# Large-Scale Simulation of the Quantum Internet

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The Quantum Internet (QI) will be a worldwide network of quantum repeater networks [1, 2], enabling quantum information services including entanglement-based cryptographic functions such as quantum key distribution [3], secure distributed quantum computation [4], and high-precision sensors [5]. The individual networks composing the Quantum Internet likely will be of disparate physical and logical technologies, operated by different organizations, and deployed over a decade or more. We are developing a large-scale simulator to study the expected behavior and quantitatively evaluate solutions to the numerous design problems.

In order to have a complete, functional network, quantum links must be developed, and methods for building end-to-end entanglement over top of a path of such links. Building a complete Internet on such technologies requires solving many additional problems, including: interoperability between disparate network types [6]; hardware requirements for repeaters; routing within and between networks [7]; how the classical control systems agree on states to be created [8]; security of QI operations [9]; behavior of applications on the QI [10]; resource management [11, 12]; and formal methods for guaranteeing correctness of operation [13]. We must also design and test the classical protocols that support each of these operations.

Simulation of a network of networks provides a concrete platform for testing design decisions. With a correctly established architecture, individual elements of the design can be replaced and quantitative evaluation of the impact conducted. A simulation can be a time machine, allowing us to peer into the future and make design decisions now that will minimize the likelihood of catastrophic problems in the future. A simulator allows us to test behavior at larger scales than can be deployed at a given point in time. It also allows us to peer inside the nodes and networks in a fashion that is hard even once running hardware is deployed.

Design and simulation of the Quantum Internet not only depends upon link hardware and path connection strategies, it feeds back into those designs by helping to determine required link-level entanglement creation rates, local gate operation fidelity, buffer memory capacities and lifetimes, link distances, choice of link architecture, and router (repeater) node degree (number of wide-area connections supported).

Our simulator is currently under construction. The most important result to date from our simulations is increased confidence that a true Quantum Internet interconnecting disparate technologies is *possible*. We have simulated a mechanism for building Bell pairs consisting of logical qubits, with the two qubits encoded in separate error correction codes [6]. Our simulation supports Jiang-style connections based on CSS codes [14] and Fowler-style connections based on the surface code [15], as well as purification and swapping of physical Bell pairs [16]. We have found that it is possible to interconnect them with high fidelity with an overhead cost similar to that of homogeneous networks. Without this assurance, the stakes in selecting a single quantum network technology would be very high, as the cost of transitioning to a newer technology would be significant and each network could potentially be required to upgrade at the same time.

We expect our simulation platform to continue answering questions for a long time to come. One such question is whether connectivity is always transitive in the Quantum Internet: if A can connect to B, and B can connect to C, is it always true that A can connect to C? Such a question depends on the semantics demanded of the quantum network, and the fidelity and entanglement rate achievable.

We are developing a framework for application patterns that will allow applications to choose when qubit measurement occurs and whether to wait for arrival of any Pauli frame corrections that occur as a result of measurements for entanglement swapping or at the opposite end of a connection. We are also examining models of traffic on large-scale networks that will allow us to create artificial traffic patterns for our simulated network.

Our engineering methodology is to apply solutions developed in the Internet community where possible. Cryptographic applications (QKD, quantum Byzantine agreement, etc.) will certainly be integrated into existing classical applications on the Internet. Distributed quantum computation (e.g., blind computation) will initially follow an ARPANET-like service model, with a few quantum mainframe or supercomputing centers being accessed remotely from less powerful local quantum computers. The organizational pressures driving deployment therefore will be similar to those on the Internet during the course of its evolution.

Our ultimate goal is simulation of ten thousand quantum repeater nodes, organized into one hundred networks each comprising about hundred nodes. At this scale, we expect to be able to study the macroscopic behavior of a Quantum Internet and potentially see and examine emergent behavior that otherwise would not occur until networks are deployed. Thus, our simulations will advance the overall design process and shorten the design-test-deploy-monitor cycle of technology development.

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