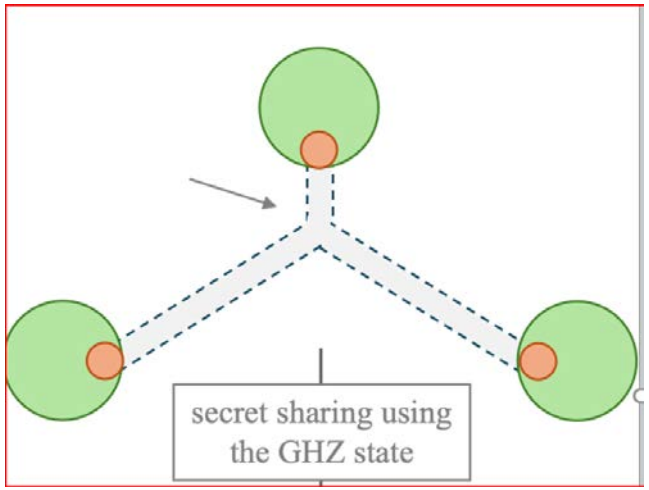
Asynchronous Routing for Multipartite Entanglement in Quantum Networks



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http://www.cse.wustl.edu/~jain/papers/maer_ccwc.htm

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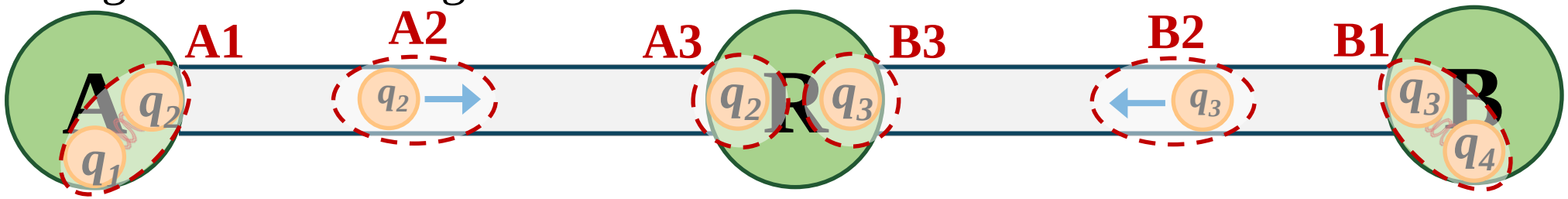
Overview

1. Problem Statement
2. Our MAER Method
3. Simulation Results
4. Conclusion

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Entanglement Swapping

- Entanglement for a long distance.



A1 / B1: Local Pair Generation:

- Node A generates an entangled photon pair (q_1, q_2)
- Simultaneously, Node B generates an entangled photon pair (q_3, q_4)

A2 / B2: Flying Qubit Transmission:

- Node A keeps q_1 and sends q_2 as a flying qubit toward the repeater.
- Node B keeps q_4 and sends q_3 as a flying qubit toward the repeater.

A3 / B3: Buffer and Storage:

- Repeater R receives and stores both q_2 and q_3 in quantum memory.
- At this point, A-R and B-R are entangled.

The Swapping Operation:

- Repeater R performs a Bell State Measurement (BSM) on the two qubits it currently holds.
- Following the BSM and classical signaling of results, q_1 and q_4 become instantaneously entangled:

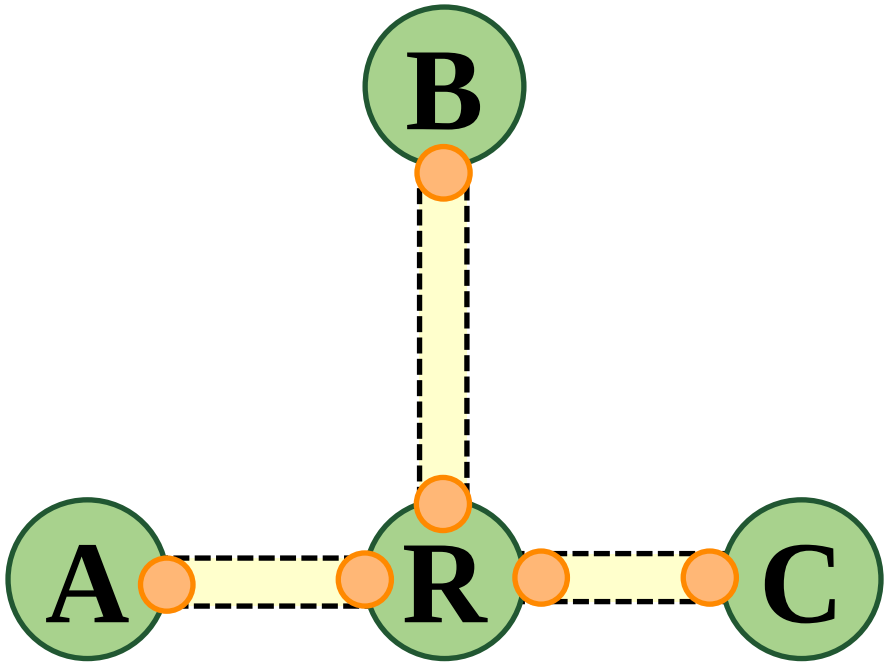


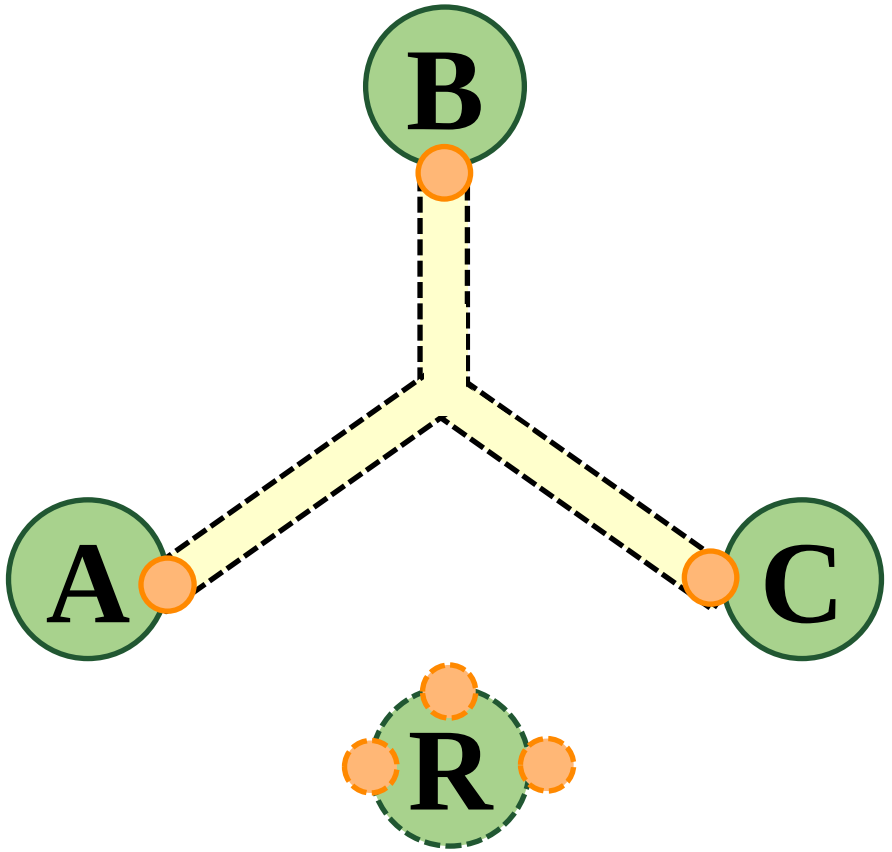
Nodes separated by multiple hops can exchange secrets using entanglement swapping

