Advancing Quantum Architecture

Michal Hajdušek

2023/12/14

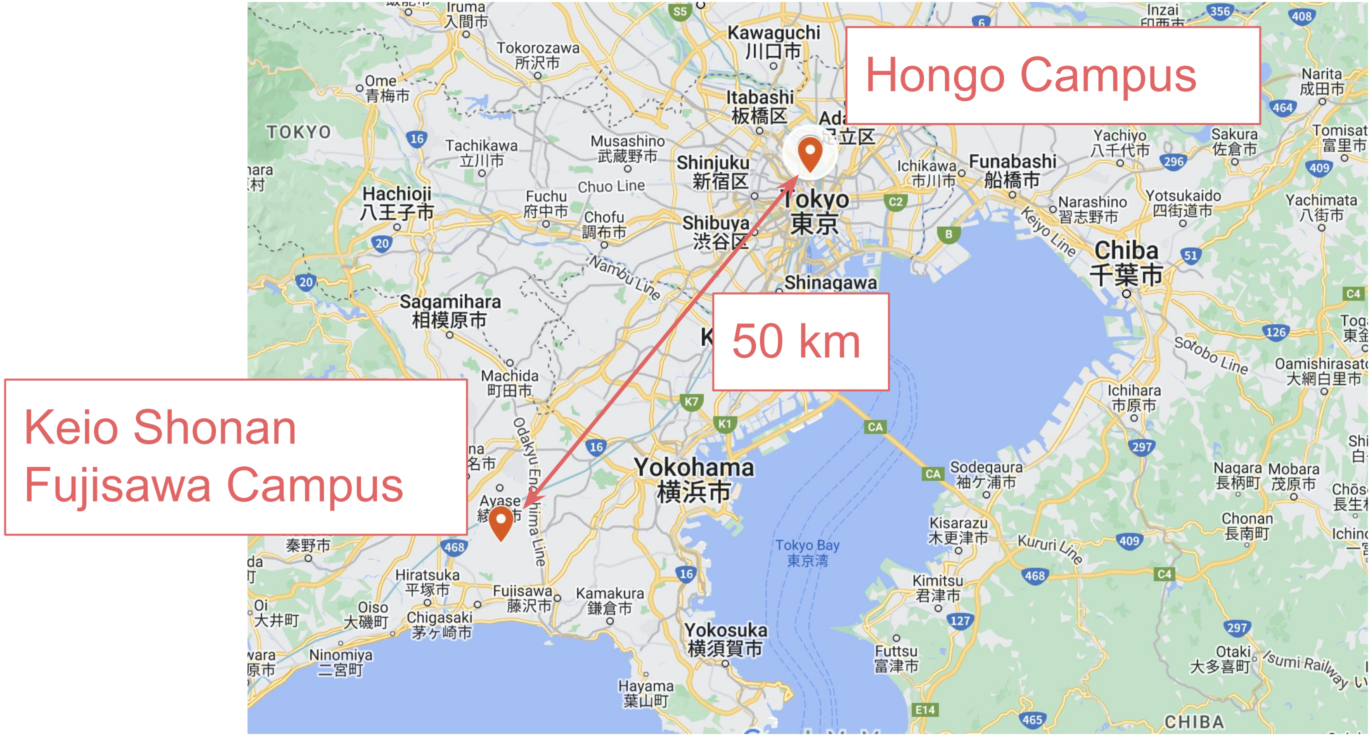
Advancing Quantum Architecture Research Group (AQUA)

Chief AQUANaut: rdv
Faculty: 6
Doctor: 3
Master: 5
Bachelor: 16

Total ≈ 30 ± few undergrads

Representing 14 countries.

Where are we?



What do we do in a …not so exhaustive… nutshell?

Looking past the NISQ era:

- How will we debug large-scale QCs?
  (Sara, Thursday at 12:30)

What do we do in a …not so exhaustive… nutshell?

