Distributed Quantum Networks
based on Trapped Ions

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Qcrypt 2016
Washington, DC, September 12-16th, 2016
Outline

• Introduction:
  – Practical Framework for Quantum Networking
  – 3 Generation of Quantum Repeaters

• Trapped Ion Technology for Quantum Networking

• Towards a Demonstration of a Repeater Node

• Conclusions
Evolution of Communication Networks

1st phone call, 1876
NY-Chicago, 1892

Vacuum Tubes
(First triode, 1907)

Long-distance
communication, 1915

“Manual” switching
networks, ~1950s

Distributed Computing
(Data Centers)

Global Internet
Since 1990s

Modern telephone networks
(WDM systems, 5ESS switches) ~1980s

Data Dominates!
~Generic Q. Networks

Voice Dominates!
~QKD
Tu Poster
Islam et al.

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Key Attributes of Quantum Networks

- Essence of “(Quantum) Data Communication between Machines”
  - Distance of Communications
    - Within a quantum processor node (~1mm-1cm)
    - Between processor nodes (~10cm-10m)
    - Long-distance nodes (~100m-10,000km)
  - Types of Applications
    - Secret key generation (measurements on both ends: easy!!)
    - Quantum repeaters (entanglement swapping operation)
    - Generic quantum interconnects (remote quantum gates)
Generation of Remotely Entangled Memories

- With a good quantum memory, the generated entanglement can be stored and used for deterministic quantum logic operation
- Opportunities for photonics technology
  - Optical networking to construct quantum networks
  - Manipulation of photonic qubits (frequency conversion, etc.)
Quantum Repeater Platform

- Quantum Repeater for Long-Distance Quantum Communication
  - Small quantum computer with two optical ports function as a quantum repeater

Entangled!!


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<table>
<thead>
<tr>
<th>Approaches</th>
<th>Example</th>
<th>Requirement</th>
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<tr>
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<td><img src="image1" alt="Heralded Generation Diagram" /></td>
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<tr>
<td><strong>Quantum Error Correction</strong></td>
<td><img src="image2" alt="Quantum Error Correction Diagram" /></td>
<td>Deterministic, <em>One-Way</em> Comm. Suppress $\epsilon \rightarrow \epsilon^{2r+1}$</td>
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<td><img src="image3" alt="Heralded Purification Diagram" /></td>
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<tr>
<td><strong>Quantum Error Correction</strong></td>
<td><img src="image4" alt="Quantum Error Correction Diagram" /></td>
<td>Deterministic, <em>One-Way</em> Comm. Suppress $\epsilon \rightarrow \epsilon^{r+1}$</td>
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(*) Experiments with ions, atoms, NVs, QDs, ensembles, …  
(**) Experiments with photons, ions, …
# Three Generations of QRs

<table>
<thead>
<tr>
<th>Approaches</th>
<th>1(^{\text{st}}) Generation</th>
<th>2(^{\text{nd}}) Generation</th>
<th>3(^{\text{rd}}) Generation</th>
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• Conclusions
Advantages of Trapped Ion Systems

• “Best” Qubits and High Fidelity Operation
  – 1–1,000 sec coherence times routine in hyperfine qubits
  – State preparation and measurement (SPAM) errors in the $10^{-3}$–$10^{-4}$ range (<$10^{-5}$ possible)
  – Single-qubit gate errors in the $10^{-4}$–$10^{-6}$ range
  – Two-qubit gate errors in the $10^{-3}$ range (<$10^{-5}$ possible)

• Introduction of New Technologies

C. Langer et al., PRL 95, 060502 (2005)
S. Olmschenk et al., PRA 76, 052314 (2007)
A. H. Myerson et al., PRL 100, 200502 (2008)
K. Brown et al, PRA 84 030303 (2011)
T. Harty et al, PRL 113 220501 (2014)
New Trapping Technology in MUSIQC

- Microfabricated Ion Traps

Advanced Trap Functionalities

Jason Amini et al., GTRI (2011)

NJP 13, 075018 (2011)
NJP 13, 103005 (2011)
NJP 14, 073012 (2012)
NJP 15, 033004 (2013)
NJP 15, 083053 (2013)
- Optical access
- High trap frequencies

