QuISP Presentation and Demonstration (Quantum Internet Simulation Package)

https://events.geant.org/event/991/

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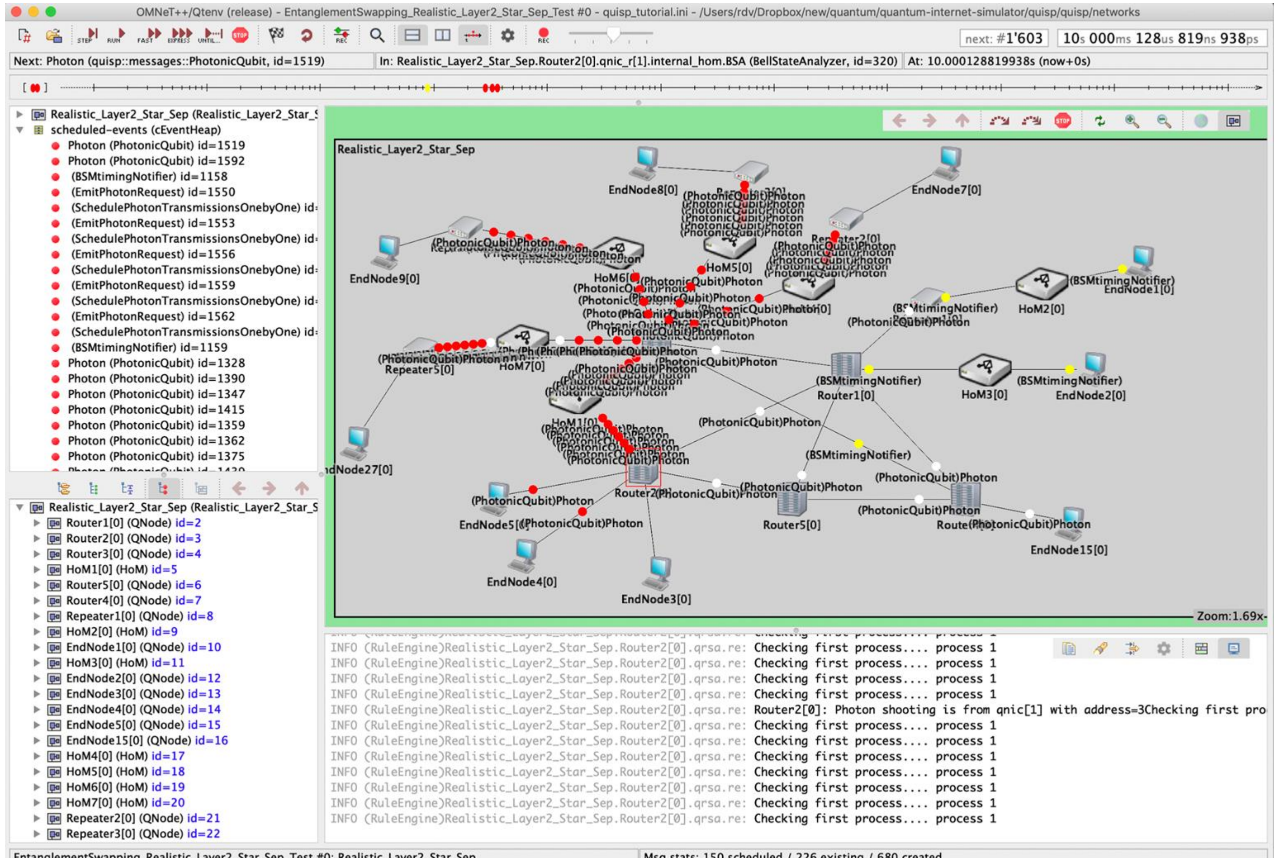
Hands-On Simulation of a Quantum Network

IEEE Quantum Week 2020 Tutorial
Rodney Van Meter, Ryosuke “cocori” Satoh
Keio University



Important (Critical!) Links

- QuISP web page
  https://aqua.sfc.wide.ad.jp/quisp_website/
- QuISP source @github
  https://github.com/sfc-aqua/quisp
- OMNeT++ download
  https://omnetpp.org/download/
- Eigen linear algebra library
  http://eigen.tuxfamily.org/index.php?title=Main_Page
- Takaaki Matsuo’s master’s thesis & Phys. Rev. A paper
  https://arxiv.org/abs/1908.10758 https://arxiv.org/abs/1904.08605

Quantum Repeaters in 5 minutes: Entanglement Swapping and Purification (and a few other things)

Networking: What’s so hard about it?

