Quantum Communications and Networks seminar, 2021/5/7
   g. Michal Hadjušek, "Generalized measure of quantum synchronization", Second Kyoto Workshop on Quantum Information, Computation, and Foundation, September 2021, Kyoto, Japan (invited).
   h. Kentaro "zigen" Teramoto, "Running OMNeT++ in Web Browser", 8th OmNeT++ Community Summit, 2021/09/08
      https://summit.omnetpp.org/2021/index.html

i. Rodney Van Meter, "Quantum Computing (and Quantum Internet) and the Sustainable Development Goals (SDGs)", 47th International Congress on Science, Technology and Technology-Based Innovation (STT47), Bangkok, Thailand (remote presentation), 2021/10/5 (invited talk) https://stt47.scisoc.or.th/
j. Naphan Benchasattabuse, DISTRIBUTING MULTIPARTITE ENTANGLED STATE OVER QUANTUM INTERNET, 47th International Congress on Science, Technology and Technology-Based Innovation (STT47), Bangkok, Thailand (remote presentation), 2021/10/5 https://stt47.scisoc.or.th/
k. Poramet Pathumsoot, OPTIMIZATION OF EXPECTED WAITING TIME IN NETWORK OF QUANTUM REPEATERS, 47th International Congress on Science, Technology and Technology-Based Innovation (STT47), Bangkok, Thailand (remote presentation), 2021/10/5 https://stt47.scisoc.or.th/
l. Rodney Van Meter, "Quantum Network & Internet Design & Simulation", EU Networking Channel seminar, 2021/11/24 https://networkingchannel.eu/quantum-networks/
m. Rodney Van Meter, "Quantum Network & Internet Design & Simulation", IPSJ Quantum Internet and Quantum Cyberspace Seminar, 2021/12/7 https://www.ipsj.or.jp/event/seminar/2021/program12.html
n. Rodney Van Meter, "The Usefulness of Quantum", 4th R-CSS International Symposium, RIKEN Center for Computational Science, 2022/02/07 https://www.r-ccs.riken.jp/R-CCS-Symposium/2022/
o. Rodney Van Meter, "Engineering the Quantum Internet", THE FIRST INTERNATIONAL WORKSHOP ON NETWORK SCIENCE FOR QUANTUM COMMUNICATION NETWORKS (NetSciQCom) keynote, https://infocom2022.ieee-infocom.org/first-international-workshop-network-science-quantum-communication-networks-netsciqcom-committee.html
p. Rodney Van Meter, ""Whole Stack" Quantum Computer Development", EMERGING DISRUPTIVE TECHNOLOGY ASSESSMENT SYMPOSIUM (EDTAS), Australia, 2022/06/22
q. Rodney Van Meter, "Quantum Airliners": Whole Stack Quantum Computer Development", QCSAA, 2022/07/18
r. Rodney Van Meter, "Engineering the Quantum Internet (aka A Quantum Internet Architecture, the long form)", University of Southern California, 2022/09/14
s. Rodney Van Meter, "Engineering the Quantum Internet (aka A Quantum Internet Architecture, the long form)", UCLA, 2022/09/15
t. Rodney Van Meter, "Distributed quantum error correction for chip-level catastrophic errors", Caltech, 2022/09/16
u. Rodney Van Meter, "The Quantum Internet", Moonshot Nagayama Project + Quantum Internet Task Force Joint Symposium, 2023/1/13

7. Tutorials

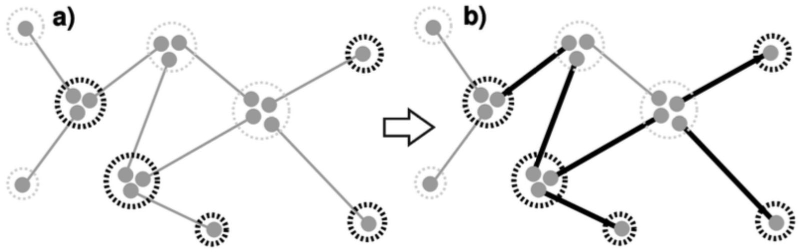
    a. “Hands-on Simulation of a Quantum Network”, half-day tutorial, IEEE Quantum Week, Oct. 12, 2020. 18 attendees, online. https://qce20.quantum.ieee.org/tutorials/#tut-vanmeter-satoh
    b. “Quantum Networks from Scratch”, 3rd Workshop for Quantum Repeaters and Networks, Chicago, August 19-21, 2022, a half-day tutorial with about 95 attendees both in person and online. https://chicagoquantum.org/events/tutorial-quantum-repeater-networks-scratch
8. Supported work in quantum networking community
    a. Continued activity in the Quantum Internet Research Group (a group of the Internet Research Task Force); Prof. Van Meter continues as co-chair. https://datatracker.ietf.org/rg/qirg/about/
    b. Prof. Van Meter continues as a member of the Workshop for Quantum Repeaters and Networks steering committee; new charter establishes rotation of steering committee membership. https://www.wqrn.org/
    c. Prof. Van Meter participated as an outside member in the quantum communications network roadmapping effort by the Q-Next center, funded by the U.S. Department of Energy. https://www.q-next.org/
9. Non-supported activities seeded in part by results from this project
    a. The Quantum Internet Collaboration Center has been officially established underneath the Keio Global Research Institute https://www.kgri.keio.ac.jp/en/project/2022/A22-18.html
    b. The Quantum Internet Task Force (https://qitf.org/) has been officially established as a consortium underneath the Keio Research Institute at SFC.
    c. Prof. Van Meter’s AQUA research group has taken responsibility for the quantum communications area of the new Quantum Academy of Science and Technology (https://qacademy.jp/, available in Japanese and English), supported by the Q-Leap office of the Japan Science and Technology agency (https://www.jst.go.jp/stpp/q-leap/jinzai/en/index.html).
    d. Prof. Van Meter has received funding from the Japanese government Moonshot program to work on distributed quantum error correction for large-scale, multi-node quantum computers. Portions of this work will use QuISP. https://www.jst.go.jp/moonshot/en/program/goal6/index.html
    e. Prof. Van Meter has received funding from the Japanese government Moonshot program to work on quantum interconnects and quantum networks for large-scale, multi-node quantum computers. Portions of this work will use QuISP. https://www.jst.go.jp/moonshot/en/program/goal6/index.html
10. Additional activities
    a. Prof. Van Meter has been appointed as Editor in Chief of IEEE Transactions on Quantum Engineering. The appointment is for three years, April 2022-March 2025, renewable once. https://tqe.ieee.org/

Key design and implementation goals for graph states in repeater networks

Multi-party Graph States

The uses of graph states in quantum repeater networks fall into two categories: application-level multi-party entangled states, and graph states for building two-party end-to-end Bell pairs more efficiently.

The basic concept for distributing multi-party states was developed by Meignant *et al.* of Sorbonne University [Phys. Rev. A 100(5), 052333, 2019]. We are initially focusing on the Steiner tree protocol for GHZ states, as shown below (image from PRA 100, 052333).

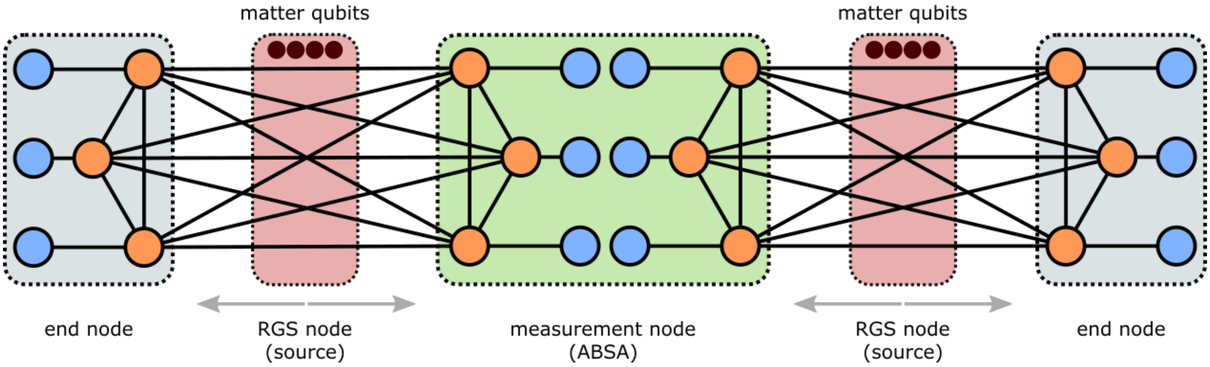


To turn this concept into a complete protocol, we have been collaborating with the Sorbonne University group to simulate the creation of GHZ states using QuISP. This project was **substantially delayed due to COVID-19**. The implementation was being led by a Sorbonne student with significant input from Keio; he was scheduled to come to Japan for six months in 2020, when Japan closed its doors completely to all foreigners for nearly two years. The basic protocol work was almost completed, and the final testing, integration and simulation work were under way, when the Sorbonne student who was leading the implementation graduated and moved to a different institution and field. The code being integrated is available at https://github.com/sfc-aqua/quisp/pull/311. Since the integration was not complete and was based on a branch of QuISP, the implementation became incompatible with the QuISP source base, and it has become necessary to reimplement the code. This project is now in progress.

