High-rate entanglement generation using real quantum memories

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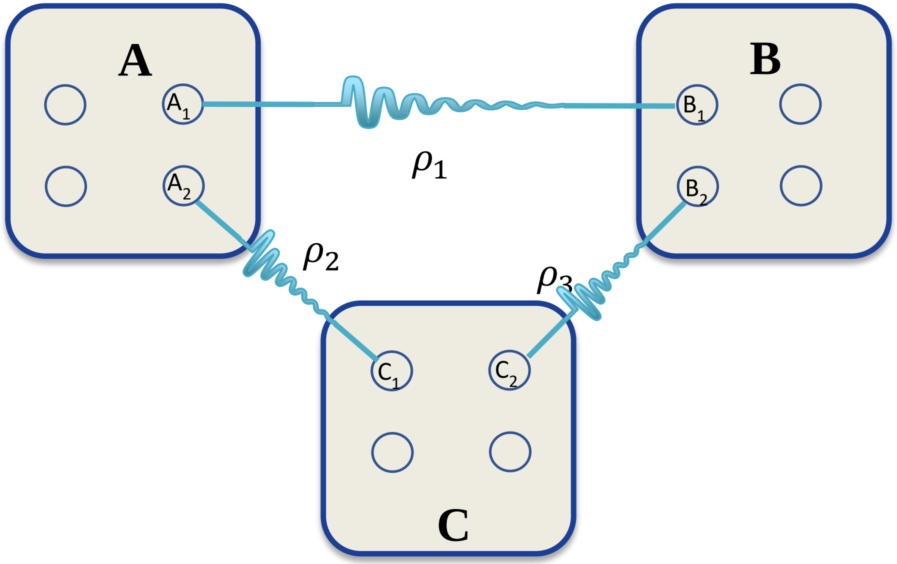
Army Science and Technology Symposium, August 23, 2018

Quantum network for the Physicist

Quantum Networks, Van Meter, Wiley 2014
Rev. Mod. Phys. 87, 1379, 2015

- Collection of quantum systems connected by quantum channels.
- Able to generate, store and manipulate entangled quantum particles.
- Provides distributed entanglement as a resource for information processing.
- Local Operations and Quantum Communications (LOQC) is possible.



A 3-node quantum network

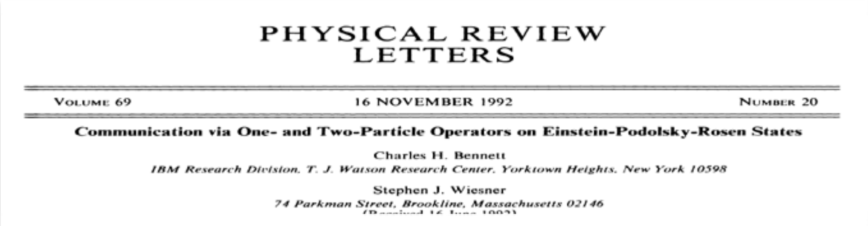
Quantum network for the Soldier

Motivation: Create unconditionally secure communications network *regardless* of an adversary's computing power, mathematical genius or cryptanalytic sophistication.

Approach: Use laws of physics to protect both data in transit and data at rest.

Applications

Communications: Superdense coding, Teleportation



PHYSICAL REVIEW LETTERS

VOLUME 69 | 16 NOVEMBER 1992 | NUMBER 20

Communication via One- and Two-Particle Operators on Einstein-Podolsky-Rosen States

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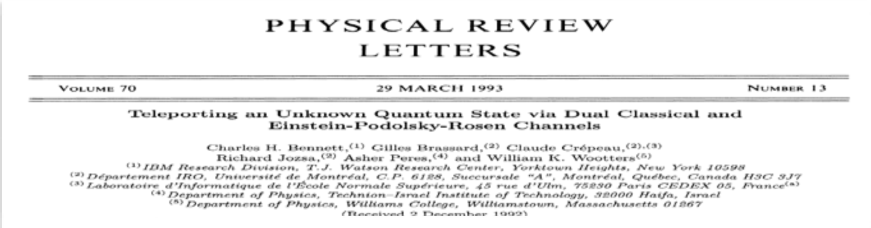

PHYSICAL REVIEW LETTERS

VOLUME 70 | 29 MARCH 1993 | NUMBER 13

Teleporting an Unknown Quantum State via Dual Classical and Einstein-Podolsky-Rosen Channels