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Multipartite States Implementation

- Introduced by Greenberger, Horne, Zeilinger (GHZ) for 3 or more qubits





- Allows **quantum multicasting**

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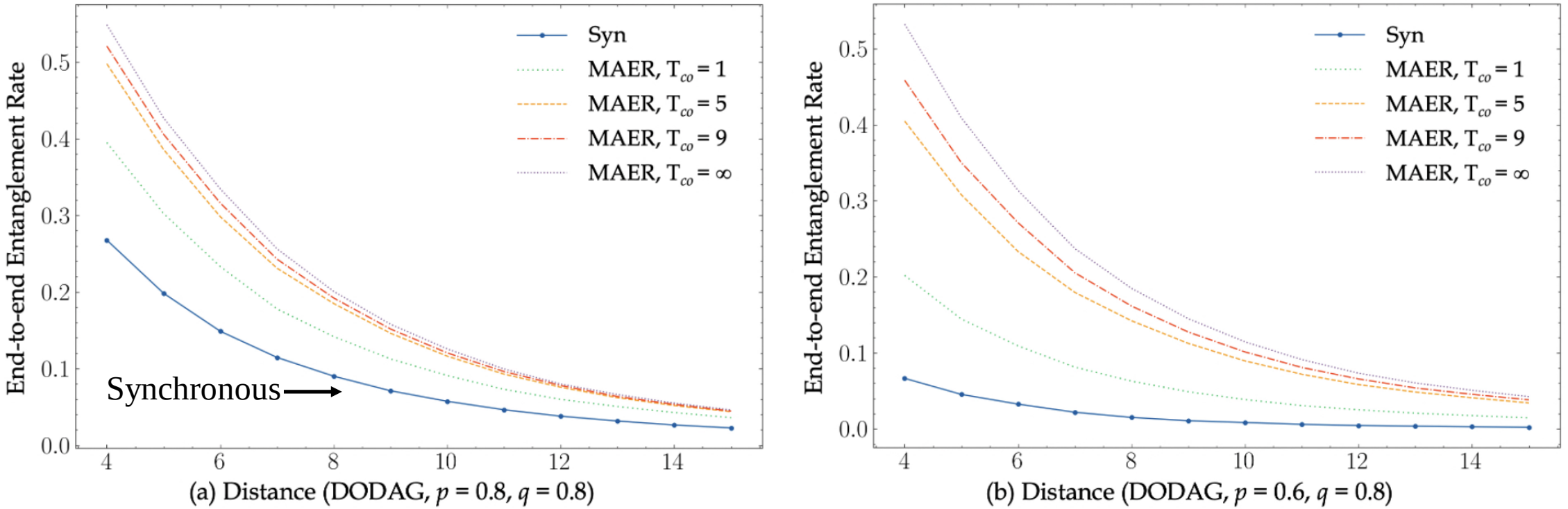
Problem Statement: Synchronous vs. Asynchronous

- Most other quantum routing uses synchronous protocols. Time is divided into slots. Entanglement is generated in one slot and swapped in another.
- **Limitations:**
  1. Global clock synchronization is difficult.
  2. The time slot has to be less than the coherence time after which the qubits lose fidelity.
  3. Static slotting creates performance bottleneck as it cannot exploit hardware advancements in coherence time.
- **Proposed Solution:**
  1. Asynchronous Entanglement Routing (AER) for two-party communication
  2. Multipartite Asynchronous Entanglement Routing (MAER) for multi-party

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MAER Performance as a Function of Distance (Hops)

- Multi-Party AER achieves higher end-to-end entanglement rates, particularly when the coherence time exceeds 1 time unit, and increases steadily with longer coherence times.