Repeater Graph States

Two-party use of graph states builds on the concept of the *repeater graph state* (RGS). We focus on the form from the Virginia Tech group [Phys. Rev. X, 7(4), 041023]. Our RuleSets that control the behavior of links and end-to-end connections using the RGS have been defined at https://github.com/sfc-aqua/quisp/blob/graph_con/doc/RGS%20RuleSets.md and code to implement them is under development. RGS and Advanced Bell State Analyzer (ABSA) nodes are arranged as follows.

Figure 2: Network link



The development of the ABSA is the most complex portion of the project as its operations and timing are dependent on the results of prior measurements. A second major technical challenge is coordination of timing along a path of RGS repeaters.

Architecture and Protocol for All-photonic Repeaters based on Repeater Graph State (RGS)

All-photonic repeaters based on graph state called Repeater Graph State (RGS) [1] as shown in Fig. 1 promises fast Bell pair generation rate which is only limited by the RGS creation time which is governed by quantum gate times and emission time of quantum emitters and not the end-to-end communication time like repeaters based on quantum memories. RGS-based repeaters also offer tolerance against photon loss and operational errors. Still the most challenging part of realizing RGS-repeaters is the generation of RGS.

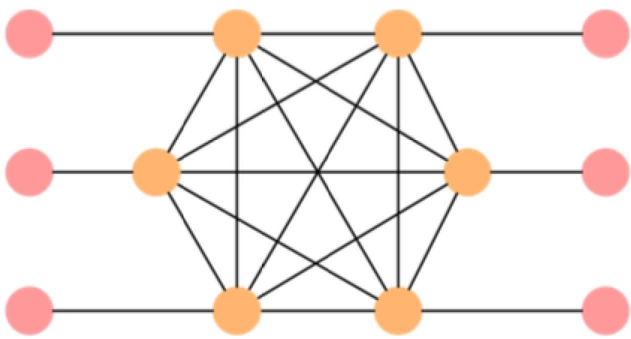


Fig.1 Repeater Graph State (RGS)

Significant advances on the generation of RGS have been proposed in recent years. The deterministic generation with ancilla assisted schemes [2-4] and delayed feedback assisted scheme [5]. Although various performance analyses have been done on the relationship between QKD protocol key rate, number of emitters, and distance between end-nodes [3, 6, 7], no concrete protocols have been investigated aside from [6] which proposed a more concrete architecture but uses GHZ-factory for RGS generation that is less efficient than the deterministic generation scheme of [2-4].

There is still a large gap between the current theoretical works mentioned and the steps to simulate them with concrete protocols. We chose deterministic ancilla-assisted RGS creation proposed in [3], as the approach for our protocol design. We found that there are technical challenges in the generation schemes that need to be overcome:

1. time synchronization between two RGS sources that need to send some subsets of photons to the same Advanced Bell State Analyzer measurement node at the same time
2. Since the emitters of the same RGS source are also shared for both sides, the time synchronization becomes not only between neighbors but will be of the whole connection path.
3. How and when correction operations are calculated and applied
4. Photon emission ordering is not the same as the measurement ordering, so photon storage or delay lines are required. The lengths of the delay lines depend on the generation time and have not been discussed explicitly.

It is shown in [3] that the correction operations can be determined locally. Thus, all analyses were done assuming that the graph state is the already corrected graph state. In practice, the correction operations are not performed directly but the next measurement/option selection is dependent on the measurement results via commutation rules.

Results so far

We studied how to integrate RGS links into our simulator QuISP [8]. We improved our proposed error tracking model to support arbitrary stabilizer states as the target states of the network tasks. QuISP uses Monte Carlo simulation method and supports Error channels including Pauli channels and excitation/relaxation channels.

Modified RGS generation - we introduce a functionally equivalent graph state to RGS (RGS') where the inner qubits (1st leaf qubits) are complete bipartite instead of a complete graph shown in Fig. 2. The generation of this RGS' is done similarly to RGS generation of [3] but we now use twice the emitter count plus 2 additional ancilla emitters to correct the photon emission ordering such that the photon storage is no longer needed.

Time synchronization - The whole path synchronization goes away with our RGS' generation scheme due to the splitting of left/right photon generations. The synchronization is only a concern between two direct neighbors.

Unequal distance between the two segments connected to ABSA - due to the splitting of the left/right generation, achieving the highest achievable end-to-end rate even when each link characteristics are different can be done via adapting the RGS' structure.

Optimal RGS structure - we investigate the reverse question of what usually asks in literature, if the distance between RGS source and ABSA and the number of hop is given, how would one choose the optimal RGS structure such that one achieves the highest secret key rate. We found there is a relationship between the number of RGS arms (m) and the two variables (Fig 3.). We can model the optimal number of arms via the equation

$$m = a\log(L_{total}) + b$$

where a and b are some coefficients which depend on the fiber loss rate.

Correction Operations - We have not fully worked out the full details of how correction operation would need to be done but we have found that the analysis using LC-equivalent graph state does not hold. This is due to the difference in success probability of logical X and logical Z measurement which is dependent on RGS/RGS' structure. When changing measurement operations due to prior measurement results via commutation rules, this will lead to a different statistics than what was analyzed in current literature. We suspect that analytical solutions might not be feasible to compute and require simulations.

Communication of RGS' structure - Initially we proposed that the generation should be managed by RuleSet protocol [9]. We found that if the photon emission ordering is fixed and if time synchronization is only needed between direct neighbors, only the number of RGS arms and the branching vector of logical tree encoding are needed for communication thus RGS-link can be treated the same way as conventional MM, MIM, or MSM links invisible to the RuleSet level.

Multipartite entanglement distribution - We found that a modified scheme from RGS' generation can be expanded to more than 2 parts. We show how one would utilize this scheme to distribute GHZ state in two different ways in Fig. 4. The two ways produce a different intermediate graph structure but will result in the same final state up to LC equivalence.