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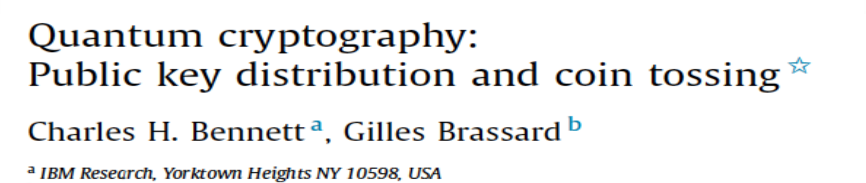
Cryptography: Key distribution, Secret sharing



Quantum cryptography: Public key distribution and coin tossing ☆

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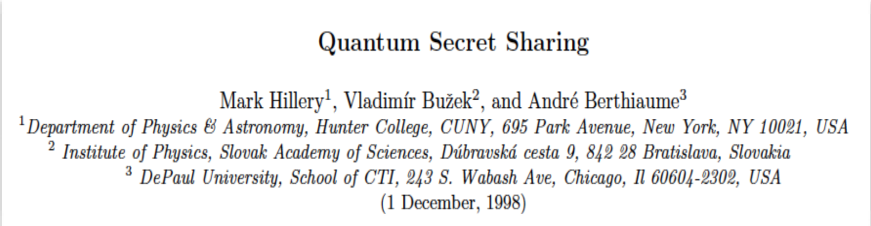

Quantum Secret Sharing

Mark Hillery[1], Vladimír Bužek[2], and André Berthiaume[3]
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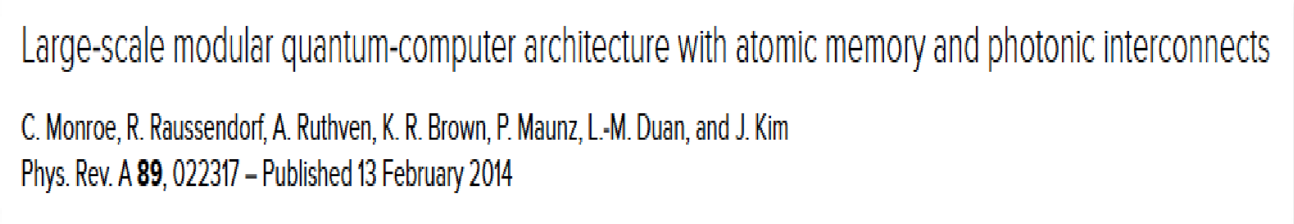
[3] *DePaul University, School of CTI, 243 S. Wabash Ave, Chicago, Il 60604-2302, USA*
(1 December, 1998)

Distributed quantum information processing: Interferometry, Sensing

A quantum network of clocks

P. Kómár, E. M. Kessler, M. Bishof, L. Jiang, A. S. Sørensen, J. Ye & M. D. Lukin

Nature Physics **10**, 582–587 (2014) | Download Citation ⤓



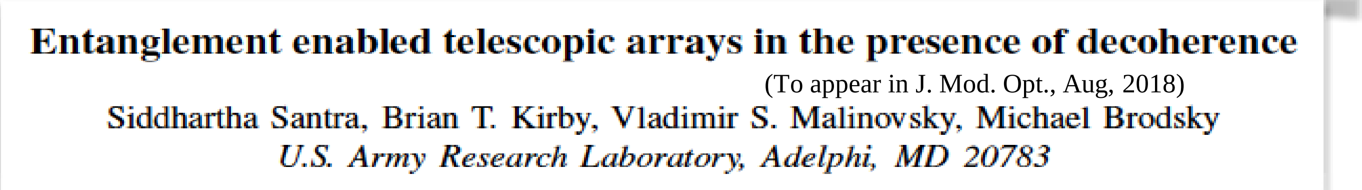
Large-scale modular quantum-computer architecture with atomic memory and photonic interconnects

C. Monroe, R. Raussendorf, A. Ruthven, K. R. Brown, P. Maunz, L.-M. Duan, and J. Kim
Phys. Rev. A **89**, 022317 – Published 13 February 2014

The quantum internet

H. J. Kimble

Nature **453**, 1023–1030 (19 June 2008) | Download Citation ⤓



Entanglement enabled telescopic arrays in the presence of decoherence

(To appear in J. Mod. Opt., Aug, 2018)