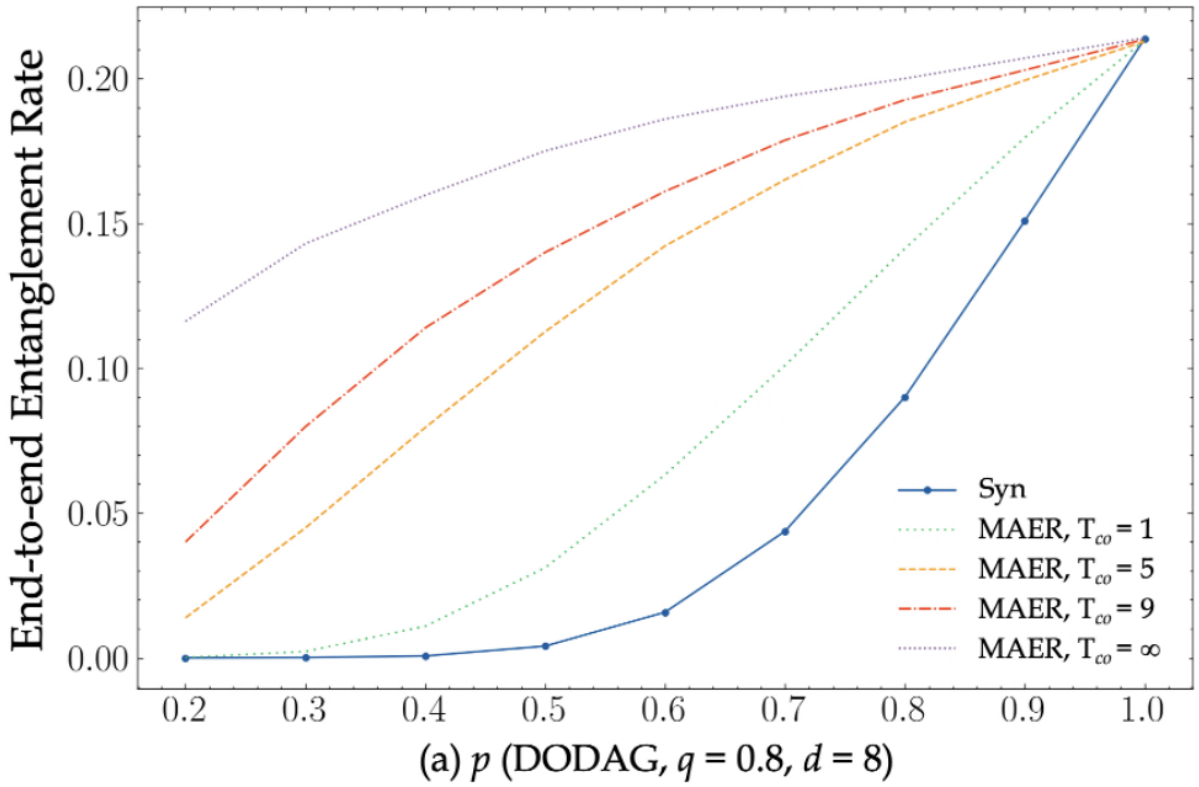


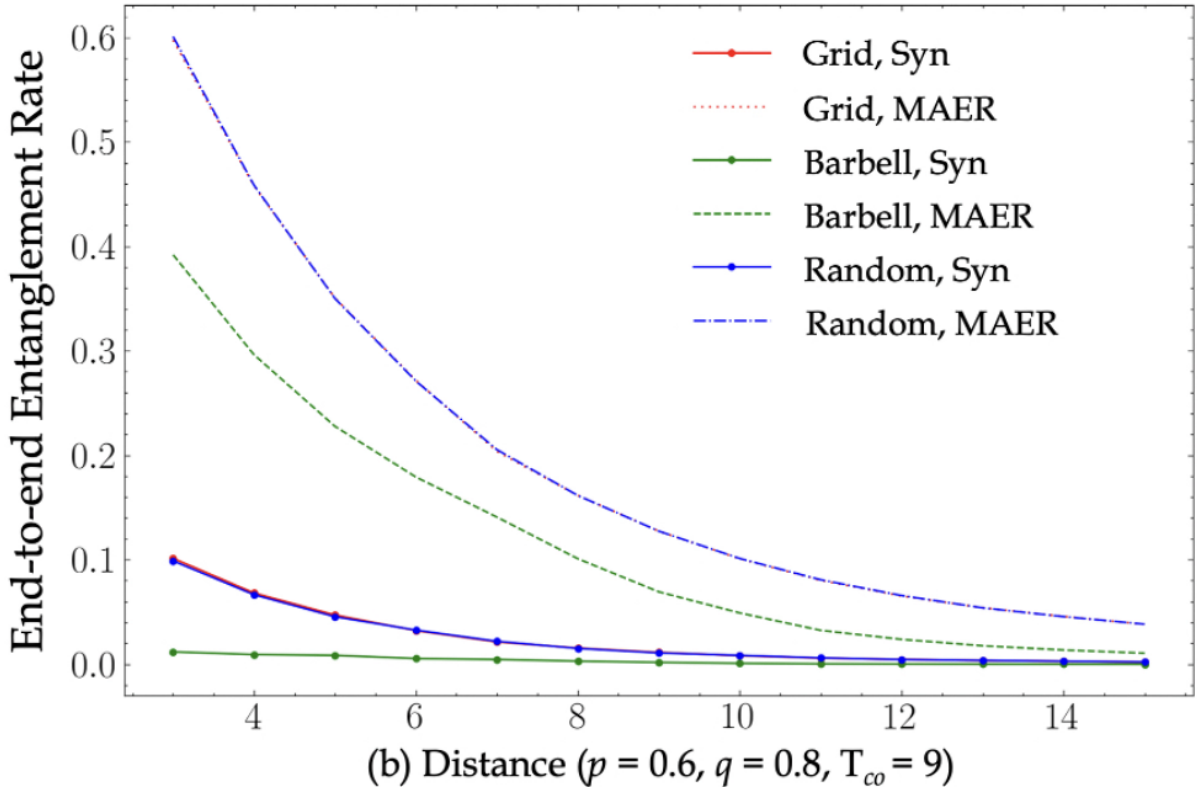
p = probability of successful entanglement, q = probability of successful swap, T_{co} = coherence time

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Performance for Varying Success Probabilities and Topologies

- MAER consistently outperforms synchronous methods across all tested parameter combinations and topologies