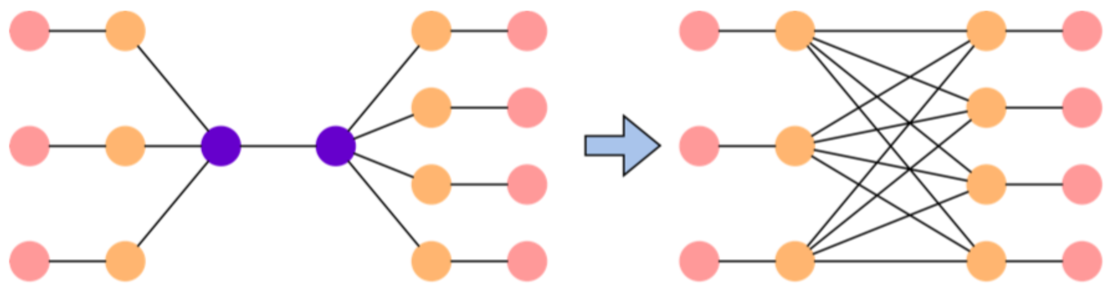


Fig. 2 Modified RGS which is generated by joining 2 tree graphs together

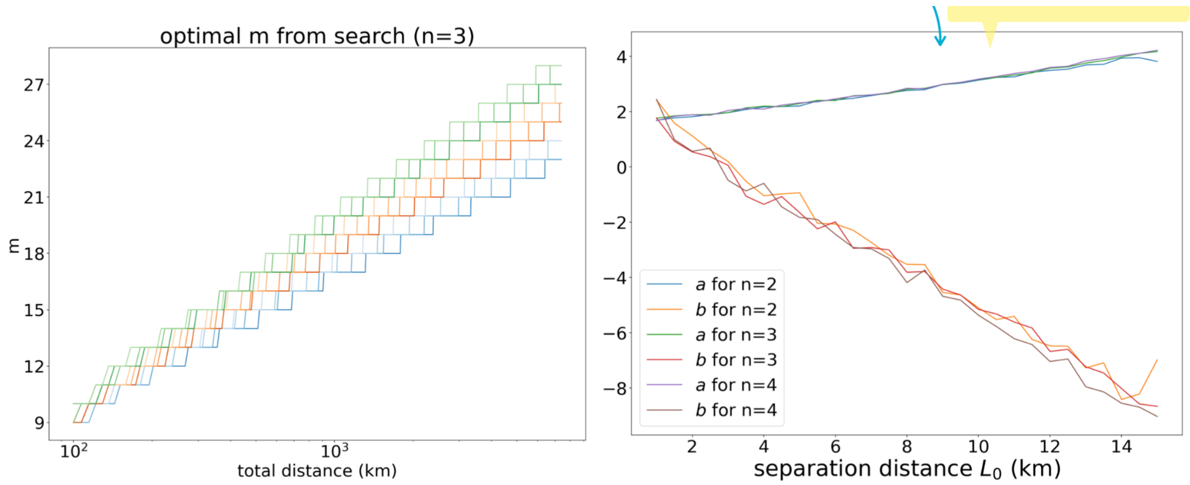


Fig. 3 (left) Plots showing the optimal number of RGS arms (m) when total distance increases. Each color line represents a different distance between RGS source and ABSA. (right) Plots showing that coefficient a and b to determine optimal m is independent of the encoding depth and only depends on distance between the two end nodes.

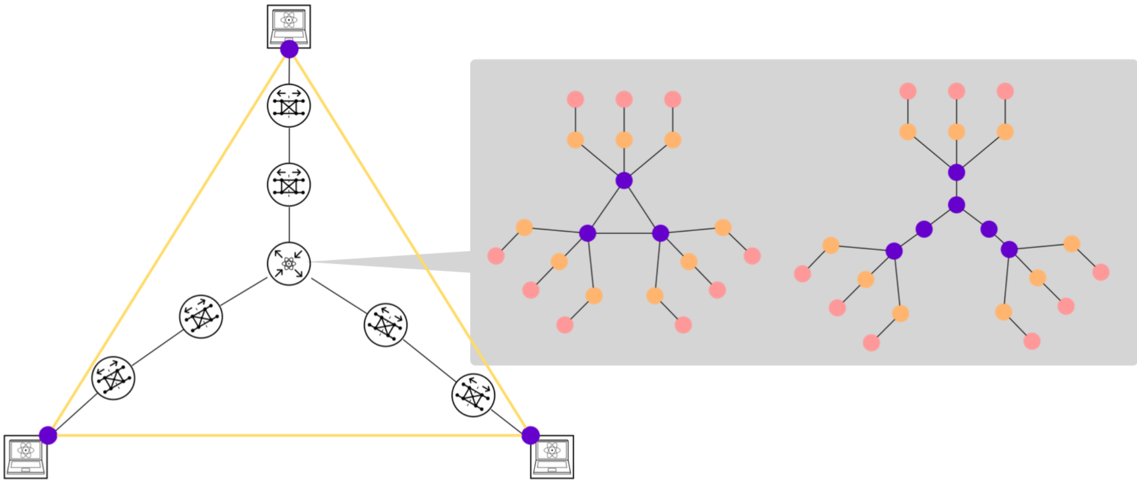


Fig. 4 All-photonic RGS' based routers which allow for multipartite GHZ distribution.

Additional technical goals and achievements

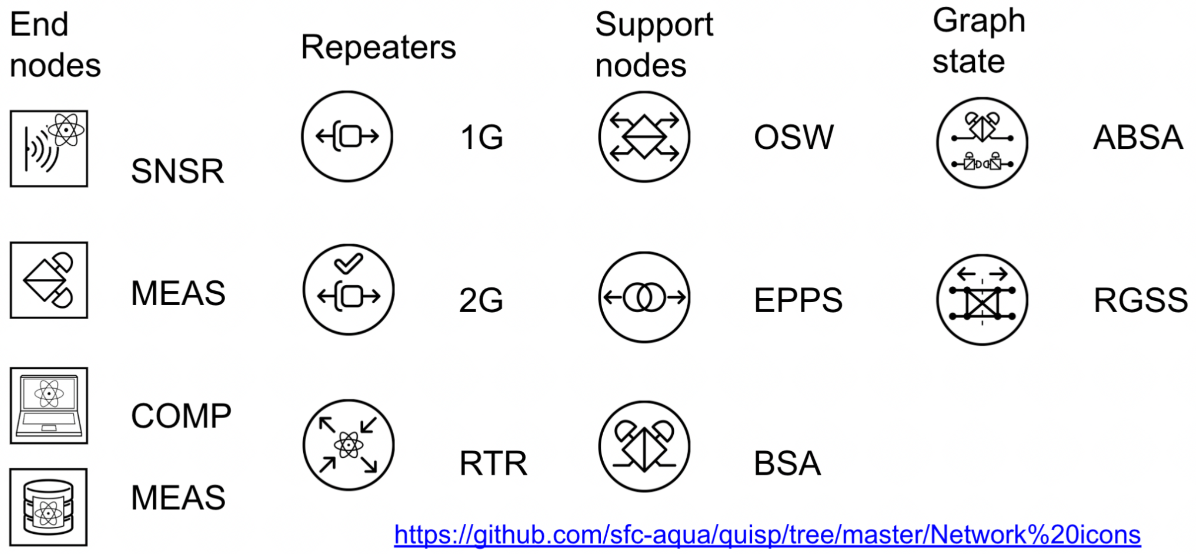
A Quantum Internet Architecture

With the first quantum repeater network testbeds starting to deploy, a key question arises: what happens as the technology matures, and as disparate networks need to interoperate? Our proposal for RuleSets for network operation can be extended to internetworking (network-to-network operations). RuleSets are coupled with a two-pass connection setup

protocol. To achieve scalability and support operational autonomy and privacy, we use QRNA, the Quantum Recursive Network Architecture.
We expect to continue developing this approach, and simulate complete, large-scale internetworks in the coming years. Details of this proposed architecture are in the paper listed above.