Siddhartha Santra, Brian T. Kirby, Vladimir S. Malinovsky, Michael Brodsky
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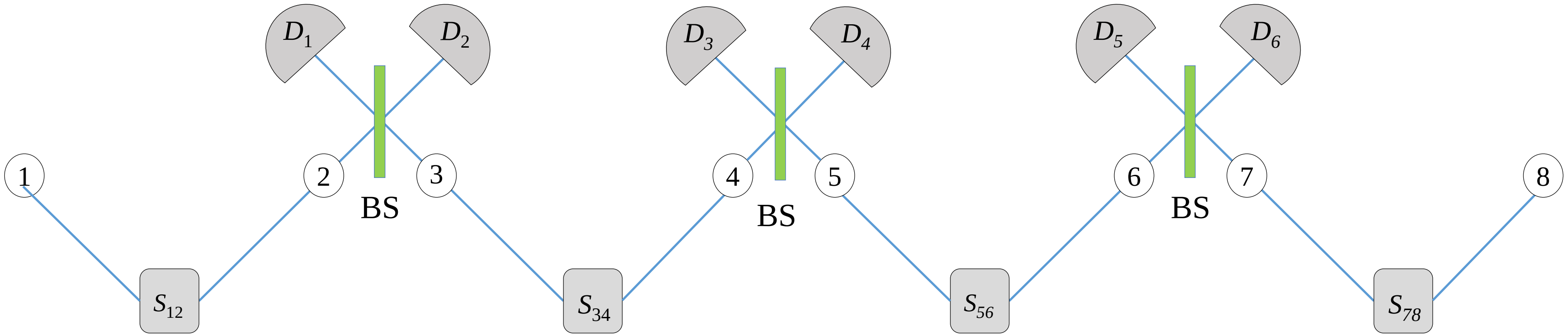
All Protocols limited by rate of entanglement distribution!!!

Divide and Conquer scheme for lab to field transition.

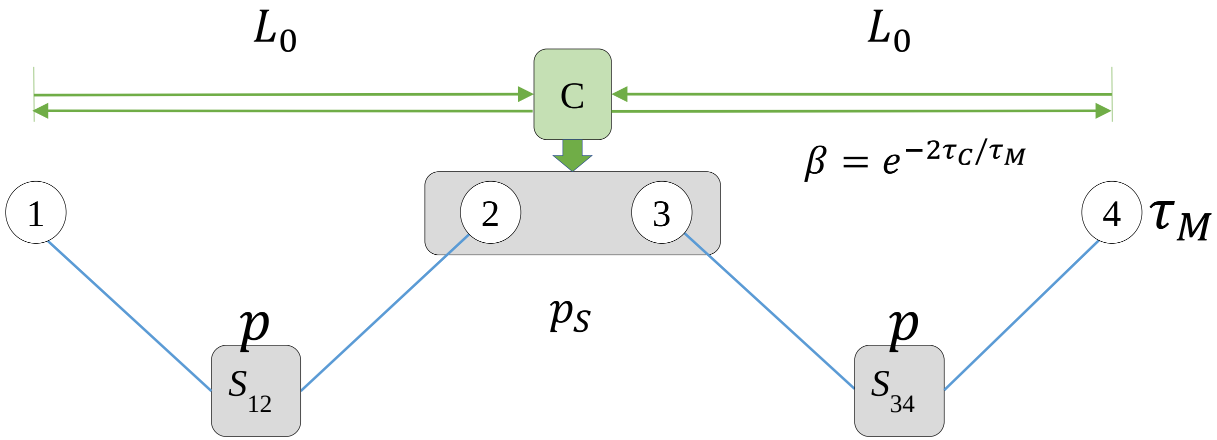
- Quantum signals cannot be amplified – No Cloning Theorem. *Nature 299, 802-803, 1982*
- Use a divide and conquer strategy to distribute quantum states. *Nature 414, 413-418, 2001*
- Distributed states are not perfect – Environment still decoheres.
- Use Swapping, Distillation, Error correction, *Optimization* to fight decoherence.



Schematic of the DLCZ scheme for entanglement distribution.

Access time of quantum memories

Entanglement swapping for arbitrarily degraded states - BK, SS, VM, MB, 2016
Quantum repeater architecture with hierarchically optimized access times - SS, LJ, VM, 2018



Memory Characteristics

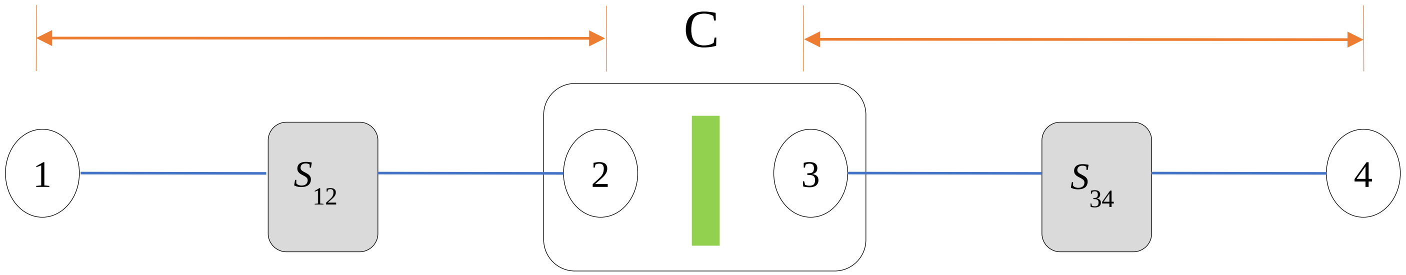
- Memory charging is probabilistic. Real memories decohere.
- **Access time**: Time spent by an entangled state in memories before being accessed/discarded.