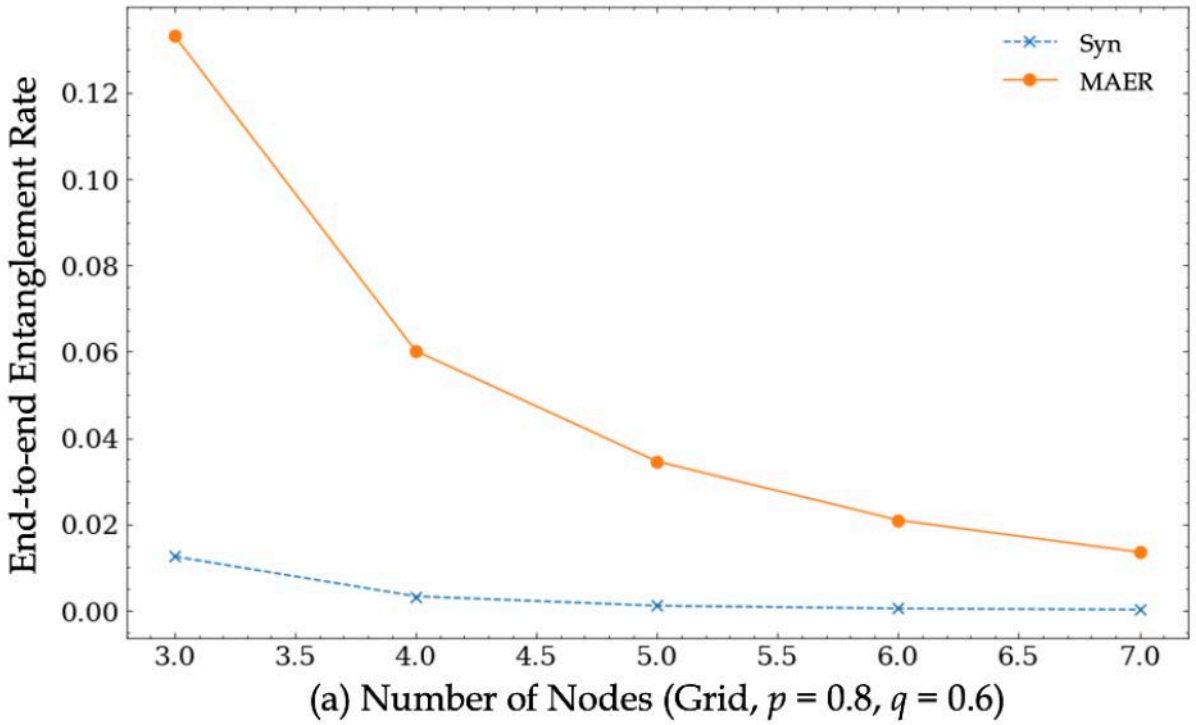


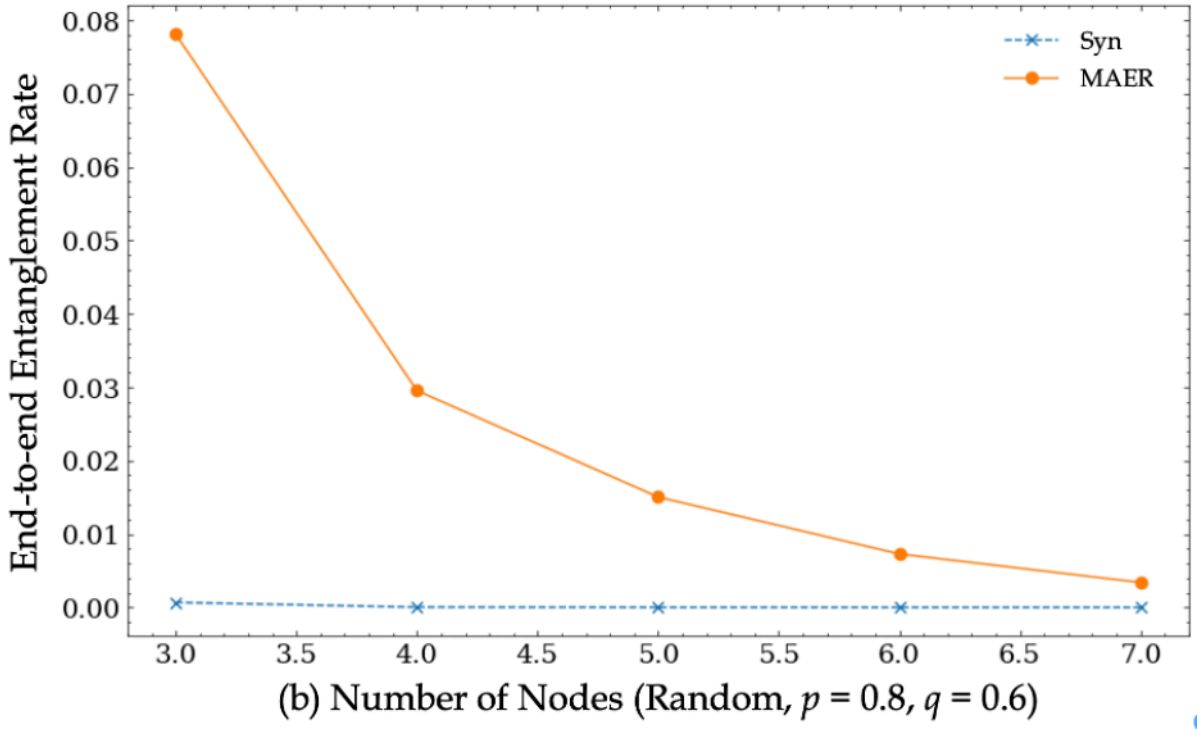
p = probability of successful entanglement, q = probability of successful swap,
d = hop distance between requesting nodes, T_{co} = coherence time