< 2μm focus possible

4 μm waist is possible
Physical Layer of a Fully Programmable QC

5-Qubit QC with Full Connectivity

CNOT [1:2]  
F=96.4(6)%

CNOT [1:3]  
F=97.6(7)%

CNOT [1:4]  
F=95.9(7)%

CNOT [1:5]  
F=97.9(5)%

CNOT [2:3]  
F=95.6(6)%

CNOT [2:4]  
F=98.4(7)%

CNOT [2:5]  
F=96.8(7)%

CNOT [3:4]  
F=96.6(5)%

CNOT [3:5]  
F=97.6(6)%

CNOT [4:5]  
F=97.2(5)%


SPAM errors reduce this by ~2%
Operation of a Fully Programmable QC

- Deutsch-Jozsa Algorithm
- Quantum Fourier Transform Algorithm

Remote Entanglement Generation via Photons

Heralded coincident events ($p_{suc}=1/4$):

\[
\begin{align*}
(H_1 & \text{ or } V_2) & \text{ or } (V_1 & \text{ or } H_2) \quad \rightarrow \quad |\downarrow\uparrow\rangle - |\downarrow\downarrow\rangle \\
(H_1 & \text{ or } V_1) & \text{ or } (V_2 & \text{ or } H_2) \quad \rightarrow \quad |\downarrow\downarrow\rangle + |\downarrow\uparrow\rangle \\
(H_1 & \text{ or } H_1) & \text{ or } (H_2 & \text{ or } H_2) \quad \rightarrow \quad |\downarrow\downarrow\rangle \\
(V_1 & \text{ or } V_1) & \text{ or } (V_2 & \text{ or } V_2) \quad \rightarrow \quad |\uparrow\uparrow\rangle
\end{align*}
\]

\[
R_{ent} = \frac{1}{4} R \left( \eta_D \cdot F \cdot \frac{d\Omega}{4\pi} \right)^2
\]

\[
R: \text{ Repetition Rate} \\
\eta_D: \text{ Detector Efficiency} \\
d\Omega: \text{ Collection Solid Angle} \\
F: \text{ Collection Efficiency}
\]

\[
R_{ent} = 0.001 - 0.025 s^{-1} \\
\tau_E / \tau_D = 27 - 670
\]

Y. L. Lim, et al., PRL 95, 030505 (2005)
Current Status on Entanglement Generation

Heralded coincident events ($p_{suc} = 1/2$):

- $(H_1 & V_2)$ or $(V_1 & H_2) \rightarrow |↓↑⟩ - |↓↑⟩$
- $(H_1 & V_1)$ or $(V_2 & H_2) \rightarrow |↓⟩ + |↑⟩$
- $(H_1 & H_1)$ or $(H_2 & H_2) \rightarrow |↓⟩$
- $(V_1 & V_1)$ or $(V_2 & V_2) \rightarrow |↑⟩$

\[
R_{ent} = \frac{1}{\pi} R \left( \eta_D \cdot F \cdot \frac{d\Omega}{4\pi} \right)^2
\]

- $R = 470kHz$
- $p = \eta_D \cdot F \cdot \frac{d\Omega}{4\pi} = (0.35)(0.14)(0.10)$
- $R_{ent} = 4.5 s^{-1}$

\[
\frac{\tau_E}{\tau_D} = 0.22 s / 1.12 s = 0.20
\]

Y. L. Lim, et al., PRL 95, 030505 (2005)
Kim, Maunz & Kim, PRA 84, 063423 (2011)

Fiber Coupling using High NA Optics


\[
R_{ent} = \frac{1}{2} p^2 = 4.5/\text{sec}
\]

\[
p = \eta_D F \frac{d\Omega}{4\pi} = 0.5\%
\]

\[
\Gamma = 600kHz \quad \text{trial rate}
\]

**Parameter** | Jun 15
---|---
\(\eta_D\) | 0.3
\(F\) | 0.2
\(R_{ent} \text{ (per sec)}\) | 4.5

After gross correction

Airy Radius 135\(\mu\)m (Diffraction Limit)
Waist in x: 176\(\mu\)m
Waist in y: 217\(\mu\)m

J. Wong-Campos et al., Nat. Phot. (2016)
Cavity Integrated Trap at Duke

- Small waist, modest length leads to good coupling while lowering requirements for the mirror coatings

\[
L_{\text{cavity}} = 300 \, \mu m \quad \text{g} = 60 \, \text{MHz} \\
Z_{\text{ion}} = 50 \mu m \quad \kappa = 160 \, \text{MHz} \\
W_{\text{ion}} = 4 \mu m \quad \gamma_{\text{Yb}} = 10 \, \text{MHz}
\]

- Alignment is critical, mirror needs to be positioned to better than 1mm in all directions
- \(\geq 70\%\) collection efficiency expected in a practical system
Fully Integrated Wavelength Conversion

- Two-step conversion to eliminate spontaneous parametric down-conversion (SPDC) and Stokes-Raman noise
- Fully integrated device to convert 650nm photon to 1595nm

Double-pass configuration w/ integrated U-bend & WDMs
Fully Integrated Wavelength Conversion

- Two-step conversion to eliminate spontaneous parametric down-conversion (SPDC) and Stokes-Raman noise
- Fully integrated device to convert 650nm photon to 1595nm

Both processes can be driven to near unity conversion
Both processes operate at identical pump wavelength and temperature
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“Inverted” MA-MDI-QKD (Jiang, Lütkenhaus)