Network Node Icons

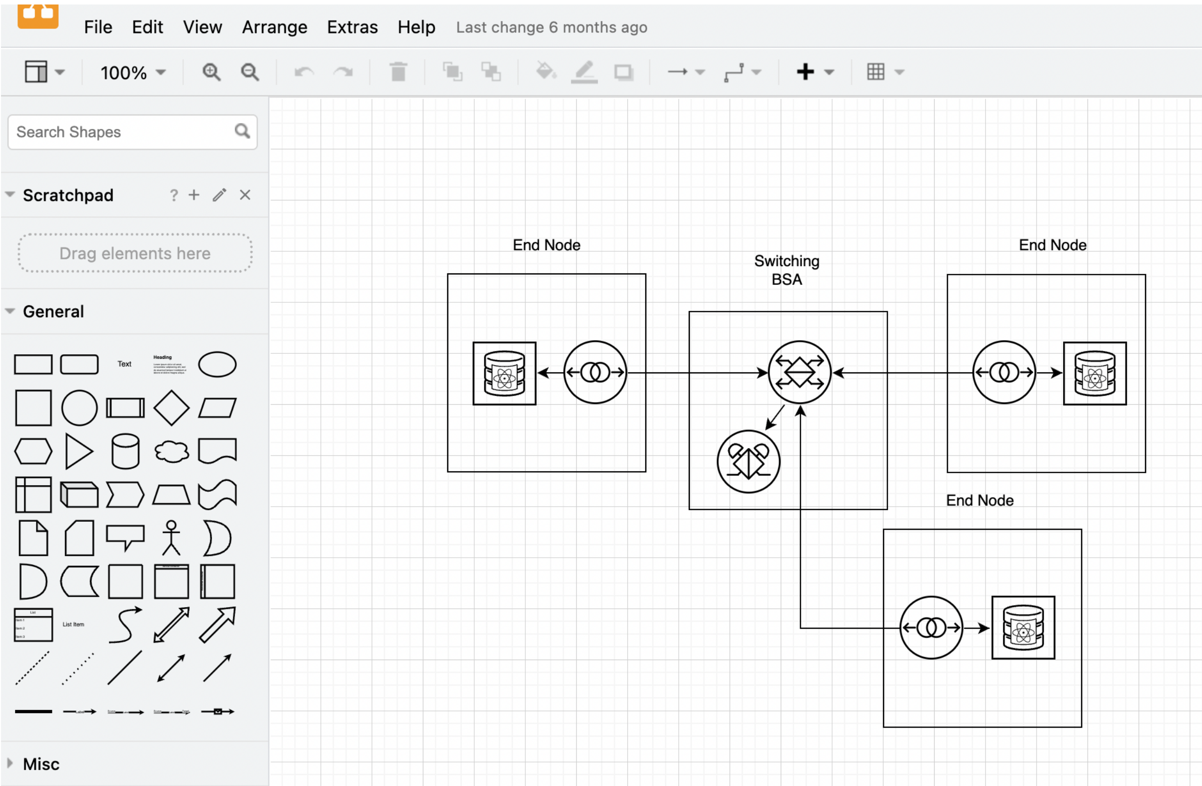
We have proposed a set of icons for the various node types, to be used in network diagrams such as those commonly created in diagrams.net (formerly known as Draw.IO). In conjunction with RFC 9340 and the network architecture discussed above, a shared vocabulary must include a shared graphical language that can quickly convey an accurate picture of the topology and capabilities of a network.



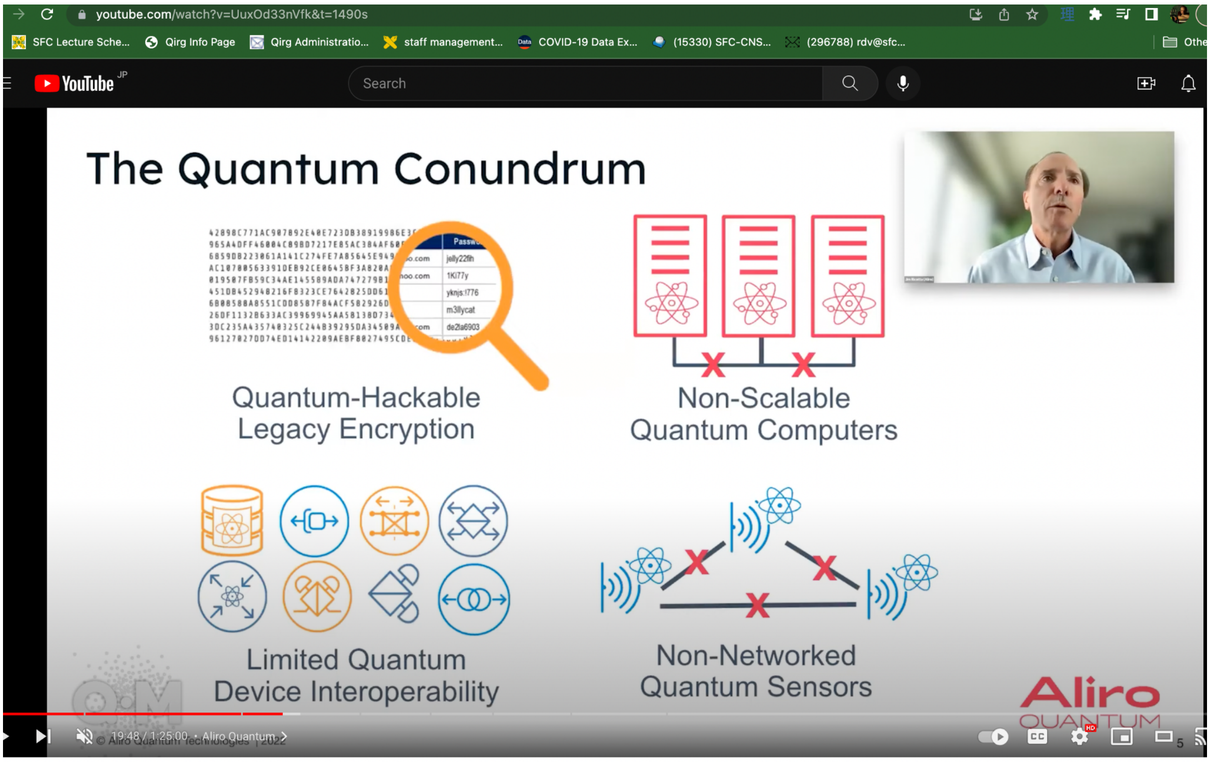
https://github.com/sfc-aqua/quisp/tree/master/Network%20icons

The icons can be imported as a library directly online in diagrams.net.

DISTRIBUTION A: Distribution approved for public release.

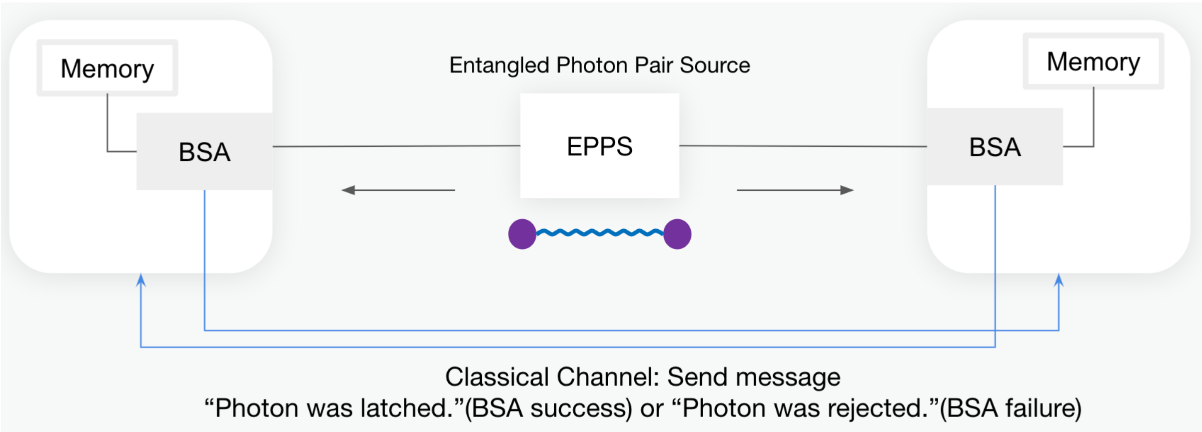


These icons have already begun to be adopted in industry, such as on Aliro Quantum's website and in a talk by them (https://www.youtube.com/watch?v=UuxOd33nVfk&t=1490s), below:



MSM Links

For two-party use of graph states, e.g. on the link, an important preparatory step is the creation of "MSM", or memory-source-memory, links, as designed by Jones *et al.* [New J. Physics, 8(8), 2016] and shown in the figure below. These links use an entangled photon pair source (EPPS) node, which serves as a model for graph state generation. EPPS uses a technique such as SPDC, whereas the approach to RGS generation we are taking will use a node with memory to generate the complex state. However, in both cases, timing of reception of photons must be carefully regulated, making the MSM link a good developmental model for RGS. The source code for the MSM link is available at https://github.com/sfc-aqua/quisp/tree/MSM_link.