- Naming
- Resource management
- Heterogeneity
  - In technology, resources, operations
- Dealing with out-of-date information
- Sheer scale

The job of a quantum repeater network is…

- …to make end-to-end entanglement (modulo some arguments about temporal matters).
- And, entanglement is a consumable resource, so we have to make lots of it.

So the job of a quantum repeater is…

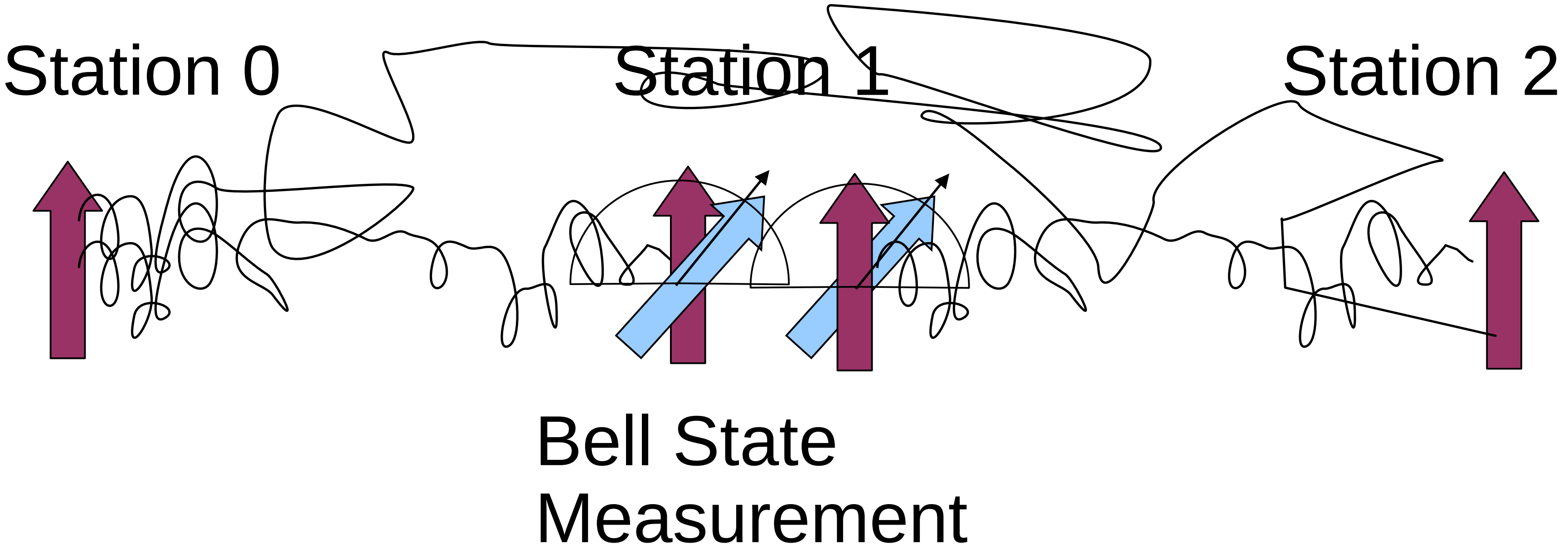
- 1) to make base-level entanglement over a link
- 2) to couple entangled links along an end-to-end path to meet the applications' needs
- 3) to monitor and manage errors (purification, QEC, or both)
- 4) to participate in the management of the network

And the job of a Quantum *Internet* is…

To do all of this:

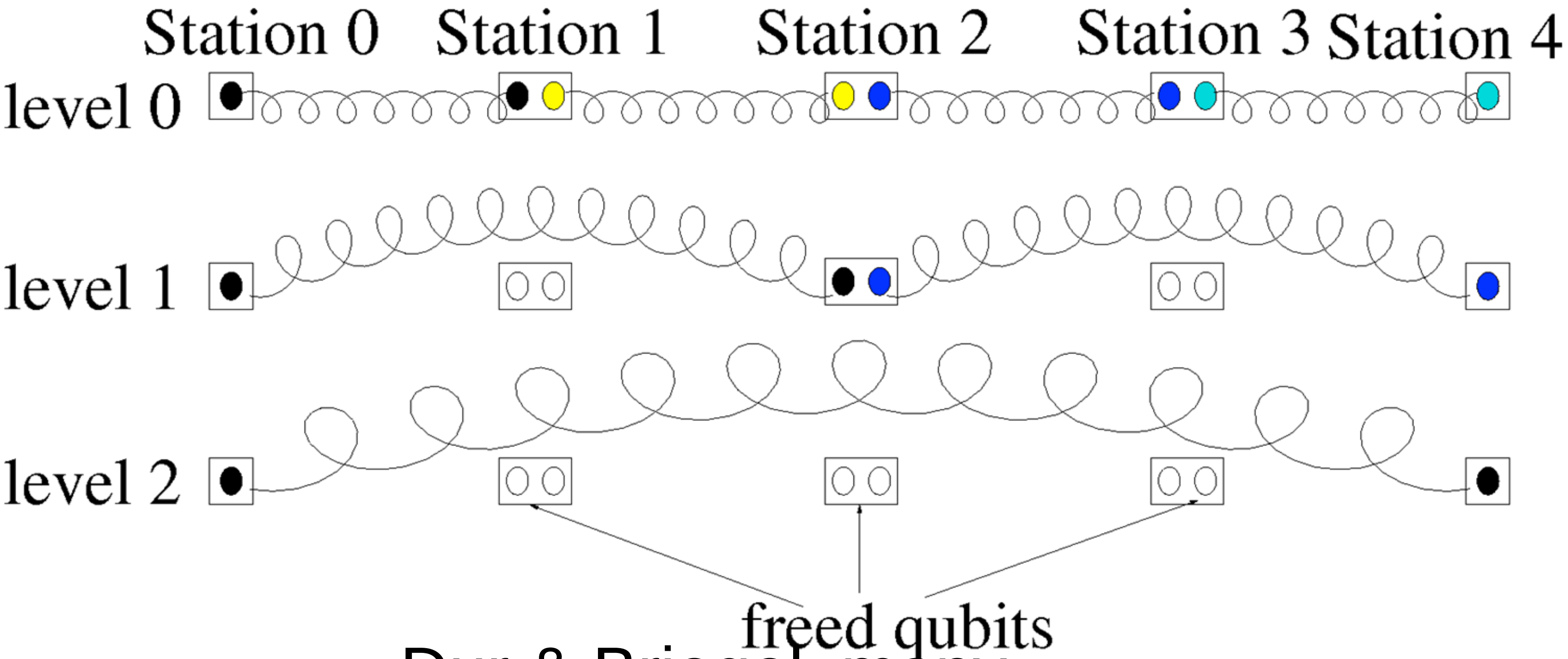
- across *heterogeneous* networks
  (both physically and logically hetero)
- in an environment with *minimal trust* between networks
  - no knowledge of the internals of autonomous networks