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Performance as a Function of Network Size

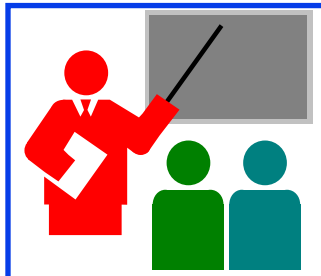
- MAER demonstrates its effectiveness in handling multipartite entanglement requests of varying sizes.





p = probability of successful entanglement, q = probability of successful swap

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Summary

1. Multipartite GHZ states can be used for multicasting in quantum networks.
2. Our paper presents a method of finding routes for multicasting applications, such as quantum multicast key distribution.
3. Our Multi-party Asynchronous Entanglement Routing (MAER) eliminates the need for global synchronization used in other synchronous methods.
4. We showed that the method achieves better performance as a function of entanglement probabilities, swap probabilities, and hop distance for various topologies.
5. Performance will improve as coherence time increases with advances in quantum technologies.

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Our Publications on Quantum

- Zebo Yang, Ali Ghubaish, Raj Jain, Ala Al-Fuquha, Aiman Erbad, Ramana Compella, Hassan Shapourian, Reza Nejabati, "Layer-Wise Security Framework and Analysis for the Quantum Internet," IEEE Selected Areas in Communications, Vol. 43, Issue 8, pp. 2825-2840, Aug. 2025, http://www.cse.wustl.edu/~jain/papers/quint.htm
- Zebo Yang, Ali Ghubaish, Raj Jain, Ramana Kompella, and Hassan Shapourian, "Multi-Tree Quantum Routing in Realistic Topologies," IEEE Communications Magazine, Vol. 62, No. 10, October 2024, pp. 78-85, http://www.cse.wustl.edu/~jain/papers/multitree.htm
- Zebo Yang, Ali Ghubaish, Raj Jain, and H. Shapourian, "Asynchronous Entanglement Routing for the Quantum Internet," AVS Quantum Sci. 6, 013801, Jan 2024, http://www.cse.wustl.edu/~jain/papers/qrout.htm
- Zebo Yang, Haneen Alfauri, Behrooz Farkiani, Raj Jain, Roberto DiPietro, and Aiman Erbad, "A Survey and Comparison of Post-quantum and Quantum Blockchains," IEEE Communications Surveys & Tutorials, 2nd Quarter 2024, Vol. 26, Issue 2, http://www.cse.wustl.edu/~jain/papers/qbpqb.htm
- Zebo Yang, Maede Zolanvari, Raj Jain, "A Survey of Important Issues in Quantum Computing and Communications," IEEE Communications Surveys and Tutorials, March 2023, http://www.cse.wustl.edu/~jain/papers/qsurvey.htm

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Our Publications on Quantum (Cont)

- Zebo Yang, Tara Salman, Raj Jain, and Roberto Di Pietro, "Decentralization using Quantum Blockchain: A Theoretical Analysis," IEEE Transactions on Quantum Engineering, September 2022, 16 pp., http://www.cse.wustl.edu/~jain/qbif.htm
- Zebo Yang, "Scaling Quantum Systems: Quantum Networks, Distributed Quantum Computing, and Security," Ph.D. Thesis, Washington University, May 2025, http://www.cse.wustl.edu/~jain/theses/zebophd.htm

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