Name of the Research Project: "Science 2.0" for the Quantum Internet
Name of the Research Project Leader: Jun Murai
Affiliation: Graduate School of Media and Governance
Job Title: Vice President, Professor

Taikichiro Mori Memorial Research Fund
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Final Report

Research Staff and visitors:
Rodney Van Meter, Assistant Professor, Faculty of Environment and Information Studies, Keio University
Shota Nagayama, bachelor's student, Faculty of Environment and Information Studies
Takahiko Satoh, Faculty of Environment and Information Studies
Agung Trisetyarso, Ph.D. student, Kohei Itoh Laboratory, Faculty of Science and Technology
Byung-Soo Choi, Research Assistant Professor, Ewha Women's University, Seoul, Korea

Summary of Results:

The Mori Kikin funds were used primarily to support travel for researchers, advancing research on quantum networking and applications for distributed quantum computing systems. Physicists are developing the underlying technologies for quantum networking, equivalent to transceivers and transistors in classical hardware systems. However, there is a great deal more to a computer system (especially a distributed system) than simply the pieces; the *software* (both *system software* and *applications)* and the *architecture* are equally important in determining what can and cannot be done. The underlying technology of quantum computing and the theory of quantum computation (computational complexity, etc.) and quantum information are developing rapidly, but the *systems-level* work that will tie all of these together into a functioning distributed quantum computing system has been lacking. Work performed at SFC using the Mori Kikin funds, therefore, places SFC at the forefront of this key field, both accelerating the arrival of quantum technology and solidifying Keio's position as a world-class research institution.

The results include:

- Advances in the engineering of quantum repeater networks, designed for wide-area systems:
  - ① Protocol state machine design: Network protocols are often defined in terms of their protocol state machine, detailing the actions to be taken when specific events occur. This network engineering approach has never before been applied to quantum repeater networks.
  - ① Studies of the behavior of heterogeneous quantum repeater networks: All quantum repeater studies to date have simulated regular networks where all links are of identical distance and quality. We are studying chains of repeaters with "weak links." Simulations suggest that throughput declines with the first weak link, but having two or more similarly weak links does not further degrade the performance.
  - ① Cost in quantum networks: In conjunction with the above, we are studying how to measure the *cost* of transmitting data along a particular *path* in a complex quantum network. The current leading candidates are a) the number of *measurement* operations necessary, and b) *qubit-seconds*, the total amount of time that qubits in the system are busy holding data. Work in this area is ongoing.
- Advances in applications for distributed quantum computing systems:
  - ① Quantum arithmetic: Any digital quantum application algorithm is likely to involve arithmetic, and studies have shown that the arithmetic portion of important algorithms

such as Shor's quantum algorithm for factoring large numbers is actually dominated by the performance of the arithmetic subroutines. Thus, we are investigating both the theoretical limitations on the performance of arithmetic and specific circuits for addition:
    - *Graph embedding* techniques demonstrate that the limit on performance of addition is the propagation of quantum information through the physical system; a one-dimensional chain of qubits is limited to O(*n*) performance for adding *n*-qubit registers.
    - Using the unique quantum technique of *cluster state computation*, it is possible to propagate quantum information to anywhere in the system in a single time step, even when the underlying physical system supports only nearest-neighbor operations in a two-dimensional lattice.