Looking past the NISQ era:

- How will we debug large-scale QCs?
  (Sara, Thursday at 12:30)

- Assuming fault-tolerance, what other errors should we worry about?
  (fighting cosmic rays by Bernard, today at 15:30)

Algorithms:

- Towards better understanding of QAOA's performance.
  (lower bounds for the number of runs by Naphan, today at 15:00)

Compilation of fault-tolerant graph states

arXiv > quant-ph > arXiv:2306.03758

Quantum Physics

[Submitted on 6 Jun 2023 (v1), last revised 4 Sep 2023 (this version, v2)]

A Substrate Scheduler for Compiling Arbitrary Fault-tolerant Graph States

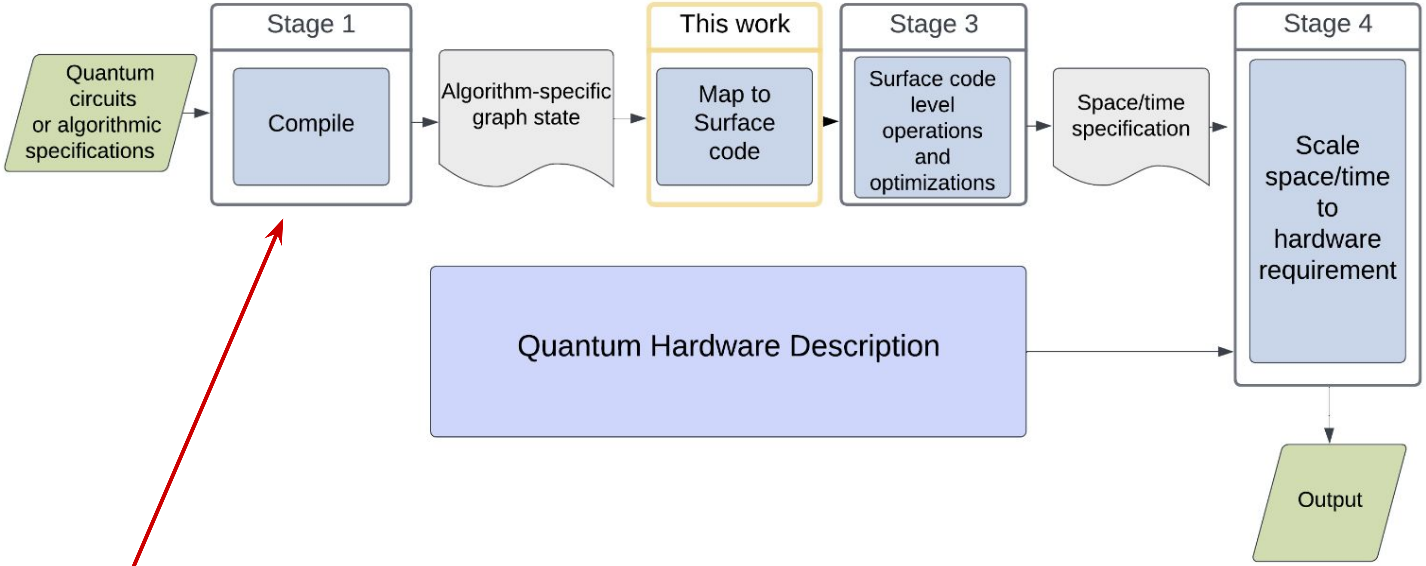
Sitong Liu, Naphan Benchasattabuse, Darcy QC Morgan, Michal Hajdušek, Simon J. Devitt, Rodney Van Meter

Graph states are useful computational resources in quantum computing, particularly in measurement-based quantum computing models
tolerant surface code execution and accurately estimating the compilation cost and the run-time resource cost remains an open problem
fault-tolerant graph state compilation. The Substrate Scheduler aims to minimize the space-time volume cost of generating graph states
thousands of vertices for "A Game of Surface Codes"-style patch-based surface code systems. Our results show that our module generat
graph state generation time complexity that is at or below linear in the number of vertices and demonstrating specific types of graphs to
foundation for developing compilers that can handle a larger number of vertices, up to the millions or billions needed to accommodate a

Comments: 11 pages, 11 figures
Subjects: **Quantum Physics (quant-ph)**
Cite as: arXiv:2306.03758 [quant-ph]
(or arXiv:2306.03758v2 [quant-ph] for this version)
https://doi.org/10.48550/arXiv.2306.03758

Compilation of fault-tolerant graph states

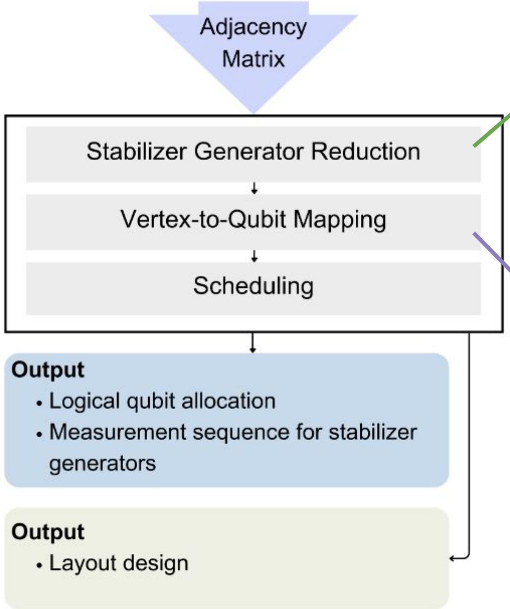
Big picture:



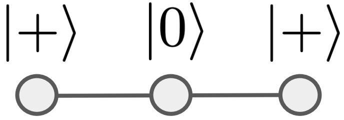
Vijayan *et al.*, Compilation of algorithm-specific graph states for quantum circuits, *arXiv:2209.07345*.

Compilation of fault-tolerant graph states

Goal: minimize the space-time volume of generating the ASG
Approach: Game of Surface Codes (GoSC)* + stabilizer measurements



Clever initialization of logical qubits.



$$g_0 = X \otimes Z \otimes I,$$
$$\boxed{g_1 = Z \otimes X \otimes Z,}$$
$$g_2 = I \otimes Z \otimes X.$$

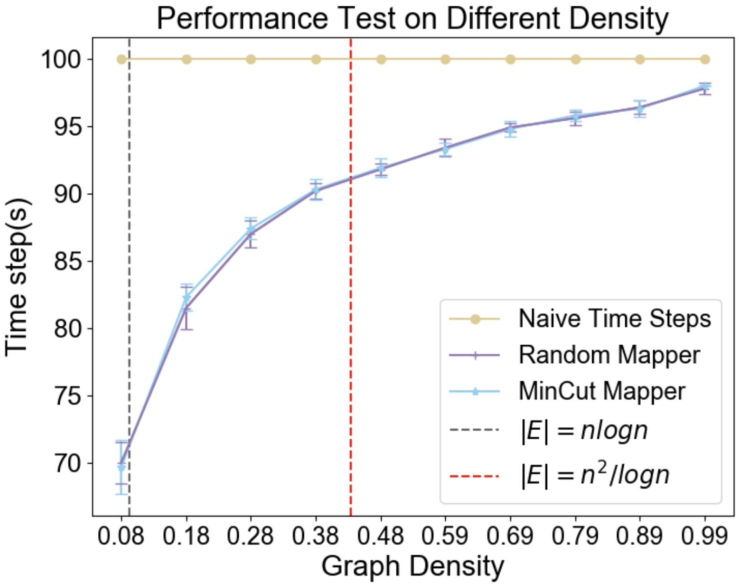
Maximize parallelizable stabilizer measurements.

*Litinski, GoSC, *Quantum* 3, 128 (2019).

Compilation of fault-tolerant graph states

So how does it perform? …Actually, we don't know much!

Random connected graph with 100 vertices:



Open questions:

- What would be an example ASG?
- Vertex-to-qubit mapping optimization.
- Does it scale?
  (so far up to ~10^3 vertices)

Going beyond single QPUs

Many applications: distributed QC, blind QC, secure communication, sensing.

How do we get to these applications? → Distribute entanglement!

Requirements for a suitable architecture:

- scalable
- robust
- secure
- internetworking
- heterogeneous

Remainder of this talk!

A Quantum Internet Architecture

arXiv > quant-ph > arXiv:2112.07092

Quantum Physics

[Submitted on 14 Dec 2021]

A Quantum Internet Architecture

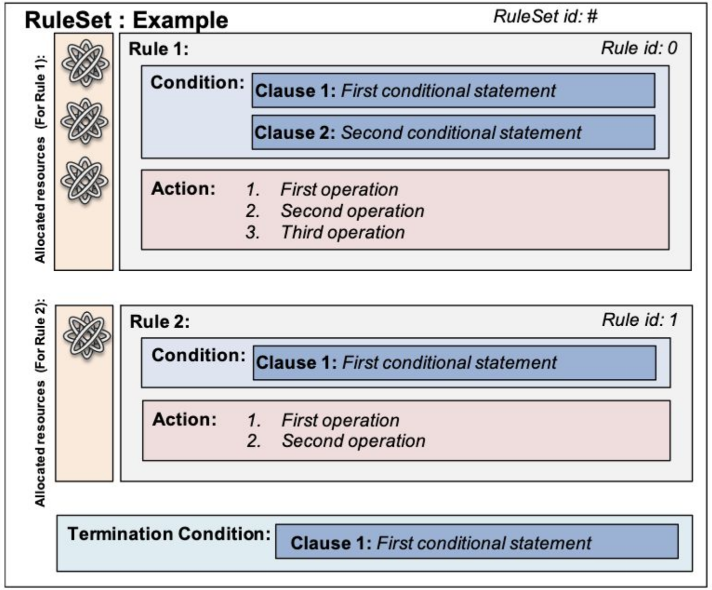
Rodney Van Meter, Ryosuke Satoh, Naphan Benchasattabuse, Takaaki Matsuo, Michal Hajdušek, Takahiko Satoh, Shota Nagayama, Shigeya Suzuki