  - possible presence of malicious nodes

Quantum Repeater Operation



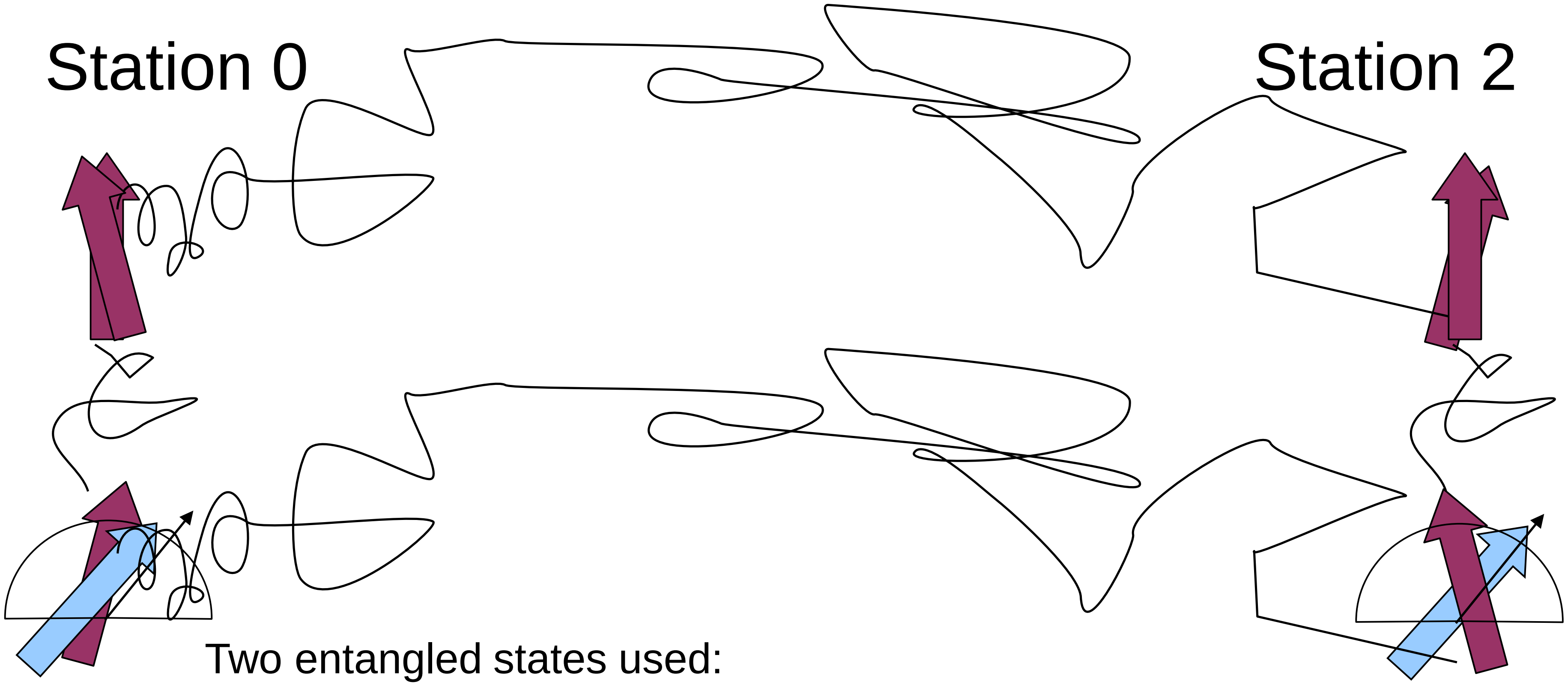
Called *entanglement swapping*.
Fidelity declines; you must *purify* afterwards