Different Protocols

- **Optimized Access-time Protocol**: Control waits for a finite time after which memories are reset.
- **Canonical Protocol**: Control waits as long as it takes to charge both pairs.

How long should Quantum memories hold their charge before a refresh?

Rate of entanglement generation



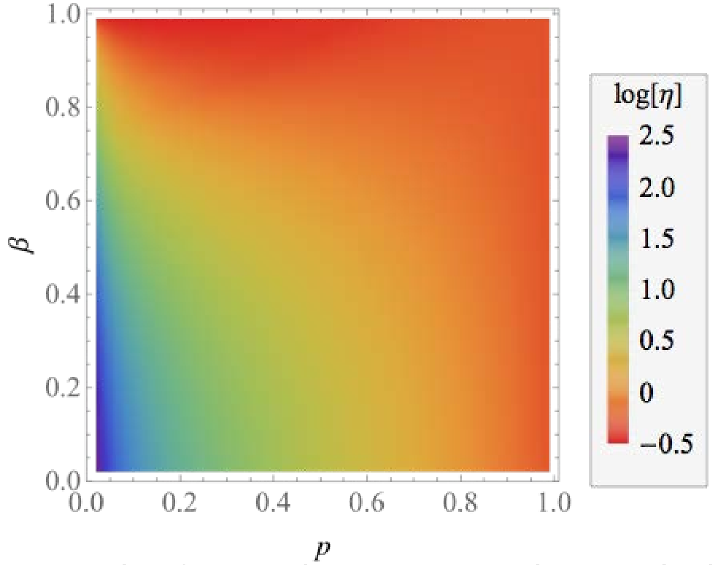
- Entangled states stored in a pair of quantum memories lose their phase coherence.
- Closer charged states yield better swapped states ((k_1, k_2) are charging steps for the pairs):

$$\rho^s(k_1,k_2) = \frac{1+\beta^{|\Delta k|+2}}{2}\rho^- + \frac{1-\beta^{|\Delta k|+2}}{2}\rho^+$$

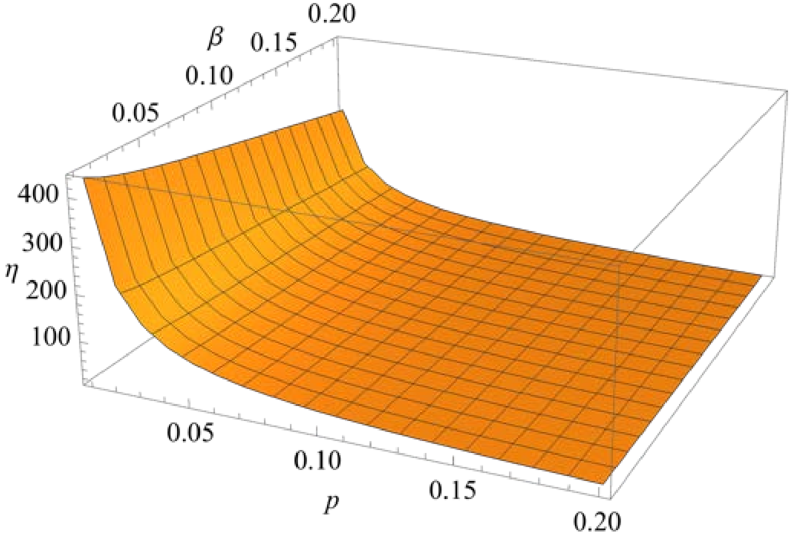
- Entanglement generation rate: R_{DE}^O = Rate of obtaining average state x Distillable entanglement of the state

$$R_{DE}^O = \frac{p_S[1-(1-p)^n]^2}{n(2\tau_C)} E[\rho^O(p,\beta,n)]$$

Optimized protocol yields manifold increase of entanglement generation rate



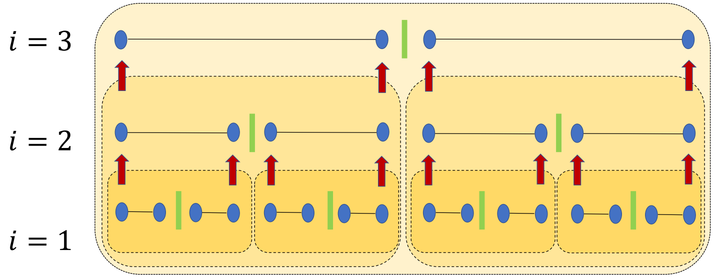
Ratio of entanglement generation rate in the optimized protocol to that in the canonical protocol