Entangled quantum communication is advancing rapidly, with laboratory and metropolitan testbeds under development, but to date there is no unifying Quantum Interne
Internet architecture centered around the Quantum Recursive Network Architecture (QRNA), using RuleSet-based connections established using a two-pass connection s
both technological and administrative boundaries) are achieved using recursion in naming and connection control. In the near term, this architecture will support end-to
hardware, and it will extend smoothly to multi-party entanglement and the use of quantum error correction on advanced hardware in the future. For a network internal g
require) qDijkstra with seconds per Bell pair as link cost for routing; the external gateway protocol is designed to build recursively. The strength of our architecture is sh
demonstrating how robust protocol operation can be confirmed using the RuleSet paradigm.

Comments:	17 pages, 7 numbered figures
Subjects:	**Quantum Physics (quant-ph)**; Networking and Internet Architecture (cs.NI)
Cite as:	arXiv:2112.07092 [quant-ph]
	(or arXiv:2112.07092v1 [quant-ph] for this version)
	https://doi.org/10.48550/arXiv.2112.07092
Journal reference:	2022 IEEE International Conference on Quantum Computing and Engineering (QCE), pp. 341-352 (2022)
Related DOI:	https://doi.org/10.1109/QCE53715.2022.00055

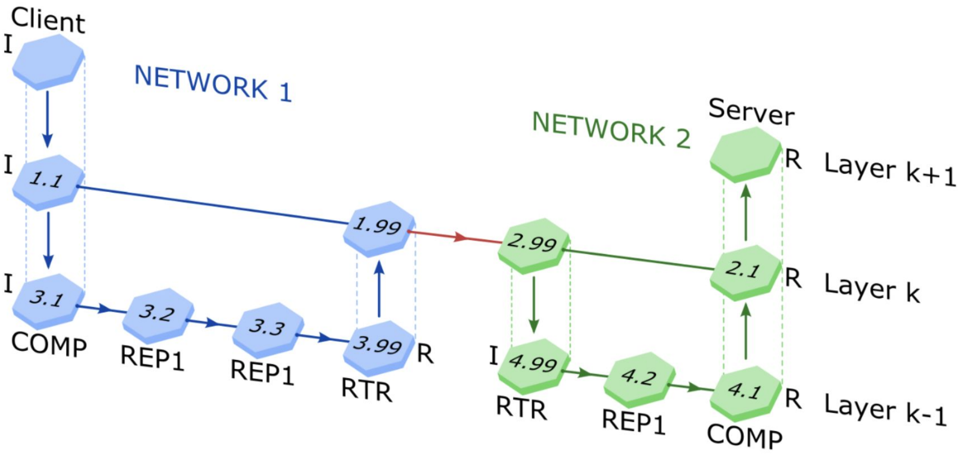
A Quantum Internet Architecture

Ruleset-based operations



Matsuo *et al.*, Phys Rev A 100, 052320 (2019)

Recursive



Quantum recursive network architecture.

A Quantum Internet Architecture

RESEARCH-ARTICLE

RuleSet-based Recursive Quantum Internetworking

Authors: Kentaro Teramoto, Michal Hajdusek, Toshihiko Sasaki, Rodney Van Meter, Shota Nagayama

Authors Info & Claims

QuNet '23: Proceedings of the 1st Workshop on Quantum Networks and Distributed Quantum Computing • September 2023 • Pages 25–30 • https://doi.org/10.1145/3610251.3610556

Design principles for quantum internetworking based on QRNA.

Quantum Internet Simulation Package (QuISP)

arXiv > quant-ph > arXiv:2112.07093

Search...