Nested Entanglement Swapping



Dur & Briegel, many others

Purification: Error Detection



Two entangled states used:
one used as a *test tool* to test an assertion about the other.
The test tool is destroyed in the process.
On success, confidence in the tested state (fidelity) improves.
On failure, tested state is discarded.

Five Repeater Schemes

- 1G: Purify and swap over ACKed links: truly a distributed computation (Dur & Briegel, Lukin, others; since 1998)
- 2G: Error Correction over ACKed links
    - CSS quantum error correction & entanglement swapping (Jiang (Lukin) *et al.*, 2009)
    - Surface code quantum error correction, sort of but not quite swap (Fowler *et al.*, 2010)
- 3G: Error Correction over no-ACK-needed links: store-and-forward
    - Quasi-asynchronous (Munro *et al.*, 2010)
    - Memoryless (Munro *et al.*, 2012)

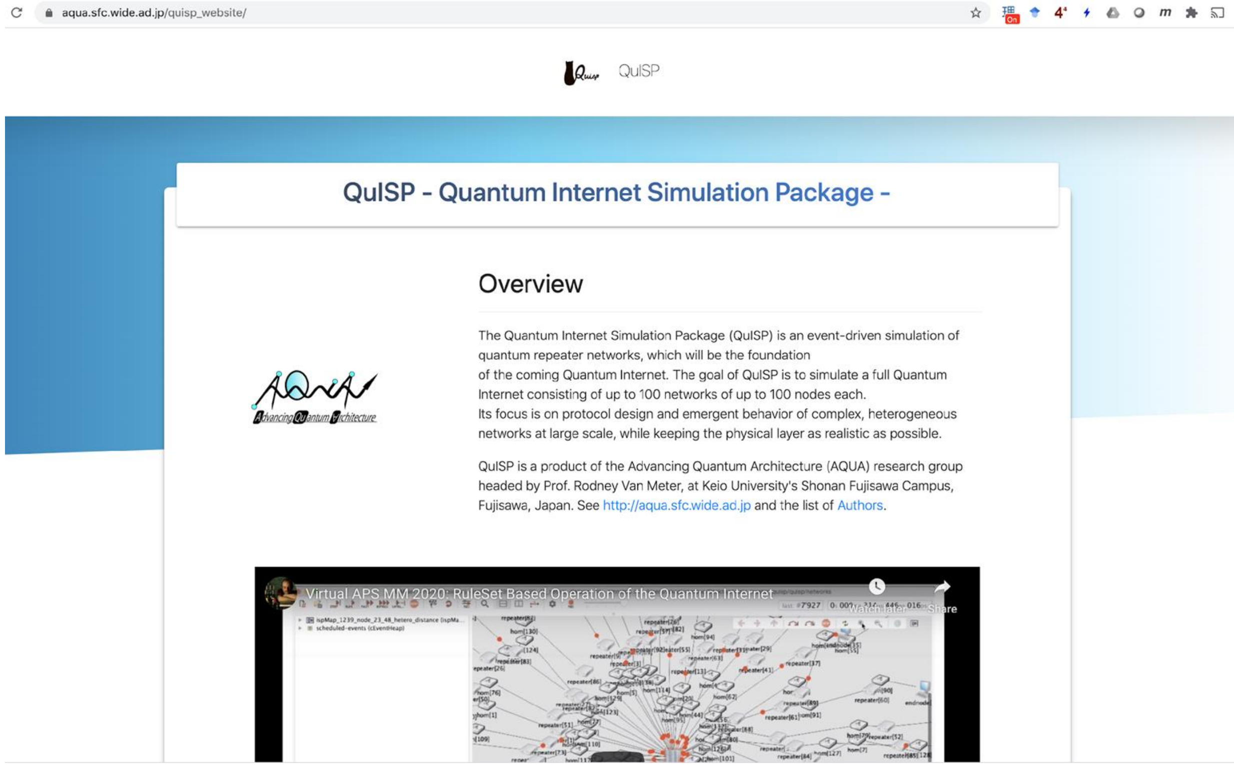
Repeater Generations

- 1G: Entanglement ACKnowledged link layer,
  purification (error detection),
  entanglement swapping
- 2G: Entanglement ACKnowledged link layer,
  quantum error correction (QEC),
  entanglement swapping
- 3G: Un-acknowledged link layer,
  quantum error correction,
  store-and-forward
- https://www.nature.com/articles/srep20463

QuISP

Matsuo *et al.*, arXiv:1904.08605
Phys. Rev. A 100, 052320 (2019)

QuISP was released as **open source** on April 5, 2020



License is commercial-friendly
3-Clause BSD.

For news:

- Watch https://aqua.sfc.wide.ad.jp
- https://aqua.sfc.wide.ad.jp/quisp_website/

Performance Targets (1)

- 1G, 2G, 3G networks
  [Muralidharan et al., *Sci. Rep.* 2016]
- Up to:
  100 networks in an Internet,
  100 nodes/network,
  100 qubits/node,
  max of **one million qubits** in a simulation (target!!!),
  ~5,000 qubits in one entangled state
  ([[23,1,7]] code across 100 hops in
  a 2G network)

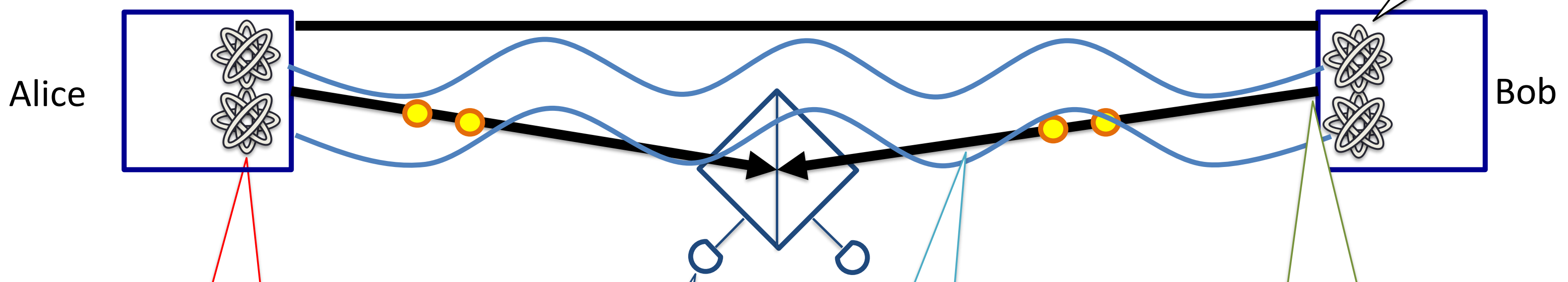
- Forces us to operate in the *error basis*, like a QEC simulator, rather than density matrix or state vector

Performance Targets (2)

- *Complete* configurability of network and device parameters
  - Link: architecture, distance, loss, error rate
  - Node: gate & memory error rates, buffer memory sizes
  - Network: topology, error management (1G, 2G, 3G)
- Complete configurability of simulation scenario
  - Traffic pattern (“incast” hub-and-spoke,
    evenly random)