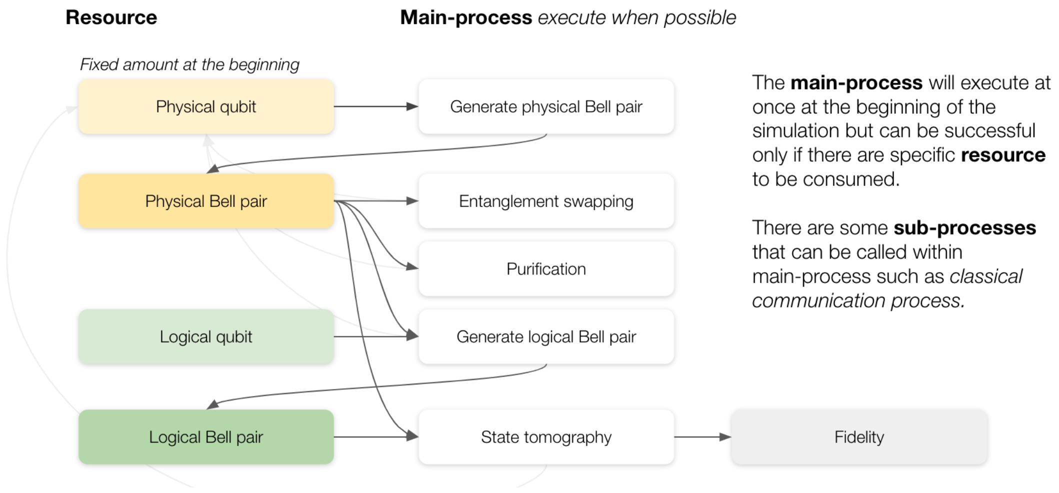


2G Network Simulation

We are collaborating with the group of Prof. Sujin Suwanna at Mahidol University, Thailand, on simulation of 2G quantum networks. 2G networks use an acknowledged physical layer that detects and reports when creation of link-level Bell pairs succeeds, then builds logical qubits at the nodes using a set of Bell pairs and performs entanglement swapping on logical Bell pairs to create end-to-end, high-fidelity entanglement. 2G's advantages over 1G include higher fidelity, and a reduction in the amount of distributed computation that must be performed to build end-to-end entanglement, reducing waiting times and improving throughput. However, the demands on fidelity, number of qubits in each node, memory lifetime, and Bell pair creation rate are substantially higher than for 1G.
Prof. Van Meter collaborated with the Lukin group at Harvard in the creation of the ideas and basic analytic models behind 2G, but to the best of our knowledge a complete simulation including the delays of stochastic entanglement generation and classical communication protocols has never been done. A conceptual design is shown below.

CONCEPT DESIGN

Simulation : Discrete-event simulation, SimPy
Concept design : [**2** OF **5** PAGES]



Traffic Generation

A *traffic matrix* describes the flow of information, people or goods in a network. For classical networks, traffic is bidirectional and each flow can be defined separately. For quantum repeater networks tasked with building end-to-end entanglement, there is no notion of “sender” and “receiver”, but the classical applications requesting the creation of entanglement presumably will be of client-server form. We refer to the client, which initiates connections, as the *Initiator*, and the server as *Responder*. In a matrix such as the one below, *T(A,B)* represents the amount of traffic initiated by end node *A* for responder *B*.

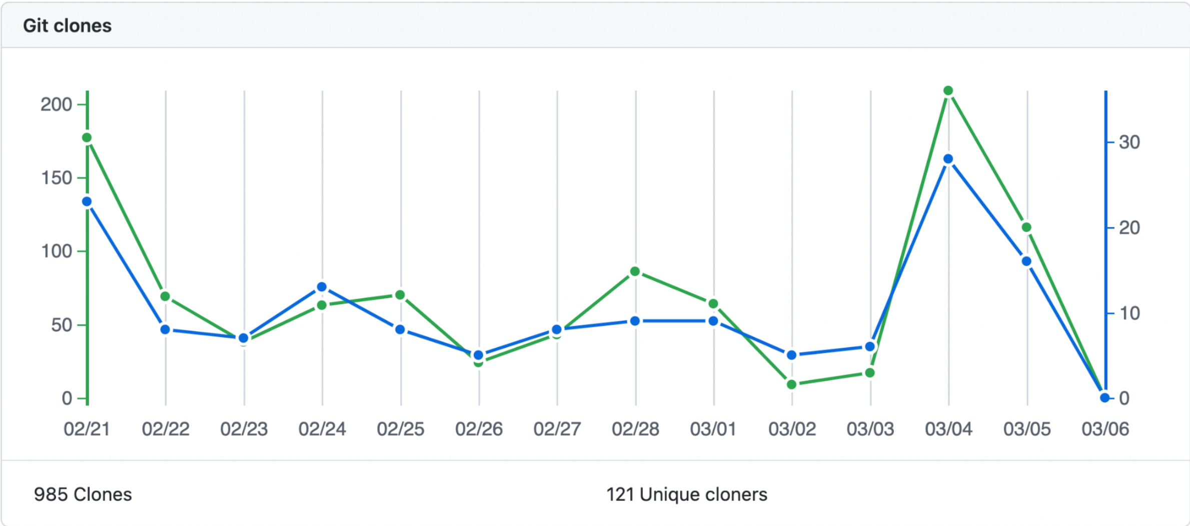
$$\begin{bmatrix} T(A,A) & T(A,B) & T(A,C) & T(A,D) \\ T(B,A) & T(B,B) & T(B,C) & T(B,D) \\ T(C,A) & T(C,B) & T(C,C) & T(C,D) \\ T(D,A) & T(D,B) & T(D,C) & T(D,D) \end{bmatrix}$$

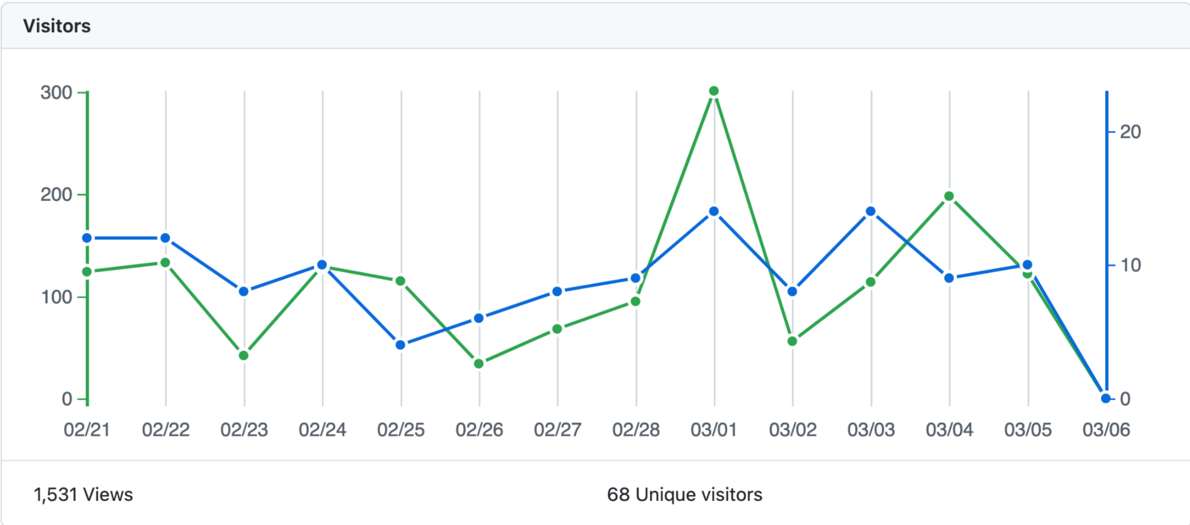
A realistic traffic matrix is absolutely necessary for large-scale simulations of networks, especially when a key goal is understanding the interaction of separate connections and studying the effectiveness and robustness of multiplexing and resource sharing mechanisms. One model that has been applied to classical Internet traffic is the *gravity model*, in which certain nodes are more popular than others. We are applying this model to quantum networks, as well.

Future work includes extension of traffic matrices to multi-party communications, useful for graph states as well as distributed states used for applications such as byzantine agreement.

Community Uptake

We believe that QuISP is receiving a substantial amount of attention in the quantum networking community and some adoption as the tool of choice. Unfortunately, Github does not provide complete historical data for the number of “clones” (complete, active copies of the source code repository) or other downloads. Moreover, the third party automated tools that are integrated into our testing system appear as independent clones to Github. However, the traffic on Github does serve as a sort of indicator of interest in our system. The chart below shows the number of times the repository was cloned in a recent two-week period.