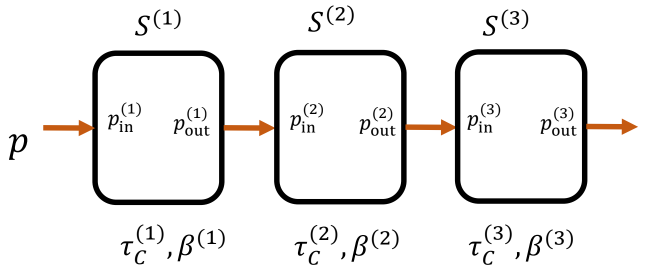


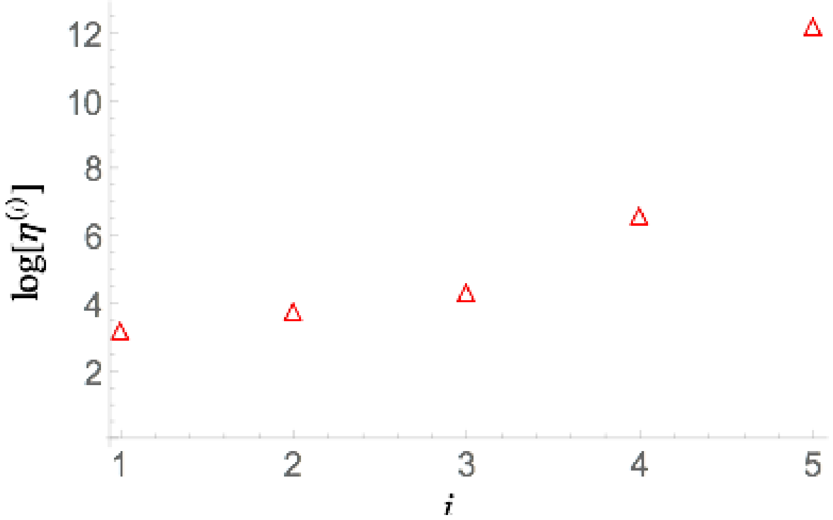
Ratio of rates scales as ($1/p$) for low (p, β) region.

- Optimal access time depends on location in parameter space: $n_{opt} \sim \frac{1}{p}\frac{\tau_M}{\tau_C}$

Optimization can be implemented hierarchically at every nesting level







Ratio of entanglement generation rates vs nesting level

- Nesting levels form self-similar systems.
- Each nesting level has own optimal access time: $n_{opt}^{(i)}(p^{(i)}, \beta^{(i)}, p_s) = ArgMax_{n^{(i)}}[R_{DE}^{O,(i)}(p^{(i)}, \beta^{(i)}, n^{(i)})]$

State of the art values for QR platforms

S. Muralidharan, PhD. Thesis, Yale 2017

	Ions	NV centers	Superconducting qubits	Atomic ensembles
Number of physical qubits/register	14	5	10	N/A
Coherence time	600 s	1 s (nuclear)	100 μs	1 ms
Gate time	10 – 100 μs	10 μs	300 ns	Linear optics gates
Gate error rate	10^{-3}	10^{-3}	6 x10^{-3}	N/A
Photon coupling efficiency	4%	15%	No demonstration	>85%
Wavelength conversion efficiency	9% (Yb)	No demonstration	10% (classical)	0.3% (including collection efficiency)
Spin-photon entanglement success probability	0.07	10^{-6}	No demonstration	3x10^{-4}

- OAP Advantage: $p = .01\%, \tau_M = 0.1\text{mS}, L_0 = 20\text{km}, \beta = 0.13, p_S = 0.5, p_T = 1 \implies \eta = 10^4$

Conclusions

- Optimizing access time mitigates decoherence allowing high-rate entanglement generation.
- Enables unconditionally secure communication, cryptography and distributed computation.
- Platform independent, universal optimization methods can bring us to the threshold of quantum enhanced information processing.

Thanks for your attention!