Dynamic, Heterogeneous Error Model

Gate error
1. X-error
2. Z-error
3. Y-error



Memory Error
1.X-error
2.Z-error
3.Y-error
4.Energy excitation
5.Energy relaxation
6.Completely mixed
※per unit time

Photon Detector Error
1. Darkcount

Quantum Channel Error
1.X-error
2.Z-error
3.Y-error
4.Photon Loss
※per unit distance

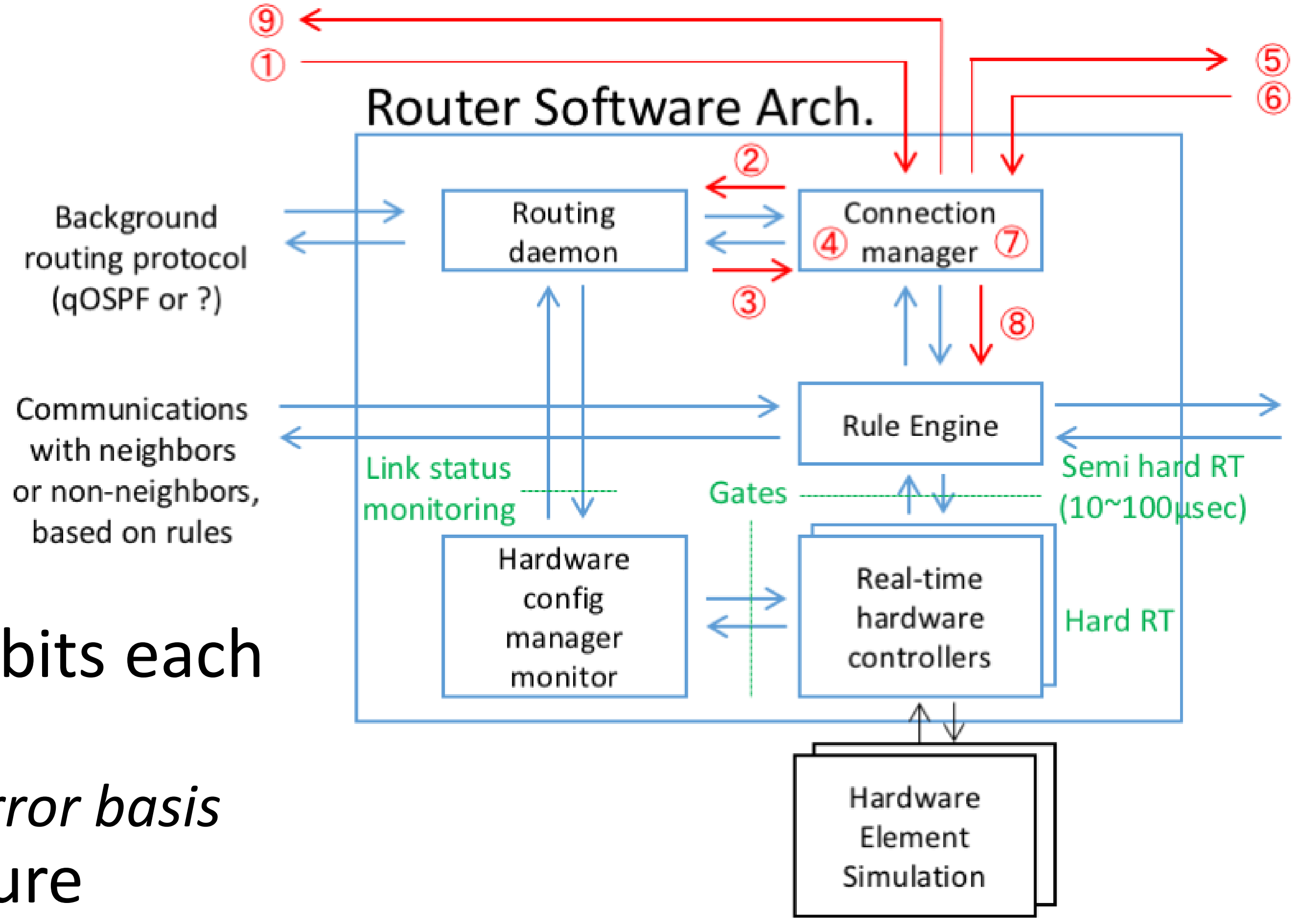
Photon Emission-time error
1. X-error
2. Z-error
3. Y-error
4. Photon Loss
※per trial