Beyond direct cloning of the simulator itself, we have received inquiries from parties in the U.S. and in France about adopting the simulator into other research.

Significant improvements to the QuISP simulator infrastructure

The addition of members to the QuISP team with prior professional software development experience is both accelerating the pace of development and improving the quality of the code being written. We have shifted from Travis-based continuous integration (CI) tests to Codacity, which has improved tracking of test coverage. Unit test coverage has improved, and end-to-end tests are being augmented.

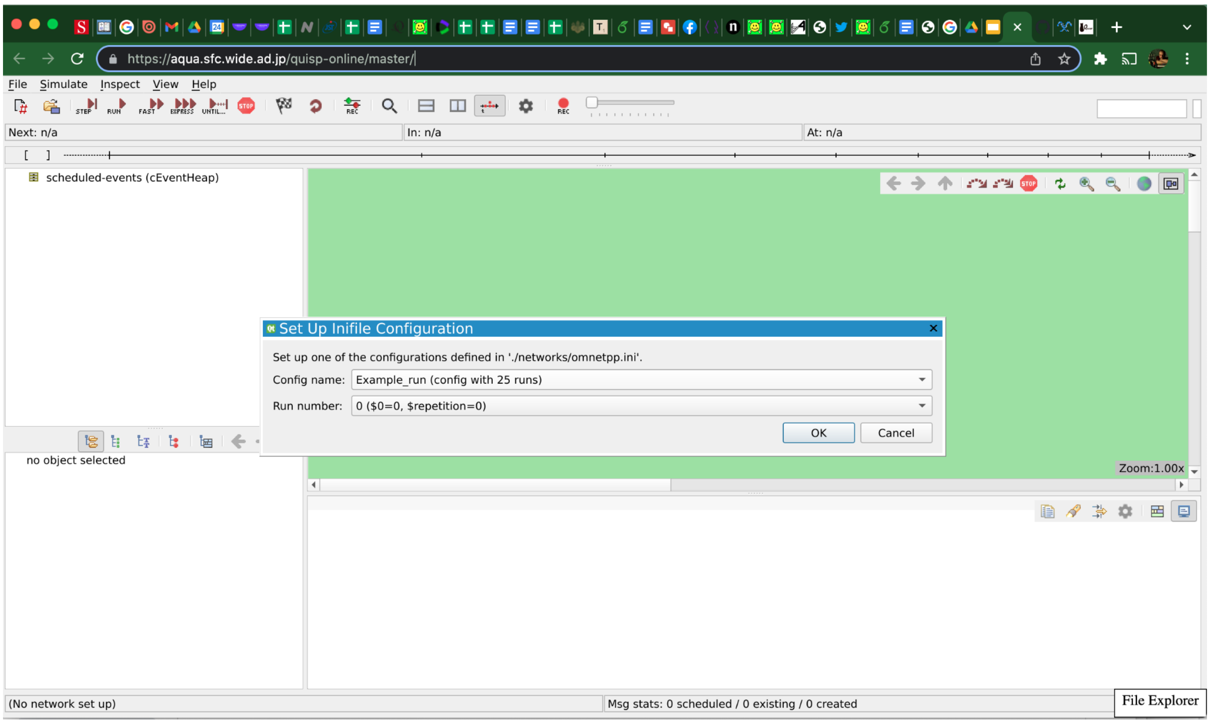
Wasm version of QuISP

One of the most important technical achievements of the year is the addition of a WebAssembly, or Wasm, version of the QuISP simulator, pictured below. One of the biggest challenges to date with QuISP has been the need for new users and prospective users to download and install a complete copy of the simulator, beginning with the OMNeT++ infrastructure and additional third-party software packages. OMNeT++ is finicky about its installation environment, creating a substantial hurdle to experimentation with and adoption of QuISP. The compilation of QuISP itself also takes a substantial amount of time and effort. Thus, the introduction of the browser-based version has the potential to substantially increase the user base, improve impromptu demos, and increase the visibility and usability of the simulator.

The security of browser-based software is always an important topic to be addressed. Wasm operates in an environment similar to a JavaScript sandbox. It is not allowed to read or write files on the local system without explicit permission. The app must be downloaded via HTTPS (not HTTP), and the default policy for any additional files is the "same origin policy", in which additional files must come from the same `<host, protocol, port>` tuple, preventing important classes of impersonation and misdirection attacks. This version of QuISP can be considered as safe as an ordinary JavaScript app, and perhaps safer than downloading and running the simulator locally, which, as with all open source software, requires a certain level of trust by the user.

Performance testing of the Wasm version is ongoing, but early indications are that it runs at about half the speed of native compiled code and that other resource consumption is within reasonable bounds.

Further details on the Wasm version and on ports to various platforms is available at https://github.com/sfc-aqua/quisp/wiki/Available-OMNeT--versions-and-Platforms.



Jupyter Version of QuISP

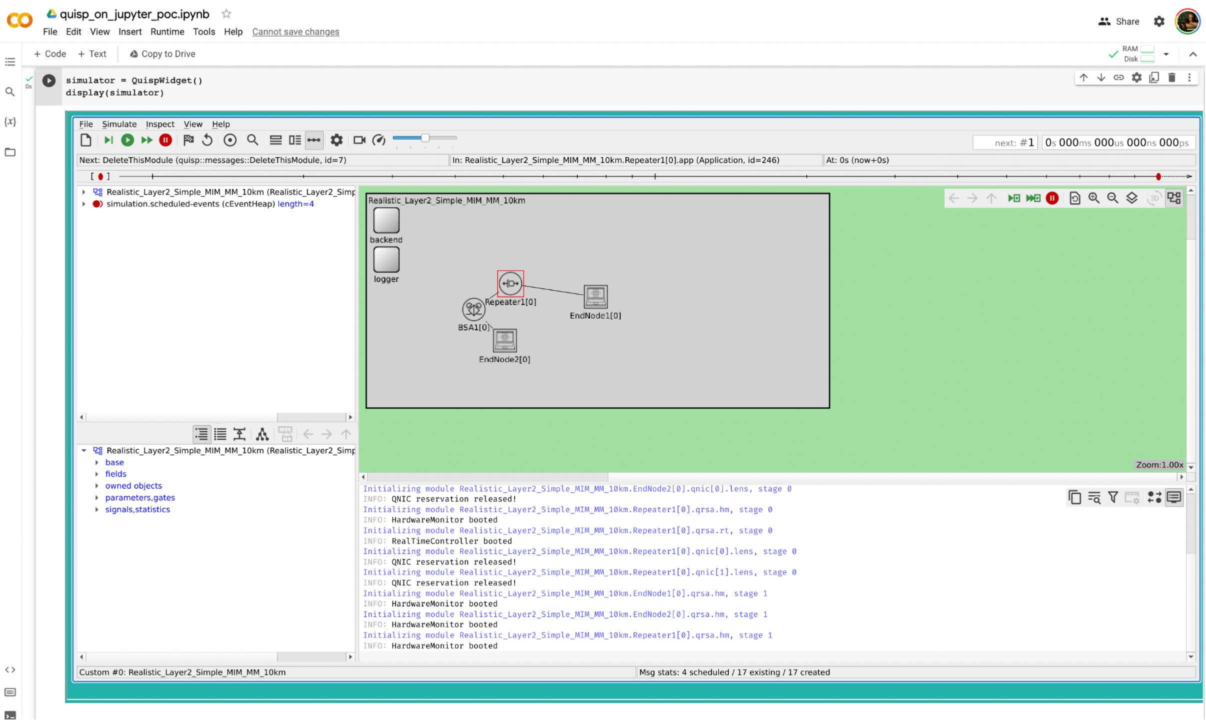
Continuing from the development of the WASM version of QuISP, we have developed a version that runs in a Jupyter notebook on Google Colaboratory. This simplifies basic demonstrations and simple tests by allowing the programmer to quickly create a network configuration in Python and run the WASM version via the notebook. Although the notebook itself runs on a remote server, execution of the WASM version downloads the current version of the simulator to the browser and runs locally on the user's laptop. The following few lines of code will load QuISP when executed on Google Colaboratory:

```
from google.colab import output
output.enable_custom_widget_manager()
!pip install quisp==0.3.0 pandas

from quisp import QuispWidget, QNode, Network, ChannelOption
import pandas as pd

simulator = QuispWidget()
display(simulator)
```