- Entanglement-based QKD (Ekert ’92)

\[ |00\rangle_{14} + |11\rangle_{14} \]

\[ |00\rangle_{12} + |11\rangle_{12} \]

\[ |00\rangle_{34} + |11\rangle_{34} \]

\[ |++\rangle_{14} + |--\rangle_{14} \]

Output “00” or “11”

Output “00” or “11”

Output “++” or “--”
“Inverted” MA-MDI-QKD (Jiang, Lütkenhaus)

- Entanglement-based QKD (Ekert ’92)
- Extending the reach by Entanglement Swapping (teleportation)

• Initial photon from QM-photon entanglement measured right away!!
• QM-QM entanglement generation NOT required!!
Trapped Ion Implementation

- **Qubit Choice**
  - Photonic Qubit: polarization (easy analysis)
  - Atomic Qubit: Zeeman, converted to Clock-state

**Experimental Order**
1. Initialization (optical pumping)
2. Fast pump to excited state
3. Collect $\sigma$ polarization light
4. Photon polarization-Zeeman state entanglement
5. Analyze photon polarization
6. Map Zeeman qubits to clock-state qubits (Individual ions)
7. Analyze atomic states
Experimental Procedure

1.3 Trap topology
An SEM/schematic image of the HOA trap is shown in Figure 4. The device is broken out into 4 types of regions:
1. a "quantum" region which is useful for transverse gates because of the slot underneath the trap and the strong trapping potential;
2. a "transition" region which connects the slotted and unslotted parts of the trap;
3. a "junction" region which can be used for reordering ions in the quantum region;
4. and a "loading" region which has a loading hole for backside ion loading. Note that the slotted quantum region can also be used for loading if convenient.

Figure 4: SEM image of the HOA trap with overlaid electrode coloring to indicate the intended functionality of each section.

1.4 Integrated optics
One of the designed additions to the HOA 1.0 trap is an integrated optic. SNL designed a Diffractive Optical Element (DOE) which could image one end of the quantum region while retaining a high NA imaging capability at the other end. A bird's eye schematic of this is shown in Figure 5 and an image of the assembled system is shown in Figure 6. This is not a standard component of the HOA trap.

Ion-Photon Entangling Beams
Ion-Ion Entangling Beam
Qubit Measurement Beams
Quantum Memory Node
Bob
Z or X
Alice
Send to Bob
a and b
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Estimated Performance

Benchmarks

1. TGW bound
2. PLOB bound
3. ideal BB84 with single photons
4. single photon BB84 with realistic detectors
5. realistic decoy-state QKD
6. BB84 with memory as single-photon source.

A) per time unit
B) per channel use

Luong, Jiang, Kim, Lütkenhaus, Appl. Phys B 122, 96 (2016)
Realistic Experimental Parameters

- $\eta_p$ (preparation efficiency) = 0.66
- $T_p$ (preparation time) = 100 $\mu$s
- $\eta_c$ (coupling efficiency) = 0.04
- $T_2$ (dephasing time) = 1 s
- $c$ (speed of light in channel) = $2 \times 10^5$ km/s
- $L_{att}$ (attenuation length) = 22 km
- $e_{mA}$ (misalignment error) = $e_{mB} = 0.01$
- $p_d$ (dark count probability) = $10^{-8}$
- $\eta_d$ (detector efficiency) = 0.3
- $p_{BSM}$ (BSM success probability) = 1
- $\lambda_{BSM}$ (BSM noise parameter) = 0.97
- $f$ (error correction inefficiency) = 1.16

---

1. TGW bound
2. PLOB
3. ideal BB84 with single photons
4. single photon BB84 with realistic detectors
5. realistic decoy-state QKD
6. BB84 with memory as single-photon source.
Conclusions

• Trapped ion platform is a compelling candidate for realizing quantum repeaters
  – Good memory-photon interface
  – “Full blown” quantum computer with deterministic gate operations is available
  – Performance enhancement efforts are on the way

• Demonstration of “useful” quantum repeater remains a challenge, yet within reach!!
  – Overall system efficiencies need dramatic improvements
  – Necessary technologies are under development
  – System integration will require substantial effort
Team and Collaboration

• Duke Team
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  Muhammed Ahsan
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  Marko Cetina
  Jason Amini
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  Shantanu Debnath
  Kale Johnson
  David Wong-Campos
  David Hucul
  Volkan Inlek
  Aaron Lee

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  David Luong
  Ryo Namiki
  Filippo Miato

• Yale University
  Liang Jiang
  Sre Muralidharan
  Linshu Li

• Stanford University
  Martin Fejer
  Carsten Langrock
  Vahid Esfandyarpour

• Sandia National Labs
  Peter Maunz
  Christian Arrington
  Drew Hollowell

• NIST
  Sae Woo Nam
  Varun Verma

• JPL
  Matthew Shaw
  Francesco Marsili
  Emma Wollman