Markov-Chain Monte-Carlo (MCMC) Simulation

Outline for QUISP training

- Session 1: Your first simulation
  - Entanglement swapping & purification: quantum repeaters in five minutes
  - QuISP: Your friendly, neighborhood, highly scalable Quantum Internet simulator
  - Install OMNeT++ → *this is the hard part!*
  - Install QuISP and run a simulation!
- Session 2: Principles of network operation and simulation
  - Simulating in the *error basis*
  - Application communication classes
  - Condition-action: RuleSets for operation
  - Distributed density matrix management
  - Network and connection performance
- Session 3: The principles in action
  - Return to simulation work

QuISP Strengths

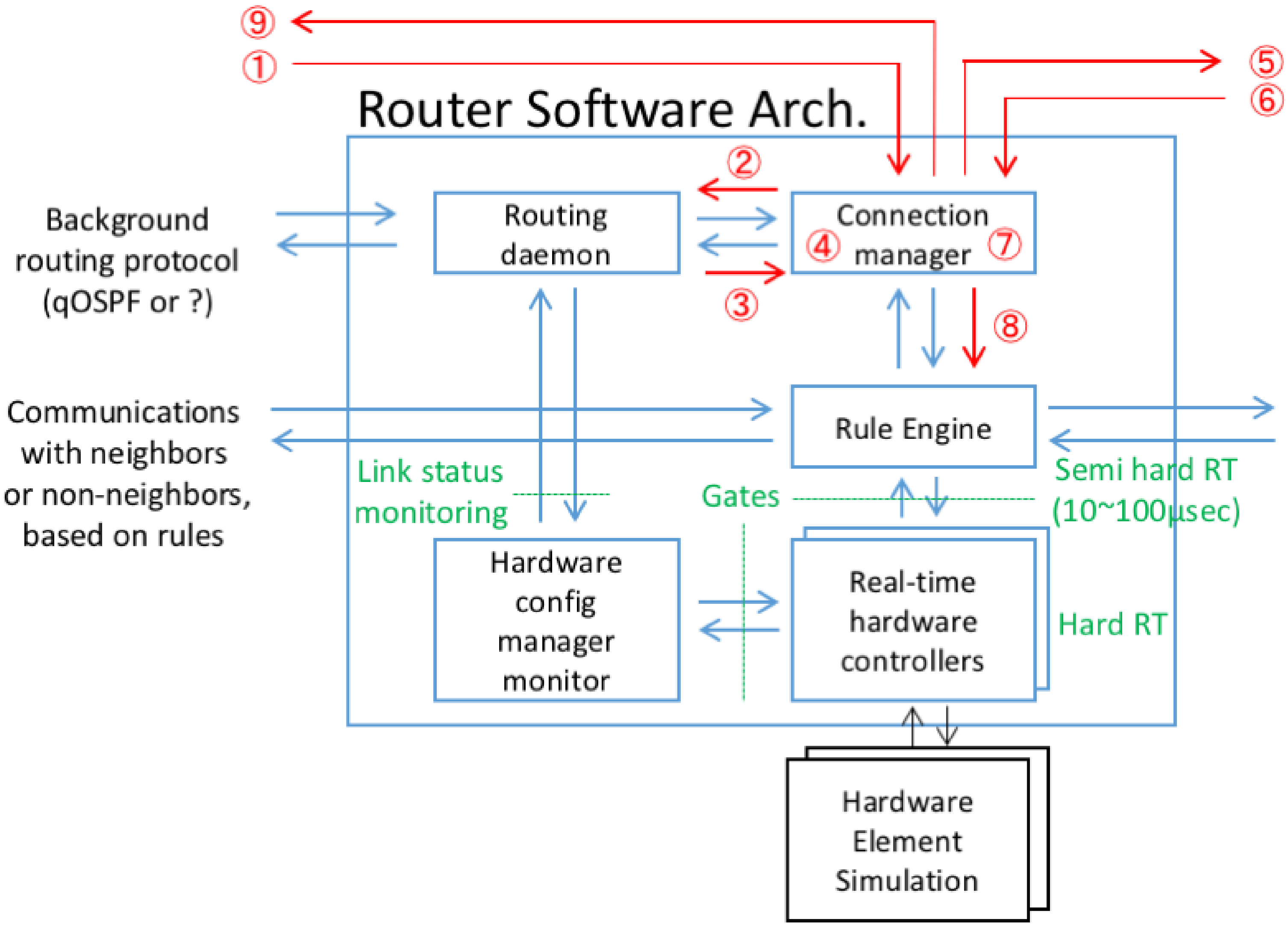


- Scalability: ultimate target is 100 networks of 100 nodes, 100 qubits each = 1 million qubits
  - made possible by operating in the *error basis*
- Clear node internal software structure
  - excellent for working on classical protocols
  - good for repeater/router software development
- Endless configurability
- Animations, inspector, etc. all built on OMNeT++ capabilities