This will produce a screen view like the below:



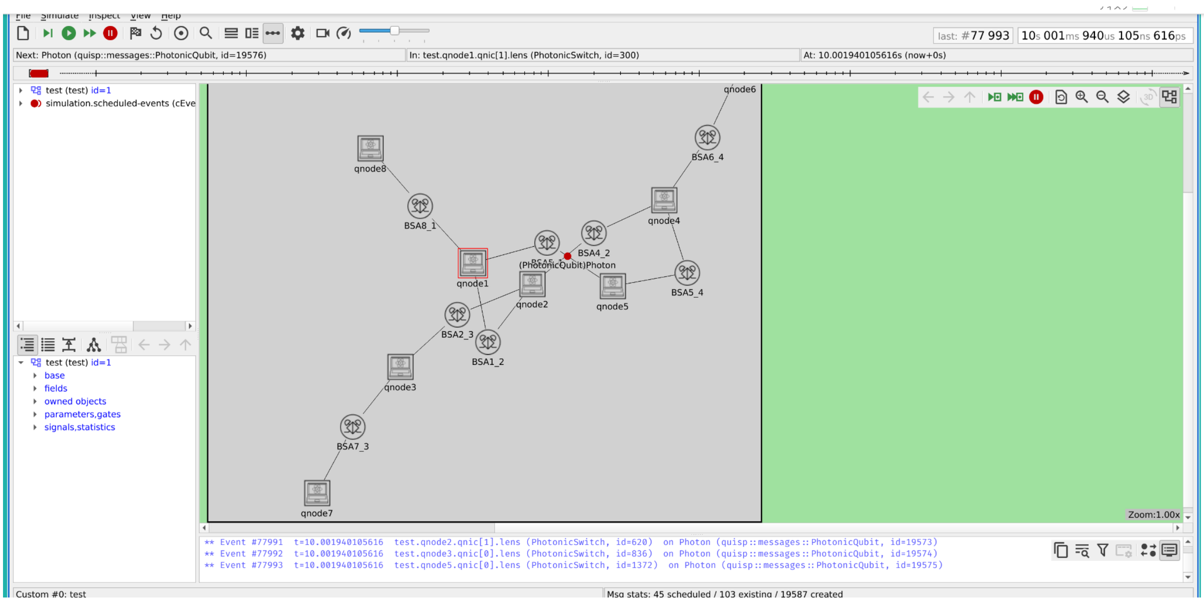
Continuing, the user can easily define a network configuration:

```
network = Network("test")
qnode1 = QNode(name="qnode1", network=network, is_initiator = True)
qnode2 = QNode(name="qnode2", network=network)
```

```
qnode3 = QNode(name="qnode3", network=network)
qnode4 = QNode(name="qnode4", network=network)
qnode5 = QNode(name="qnode5", network=network)
qnode6 = QNode(name="qnode6", network=network)
qnode7 = QNode(name="qnode7", network=network)
qnode8 = QNode(name="qnode8", network=network)

qnode1.connect(qnode2)
qnode2.connect(qnode3)
qnode4.connect(qnode2)
qnode5.connect(qnode1)
qnode5.connect(qnode4)
qnode6.connect(qnode4)
qnode7.connect(qnode3)
qnode8.connect(qnode1)
simulator.load(network)
```

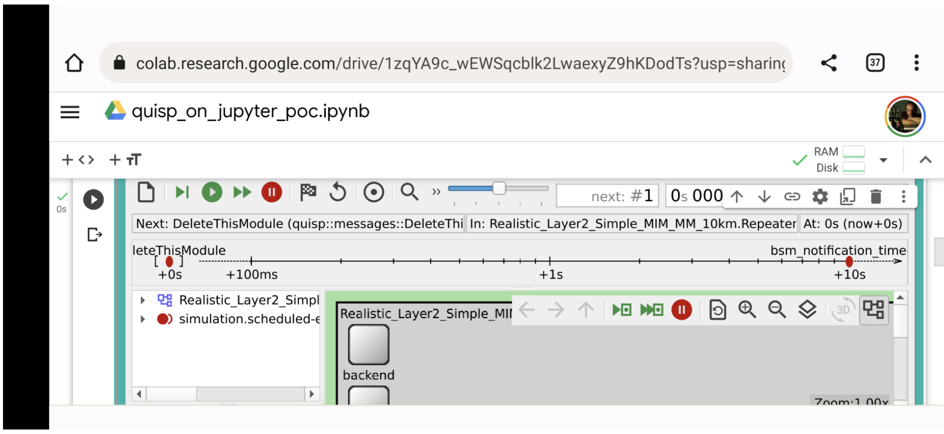
Which loads the network into the simulator:



Further simple Python commands allow control of the simulator and collection and processing of results.

This development solves the major limitation of direct use of the WASM version, which is that the browser is not allowed to directly read and write files on the local machine, limiting the ability of browser-based users to define their own network topologies. It also facilitates the processing of the large JSON files that contain the events that occurred during the simulation.

It even runs, with limited performance, on Android-based tablets and cell phones.



Experimental Work

As noted above, no progress was made on the experimental work.

Papers, Drafts, Preprints and Talks

As listed above.

Supported Work in the Quantum Community

The Quantum Internet Research Group (QIRG) is a research group chartered by the Internet Research Task Force (IRTF). IRTF research groups provide a forum for studying and developing network research topics and transitioning them from pure research toward standardization and operations. Work takes place at IETF meetings, on the mailing list, and at online seminars. The QIRG mailing list currently has 455 members. Two Internet Draft documents are nearing completion and publication as Request for Comments (RFC) documents. These will be Informational status documents, and do not have the force of standards, but will guide the further development of Quantum Internet technology and integration of the classical Internet community into the quantum community (or vice versa).
The Workshop for Quantum Repeaters and Networks has been on hold during the COVID-19 pandemic. The steering committee expects to resume regular workshops in 2022.
Q-Next is a research center supported by the U.S. DoE, involving industry, academia, and U.S. national labs. Prof. Van Meter was invited to join a roadmapping effort for planning research, development and deployment of quantum repeater networks, held online during the first half of 2021. A roadmap document was developed and published as an Argonne technical report. A peer-reviewed version with broader relevance to the community than just the Q-Next project may be published.

Non-Supported Projects Seeded by this Work

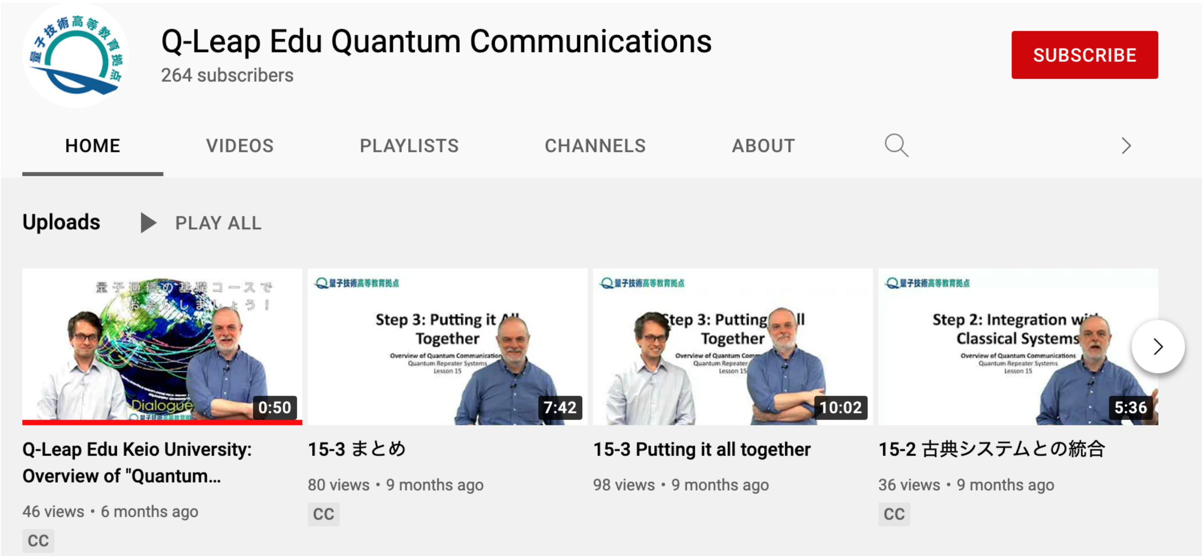
One key goal of AOARD projects is to seed work that expands over time.

