Rate-distance Tradeoff and Resource Costs for All-Optical Quantum Repeaters

arXiv:1603.01353

Mihir Pant\textsuperscript{1,2}, Hari Krovi\textsuperscript{2}, Dirk Englund\textsuperscript{1} and Saikat Guha\textsuperscript{2}

\textsuperscript{1}Massachusetts Institute of Technology

\textsuperscript{2}Raytheon BBN Technologies
The limit of repeaterless QKD

1.44 X 10^-20 bits/mode or 1 bit/2000y with 10^9 modes/s

Repeaterless bound
= -log₂(1-η) ≈ 1.44η = 1.44e⁻^αL

Pirandola, S., Laurenza, R., Ottaviani, C., & Banchi, L. Fundamental limits of repeaterless quantum communications. October 2015. arXiv preprint arXiv: 1510.08863.

Takeoka, M., Guha, S., & Wilde, M. M. (2014). Fundamental rate-loss tradeoff for optical quantum key distribution. Nature communications, 5.
Quantum Repeaters

\[ \text{Repeaterless} \approx 1.44 \eta = 1.44e^{-\alpha L} \]

With repeaters
\[ \sim \eta^s \sim e^{-s\alpha L}, \ s = 0.28 \]

Challenges with Quantum memories
- Coupling with photonics
- Dilution fridge
- Error Corrected Memories

Sinclair et. al., *Physical review letters*, 113(5), 053603 (2014).
Guha et. al., *Physical Review A*, 92(2), 022357 (2015).
All-Optical Repeaters

Simpler components
- Sources
- Detectors
- Beamsplitter
- Phase Shifters

But how practical is it?

Azuma, K., Tamaki, K., & Lo, H. K. (2015). All-photonic quantum repeaters. *Nature communications*, 6.

Varnava, M., Browne, D. E., & Rudolph, T. (2006). Loss tolerance in one-way quantum computation via counterfactual error correction. *Physical review letters*, 97(12), 120501.
Detailed analysis of the Scheme

Account for losses in all components

Optimize number of repeaters, number of communication channels

Smallest cluster that beats the repeaterless bound: **208 photons**

Number of repeater stations $N = \begin{cases} 300 \\ 50 \\ 100 \\ 200 \end{cases}$

BUT

$10^{11}$ photons required for cluster creation

200 parallel communication channels

Can this be made practical?

Pant, M., Krovi, H., Englund, D., & Guha, S. (2016). Rate-distance tradeoff and resource costs for all-optical quantum repeaters. arXiv preprint arXiv:1603.01353.
Improvements

- Store “memory” photons locally
- “Boosted” Bell measurement
  - Increasing success probability of Bell measurement to 75% using ancilla single photons*
- Better multiplexing
- Applying measurements in the beginning

Ewert, F., & van Loock, P., PRL, 113(14), 140403 (2014)
Improved performance

Pant, M., Krovi, H., Englund, D., & Guha, S. (2016). Rate-distance tradeoff and resource costs for all-optical quantum repeaters. arXiv preprint arXiv:1603.01353.

Repeaterless

Analytical Result: Optimum repeater spacing independent of total distance

| k  | size of state | # of single-photon-sources | # 3-GHZ state sources |
|----|---------------|----------------------------|-----------------------|
| 7  | 113           | 3 M                        | 15 k                  |
| 8  | 237           | 10 M                       | 50 k                  |
| 9  | 489           | 36 M                       | 180 k                 |
| 10 | 993           | 120 M                      | 600 k                 |
One way repeater based on Quantum Parity Code

\[ |\pm\rangle^{(n,m)} = \left( \frac{|0\rangle \otimes^m \pm |1\rangle \otimes^m}{\sqrt{2}} \right)^{\otimes n} \]

5 X 10^{-3} bits/mode @ 5000km

Bell measurement success probability = 1 - 1/2^n

Ewert, F., Bergmann, M., & van Loock, P. (2015). arXiv preprint arXiv: 1503.06777.

| (m,n) | size of state | # of single-photon-sources | # 3-GHZ state sources |
|-------|--------------|---------------------------|----------------------|
| (8,3) | 48           | 200k                      | 1k                   |
| (9,3) | 54           | 700k                      | 3.5k                 |
| (12,4)| 96           | 2M                        | 10k                  |
| (18,5)| 180          | 4.4M                      | 22k                  |

with Sreraman Muralidharan and Liang Jiang (in preparation)
Conclusion

• A 48 photon entangled state source can beat the repeaterless bound
  • Reduction from $10^{11}$ to $10^5$ single photon sources (1000 3 photon GHZ sources): lots of room for further improvement
    – Better error correction,
    – Efficient cluster creation
    – Fair comparison: error corrected quantum memory
• Similar ideas would also be useful for reducing resource costs in LOQC in general
  – Li, Benjamin: $10^{10}$ components/logical qubit
  – Repeaters: a nearer term target compared to full blown LOQC