QuISP Weak Points

- not tuned for very low-level simulation of physical processes
  (but does have model of both "Pauli" (symmetric error channel) and "non-Pauli" (loss, asymmetric error channel) errors)
- steep learning curve
- installation is a pain (mostly due to OMNeT++)
- many features still in development

Quantum Router Software Architecture (QRSA)



Quantum Recursive Network Architecture

QRNA *improves scalability* and *maintains operational autonomy.*

We think it’s the best way to achieve a truly *global Quantum Internet!*

See https://arxiv.org/abs/1105.1238

See the movie QuISP-connection-setup.mov in the Google Drive (or IEEE FTP site)

RuleSets (Tomography as an Example)

We believe in a Condition-Action (or Match-Action) style of protocol development for quantum networks; the actions are complex and too dependent on end-to-end factors to be as hop-by-hop simple as TCP/IP.

See https://arxiv.org/abs/1904.08605

and the file QuISP-tomography-rulesets.mov in
the Google Drive or the IEEE FTP site

Scaling Quantum Simulation

If you want physical simulation, including asymmetric error processes, you need *density matrix* sim. # of qubits in a single entangled state gives exponential memory growth (16*2^(2n) bytes):

# qubits in state	**density matrix size**
2 (e.g., Bell pair, simplest two-qubit entangled state)	128B
7 (simple error corrected state)	8KB
14 (Bell pair over simple error correction)	256KB
28 (two Bell pairs over simple error correction)	64PB (7.2E16 Bytes)
825 (application qubits for Quantum Byzantine Agreement, 5 nodes)	3.6E249 Bytes
5,000 (Bell pairs over advanced QEC across 100 hops)	3.2E3011 Bytes (not a typo)

n.b.: many caveats, shortcuts for special cases; this is worst case

QuISP Active Development Projects

2020/10/9

Major New Quantum Concepts Under Development

- **RGS (repeater graph states)**
- **Multi-party graph states**
- **2G repeaters**
- **Improved tomography**
- **CHSH violation**
- **Test & improve matching to physical experiments**
- **Sockets-like API for apps:** open! to do well, requires improvements to theory of error basis simulation and god channel
- **Internetworking:** open!
  - Add ASes for topology definition & routing, recursive behavior in connection setup
  - Can be done for 1G networks, most interesting when we get to 2G

Infrastructure & Networking Basics

- **visualization/data analysis:** cocori, but needs more (#119)
- **traffic generation:** gravity model (#19), clique (#18)
- **routing protocol**
- **improve connection setup protocol** (e.g., #97)
- **multiplexing/resource allocation** (#27)
- **improve how RuleSets are defined** (would be nice if that didn't have to involve writing C++)
- **test scalability:** goal is up to a million qubits: 100 networks, 100 nodes each, 100 qubit memories each -- can we get there?
- **more network topologies:** from real ISPs (kaaki), automated generation

Smaller but Useful Things

- Relax constraints on partner addresses when entanglement swapping
- Display, output or animate entanglement (#166, #94)
- Unit tests (#108)
- Be able to run link tomography and save the output, then be able to read that in on a later run (fast-forwarding the booting of the network, basically) (#14)
- M<--S-->M link (#15)

Research Questions

- Emergent behavior
  - quantum congestion collapse?
- Protocol design
  - condition-action (like SDN match-action)
  - emphasis on classical messaging, eliminating latencies
- Connection architecture and performance prediction
  - studies of 2G & 3G networks, evolving technology, logical & physical heterogeneity
- Dynamic behavior
  - link state changes, traffic pattern changes

References

[1] T. Matsuo, T. Satoh, S. Nagayama, and R. Van Meter, “Analysis of measurement-based quantum network coding over repeater networks under noisy conditions,” Phys. Rev. A, vol. 97, p. 062328, Jun 2018.

[2] Takaaki Matsuo, Clément Durand, Rodney Van Meter, "Quantum link bootstrapping using a RuleSet-based communication protocol" Phys. Rev. A 100, 052320 (2019)

[3] T. Matsuo, “Simulation of a Dynamic, RuleSet-base Quantum Network,” master’s thesis, Keio University, 2019. arXiv:1908.10758