AQUA members are central to the founding of Japan's Quantum Internet Task Force, which aims to build a metropolitan-area testbed network over the next several years. QITF is now officially established as a Consortium underneath the Keio Research Institute at SFC. QITF members include almost all of the important research groups in Japan working on quantum communication, both theory and experiment, in academia, industry and government laboratories. QITF is actively soliciting financial and technical support and participation from industrial partners, several of whom have agreed to join. QITF is also pursuing Japanese government funding. Important announcements about QITF are anticipated in the coming months.

Prof. Kae Nemoto of the National Institute for Informatics (NII) heads the Q-Leap Education Program flagship project. Prof. Van Meter participated in development of the proposal, including the proposed curriculum, and has taken responsibility for the field of quantum communications within the overall project. Each year for six years, one module (expected to be worth about one academic credit toward a bachelor's degree) will be produced on communications. The full educational experience is available only to students of the member universities (Tokyo, Nagoya, Kyushu, NII, and Keio) through the online learning management system built around Moodle. The full set of videos, 66 in English and 66 in Japanese, for the first year's communications module, titled "Overview of Quantum Communications", is available on YouTube and is licensed as Creative Commons. For accessibility, all videos have high-quality subtitles in the corresponding language. Lecture notes are being composed and will be available as a Creative Commons-licensed book in 2nd quarter of 2023. The first release of the book will be in English, with a Japanese version to follow later in the year.

The second module in the sequence is "From Classical to Quantum Light", consisting of 69 videos in English and Japanese. It was delivered in April 2022. The third module, "Quantum Internet", currently under development, will be delivered in April 2023.

In addition to the Japanese and English full modules supported by Q-Leap, a grant from Intel is enabling translation of portions of the first module in Chinese, Thai, Korean, Arabic, and French. Collaboration with Chicago State University and the Q-Next project is creating a version in Spanish. Collaboration with an informal group including students at the University of Illinois is enabling an American Sign Language (ASL) version.



Finally, a new project has begun underneath the Japanese government Moonshot program. We are members of the theory subgroup, Masato Koashi, program manager. Our responsibility is development of methods for distributed quantum error correction for tightly-coupled quantum multicomputers. Multicomputers are expected to be the primary means of scaling systems up, and inter-node error correction and support for heterogeneous hardware will be critical.

We are also members of the quantum interconnects subgroup, Shota Nagayama, program manager. Our responsibility is network architecture, protocols and simulation, to be based on QuISP.

Students and Staff

Participating in this Work

(n.b.: Not all of the below received direct financial support during this project.)

Michal Hajdušek is a Project Assistant Professor hired to work on this project. He has led all of the physics work and guided much of the simulation work and design for elements such as the ABSA. With the completion of this project, he continues via support from Moonshot and the Q-Leap Education project.

Naphan Benchasattabuse joined the AQUA group as a Ph.D. student in fall 2020 after completing his master's degree at Chulalongkorn University, Bangkok, Thailand. His research interests are broad, and his strength in both quantum computation and classical software engineering have benefited the group tremendously. He has been the primary software developer for the ABSA and has contributed substantially to the overall design of QuISP as well as RGS-based systems. His Ph.D. thesis topic will involve advanced design of quantum networks. Beginning in March 2023, he will be an intern at Los Alamos National Laboratory.

Ryosuke Satoh completed his master's degree in March, 2023. He joined AQUA in April 2018 as a sophomore undergraduate. He has been the central developer of QuISP since joining the group. In fall 2023, he plans to take a position as a software engineer in IBM's T.J. Watson research center in New York, where he will work on system software for the systems that run IBM's quantum computers.

Poramet Pathumsoot joined the AQUA group as a full time Ph.D. student in fall, 2022, after completing his master's degree at Mahidol University, Bangkok, Thailand. He had already joined the group as a summer intern in 2019, followed by regular participation remotely after returning to Thailand. Prof. Van Meter was a member of his master's thesis committee at Mahidol.

Kentaro "zigen" Teramoto expects to complete his master's degree in September, 2023. He is a part-time student attracted to the Quantum Internet projects, and is a full-time software engineer for a major Japanese e-commerce company. He developed the WASM and Jupyter versions of QuISP, and has brought substantial professionalism and mentoring to the software engineering process.

Makoto Nakai will complete his master's degree in March, 2024. He joined AQUA in April, 2019 as a sophomore undergraduate. His undergraduate thesis in March, 2022, concerned distribution of program variables among nodes in a tightly-coupled quantum network for distributed computation. He is currently working on multiplexing for multiple connections on quantum networks and contributing to QuISP. He has accepted a job in one of Japan's leading e-commerce companies following graduation.

Nozomi Tatetani will complete his master's degree in March, 2024. He joined AQUA in April, 2019 as a sophomore undergraduate. His undergraduate thesis in March, 2022, concerned generation of traffic patterns for quantum networks. He currently contributes to QuISP.

Others

Other students, staff and collaborators have worked on QuISP, on related quantum networking projects, quantum computing (algorithms as well as system software) and quantum community and education. Over the last four years, the size of the AQUA group has more than doubled, to about 35 people from ten countries and speaking at least a dozen languages. The photo below shows about two-thirds of the AQUA group in November, 2022.

References

[1] K. Azuma, K. Tamaki, and H.-K. Lo, “All-photonic quantum repeaters,” Nat Commun, vol. 6, no. 1, p. 6787, Apr. 2015, doi: 10.1038/ncomms7787.

[2] D. Buterakos, E. Barnes, and S. E. Economou, “Deterministic Generation of All-Photonic Quantum Repeaters from Solid-State Emitters,” Phys. Rev. X, vol. 7, no. 4, p. 041023, Oct. 2017, doi: 10.1103/PhysRevX.7.041023.

[3] P. Hilaire, E. Barnes, and S. E. Economou, “Resource requirements for efficient quantum communication using all-photonic graph states generated from a few matter qubits,” Quantum, vol. 5, p. 397, Feb. 2021, doi: 10.22331/q-2021-02-15-397.

[4] B. Li, S. E. Economou, and E. Barnes, “Photonic resource state generation from a minimal number of quantum emitters,” npj Quantum Inf, vol. 8, no. 1, Art. no. 1, Feb. 2022, doi: 10.1038/s41534-022-00522-6.

[5] Y. Zhan and S. Sun, “Deterministic Generation of Loss-Tolerant Photonic Cluster States with a Single Quantum Emitter,” Phys. Rev. Lett., vol. 125, no. 22, p. 223601, Nov. 2020, doi: 10.1103/PhysRevLett.125.223601.

[6] M. Pant, H. Krovi, D. Englund, and S. Guha, “Rate-distance tradeoff and resource costs for all-optical quantum repeaters,” Phys. Rev. A, vol. 95, no. 1, p. 012304, Jan. 2017, doi: 10.1103/PhysRevA.95.012304.

[7] Y. Zhan, P. Hilaire, E. Barnes, S. E. Economou, and S. Sun, “Performance analysis of quantum repeaters enabled by deterministically generated photonic graph states,” Quantum, vol. 7, p. 924, Feb. 2023, doi: 10.22331/q-2023-02-16-924.

[8] R. Satoh et al., “QuISP: a Quantum Internet Simulation Package,” in 2022 IEEE International Conference on Quantum Computing and Engineering (QCE), Sep. 2022, pp. 353–364. doi: 10.1109/QCE53715.2022.00056.
[9] R. Van Meter et al., “A Quantum Internet Architecture,” in 2022 IEEE International Conference on Quantum Computing and Engineering (QCE), Broomfield, CO, USA, Sep. 2022, pp. 341–352. doi: 10.1109/QCE53715.2022.00055.