Help | Advanc

Quantum Physics

[Submitted on 14 Dec 2021]

QuISP: a Quantum Internet Simulation Package

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

We present an event-driven simulation package called QuISP for large-scale quantum networks built on top of the OMNeT++ discrete event simulation framework. Although the behavior of quantum networking devices have been revealed by recent research, it is still an open question how they will work in networks of a practical size. QuISP is designed to simulate large-scale quantum networks to investigate their behavior under realistic, noisy and heterogeneous configurations. The protocol architecture we propose enables studies of different choices for error management and other key decisions. Our confidence in the simulator is supported by comparing its output to analytic results for a small network. A key reason for simulation is to look for emergent behavior when large numbers of individually characterized devices are combined. QuISP can handle thousands of qubits in dozens of nodes on a laptop computer, preparing for full Quantum Internet simulation. This simulator promotes the development of protocols for larger and more complex quantum networks.

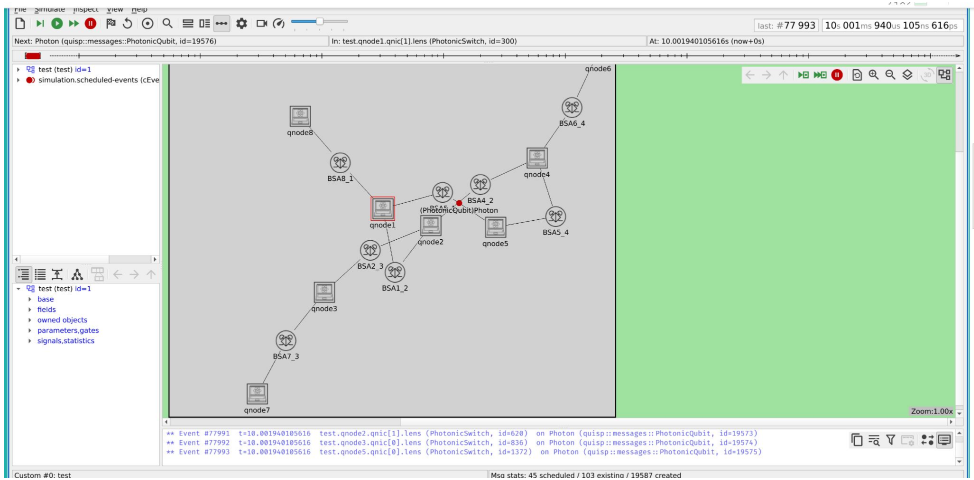
Comments:	17 pages, 12 figures
Subjects:	**Quantum Physics (quant-ph)**; Networking and Internet Architecture (cs.NI); Software Engineering (cs.SE)
Cite as:	arXiv:2112.07093 [quant-ph]
	(or arXiv:2112.07093v1 [quant-ph] for this version)
	https://doi.org/10.48550/arXiv.2112.07093
Journal reference:	2022 IEEE International Conference on Quantum Computing and Engineering (QCE), pp 353-364 (2022)
Related DOI:	https://doi.org/10.1109/QCE53715.2022.00056

Always looking for more help with development.

Building a quantum network system

Real testbed (small-scale):

Simulation (large-scale):



Go from an experiment to a **quantum network system**.

RFC9340!!!

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

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

Architectural Principles for a Quantum Internet

draft-irtf-qirg-principles-11

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

Versions:

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

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

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

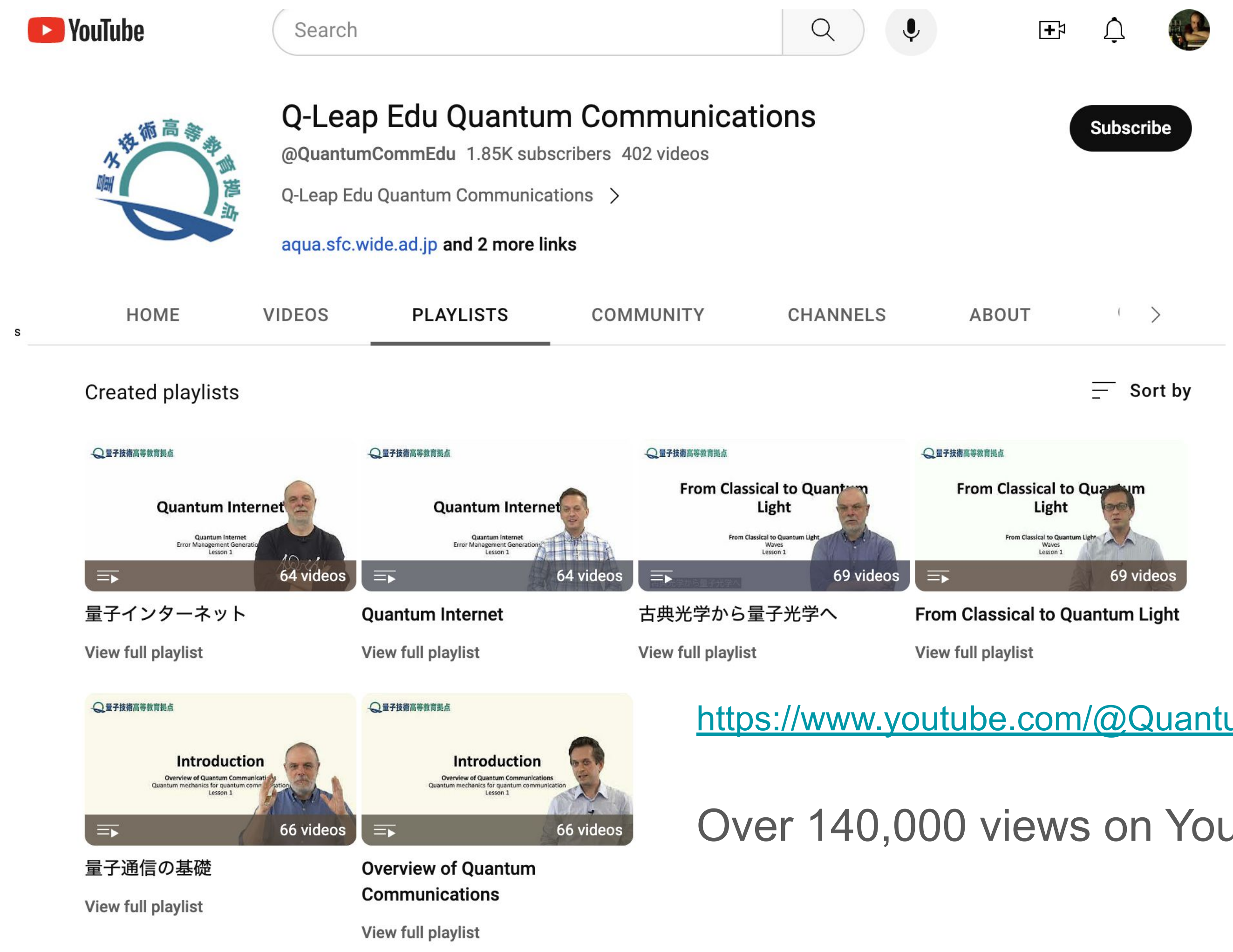
RFC 9340
Architectural Principles for a Quantum Internet

Abstract

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

Status of This Memo

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



https://www.youtube.com/@QuantumCommEdu

Over 140,000 views on YouTube.

Quantum Communications undergrad textbook

arXiv > quant-ph > arXiv:2311.02367

Search...

Help | Advanced

Quantum Physics

[Submitted on 4 Nov 2023]

Quantum Communications

Michal Hajdušek, Rodney Van Meter

The second quantum revolution has been picking up momentum over the last decade. Quantum technologies are starting to attract more attention from governments, private companies, investors, and public. The ability to control individual quantum systems for the purpose of information processing and communication is no longer a theoretical dream, but is steadily becoming routine in laboratories and startups around the world. With this comes the need to educate the future generation of quantum engineers. This textbook is a companion to our video lectures on Overview of Quantum Communications from the Q-Leap Education project known as Quantum Academy of Science and Technology. It is a gentle introduction to quantum networks, and is suitable for use as a textbook for undergraduate students of diverse background. No prior knowledge of quantum physics or quantum information is assumed. Exercises are included in each chapter.

Comments: 308 pages, still an early draft, all comments are welcome!

Subjects: **Quantum Physics (quant-ph)**

Cite as: arXiv:2311.02367 [quant-ph]

(or arXiv:2311.02367v1 [quant-ph] for this version)

https://doi.org/10.48550/arXiv.2311.02367

- Released Creative Commons (CC-BY-SA)
  - https://github.com/sfc-aqua/Overview-of-Quantum-Communications-E
- Supported by Q-Leap Education project
  - https://qacademy.jp/en/

Things I have not mentioned…

- noise mitigation with **spectator qubits** (Poramet)
- **noise estimation** using distillation protocols (joint work with OIST)
- architecture and protocols for **all-photonic quantum repeaters** (Naphan)
- simulating entanglement distribution with **satellites** (Paolo + Fred)
- simulation of the Dirac equation using **quantum walks** (Shigetora, now at UTokyo)
- **hybrid error-management strategies** for quantum repeater networks (Poramet)
- some of my orthogonal work (dynamical synchronization, time crystals)

Thank you for your attention