  These two results will impact our ability to build a *quantum multicomputer*, a large-scale, distributed-memory quantum computing system.
  1. Analog entanglement/gyroscopic reference: Preliminary analysis of applications that could use the long-distance entanglement created by quantum repeater networks found several candidates that we hope to pursue in the coming years, including the possibility of enhanced sensitivity for the LIGO (Laser Interferometer Gravity Wave Observatory) sensors.
- Quantum Key Distribution (QKD):
  1. In collaboration with NEC, the Internet Protocol security suite IPsec is being adapted to utilize keys generated by QKD. The software is functional, and was demonstrated at SFC's Open Research Forum, November, 2008; it will be demoed again at WIDE Camp, March, 2009.
- Organizational and collaborative advances:
  1. A "wiki" for quantum information exists, known as *Qwiki*, and hosted at Stanford University. We have previously developed a Qwiki page on quantum arithmetic, which we maintain, and are adding pages on quantum networking and the Quantum Internet.
     http://qwiki.stanford.edu/wiki/Quantum_Arithmetic
     http://qwiki.stanford.edu/wiki/Quantum_Internet
     At a recent conference (SQuInT), we convened a "BoF" (birds of a feather) session on quantum networking, and are developing a mailing list for this specific topic. Our goal is to educate physicists on networking technology, as well as use the mailing list to track advances in the field.
  1. At the conference on Updating Quantum Cryptography, Assistant Professor Van Meter was invited to join the ETSI working group on standardization of quantum cryptography.

These results were communicated through a series of meetings, conference presentations, and publications, as described below.

Conference Presentations & Attendance:

Presentations:

- R. Van Meter,
  Resource Handling for Quantum Networks of Arbitrary Topology,
  Southwest Quantum Information and Technology (SQuInT),
  Eleventh Annual Meeting, February 19-22, 2009
  Seattle, Washington, U.S.A.
- R. Van Meter and Byung-Soo Choi,
  Applications of an Entangled Quantum Internet,
  Third International Conference on Future Internet Technologies (CFI08), June 18-20, 2008
  Seoul, Korea.
- R. Van Meter,
  Applications of an Entangled Quantum Internet,
  WIDE Camp,
  March 10-13, 2009 (scheduled)
  Nagano, Japan.
- S. Nagayama, T. Satoh, A. Tanaka (NEC), R. Van Meter,
  IPsec with Quantum Key Distribution,
  WIDE Camp,
  March 10-13, 2009 (scheduled)
  Nagano, Japan.

Poster:

- A. Trisetyarso, R. Van Meter and Kohei M. Itoh,
  Resources for Measurement-Based Quantum Carry-Lookahead Adder,
  International Symposium on Nanoscale Transport and Technology (ISNTT2009),
  January 20 – 23, 2009
  NTT Atsugi R&D Center, Kanagawa, Japan.

Attendance:

- R. Van Meter, T. Satoh, and S. Nagayama attended
  Updating Quantum Cryptography (UQC) 2008,
  December 1-2, 2008
  Akihabara, Tokyo, Japan.

Journal Papers:

- Byung-Soo Choi and R. Van Meter,
  Effects of Interaction Distance on Quantum Addition Circuits,
  submitted to *Quantum Information and Computation*, September 2008;
  available from the arXiv as quant-ph:0809.4317.
- A. Trisetyarso and R. Van Meter,
  Circuit Design for a Measurement-Based Quantum Carry-Lookahead Adder,
  in preparation; to be submitted in March, 2009.

Demonstrations and Other Activities:

- Murai Laboratory,
  S. Nagayama, T. Satoh, and R. Van Meter (cooperation: A. Tanaka, NEC),
  IPsec with Quantum Key Distribution,
  SFC Open Research Forum,

November 19-22, 2008
Roppongi, Tokyo, Japan.

- Murai Laboratory,
  S. Nagayama, T. Satoh, and R. Van Meter (cooperation: A. Tanaka, NEC),
  IPsec with Quantum Key Distribution,
  WIDE Camp,
  March 10-13, 2009 (scheduled)
  Nagano, Japan.
- Byung-Soo Choi visited SFC for collaborative research,
  February 10-15, 2009.
- "BoF" (Birds of a Feather) session organized at SQuInT,
  February 20, 2009
  Seattle, Washington, U.S.A.

Attachments

- R. Van Meter and B.-S. Choi, "Applications for an Entangled Quantum Internet," CFI08
- B.-S. Choi and R. Van Meter, "Effects of Interaction Distance on Quantum Addition Circuits"
- R. Van Meter, "Resource Handling for Quantum Networks of Arbitrary Topology," SQuInT 2009 (presentation slides)