On Topology Design for the Quantum Internet

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Abstract

Imagine a Quantum Internet where people can freely establish physically secure communication channels or migrate quantum programs between anywhere in the world. What would it look like? Despite the very exciting recent advances around building prototypes of quantum networks, little is known about how lab-scale prototypes can be expanded into a global infrastructure that is as capacitated, robust, and cost-efficient as the digital Internet right now. Part of the difficulty lies in our lack of understanding of how the structure of a quantum network affects its capacity and performance when serving multi-commodity quantum communication demands. This article studies the problem of designing high-performance network topologies for the quantum Internet. Utilizing abstract models of the basic quantum network operations and an optimal entanglement distribution protocol, we characterize the capacity and performance of various candidate topologies for the quantum Internet, in terms of the rate of entanglement distribution between source-destination pairs and the fidelity of entangled pairs, respectively. We discuss the implications of our preliminary results, and propose directions for further investigation. As the feasibility of large-scale quantum network deployment continues to increase, we hope this article can draw attention to these macroscopic design problems, such as topology design, which potentially have a profound influence on how the entire technology evolves, just as we have observed with the digital Internet in the past decades.

Introduction

The concept of the Quantum Internet emerged from marrying the Internet, the protagonist of our first information revolution, with quantum computing, one of the much anticipated principal characters in our next. The ability to transmit quantum information between any points on earth will enable applications that are provably non-viable with classical technologies, such as physically secure communication, quantum state teleportation, and distributed quantum computing. Recent advances in quantum hardware, protocols and system design have brought the very first quantum networks into life, shedding light on possible large-scale deployment not too distant in the future.

The networking community has recently picked up interest in quantum networking, owing to the seeming realizability of the technology and better understanding of the abstract models of quantum networks. A quantum network differs from a classical network in terms of the underlying mechanics. A classical network such as the Internet transmits *copies* of classical information, formatted as bit streams, hop-by-hop along transmission paths between end devices. In quantum physics, the no-cloning theorem prevents quantum information from being copied, thus invalidating store-and-forward information delivery as in classical networks. Nevertheless, a quantum network can pre-establish carriers of quantum information, in the form of *entangled quantum pairs*, which can be utilized to transmit quantum information without copying and directly from end to end. These carriers can be established over multi-hop paths with the help of intermediate quantum repeaters. Such a capability is analogous to circuit switching in classical networks, where physical or virtual circuits are pre-established through intermediaries before end-to-end communication can start. The fundamental difference is that an entangled pair is a *one-time* resource: it is established momentarily, and is consumed right away when transmitting one unit of quantum information; a switching circuit on the other hand can last for an extended period of time and support continuous communications during its lifetime. Despite these differences, however, a quantum network share similar upper-level functionalities such as routing and scheduling as a classical network, motivating knowledge transfer from decades of Internet research into this new realm.

As with any transformative technology, early research primarily focused on proof-of-concepts and small-scale testbeds. The repeater chain topology, for instance, has been dominantly used to demonstrate feasibility of long-range multi-hop entanglement establishment. In general, existing literature largely focused on regular or small-scale network topologies, while neglecting many real-world constraints such as costs and node locations which could impact the quantum network topology and hence performance. With neither real-world realization nor abstract evaluation of quantum network topologies, it comes the risk that current studies of quantum networking protocols may be superficial, and would not apply to or perform well in real quantum networks when they come in drastically different shapes than what has been presumed till now.

This article does not attempt to address the aforementioned problem, but would instead raise it and emphasize its importance with preliminary

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results. We specifically target a *multi-commodity* quantum network, since the Quantum Internet is meant to serve a broad range of quantum applications and end points distributed across the globe. With an introductory illustration of the basics, concept and components of the Quantum Internet, we evaluate and show the results of a number of topology choices for the Quantum Internet. We design multi-commodity metrics for evaluating both the *volume* and *quality* of entanglement distribution in a given quantum network. These metrics are computed by an existing optimal entanglement distribution protocol, coupled with heuristic entanglement path decomposition. Our results have suggested tendency toward certain categories of topologies over others for building the Quantum Internet or evaluating quantum networking protocols. We also point out limitations of our approach and discuss future research directions. To enable systematic research on quantum network design, many prerequisite problems remain open, including characterization of the EDR-fidelity trade-off of a quantum network, optimal purification design, and optimal network augmentation. We hope this article will raise attention and motivate future research along the line.

Quantum Communication Basics

Let us first review some basics behind quantum networking. A quantum bit (*qubit*) is the quantum analog to a classical bit. Whereas a classical bit can only be in one of the two (classical) basis states 0 and 1 at a time, a qubit can be in the superposition of the two quantum basis states, $|0\rangle$ and $|1\rangle$. Here a *ket* denoted by $|\cdot\rangle$ represents a quantum state written as a column vector. The two basis states $|0\rangle$ and $|1\rangle$ are orthogonal, and commonly written as $|0\rangle = (1, 0)'$ and $|1\rangle = (0, 1)'$ respectively. A qubit in a general state is written as $|q\rangle = (\alpha, \beta)' = \alpha|0\rangle + \beta|1\rangle$, with the constraint that $\alpha^2 + \beta^2 = 1$. Upon a perfect measurement in the Pauli Z basis for instance, a qubit collapses and is projected into the basis state $|0\rangle$ (corresponding to classical bit 0) with probability α^2 and $|1\rangle$ (corresponding to classical bit 1) with probability β^2. A measurement thus can map a qubit into a classical bit with probabilities defined by the parameters α and β.

Quantum communications are based on the principle of *quantum entanglement*. An entanglement is a quantum system with two or more qubits as a whole, such that measurements on both/all qubits reveal correlated results. For instance, consider the state of

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle),$$

which is a maximally entangled 2-qubit state (also called Bell state or EPR pair). A measurement on one of the qubits can yield a random result between $|0\rangle$ and $|1\rangle$, each with 1/2 probability. However, after the first measurement, a second measurement on the other qubit must always yield the same result as the first one. This is because the state $|\Phi^+\rangle$ is a superposition of only two of the four 2-qubit basis states, $|00\rangle$ and $|11\rangle$, and does not contain the other two basis states $|01\rangle$ and $|10\rangle$.

The principle of quantum entanglement holds regardless of physical locations of the entangled qubits. Hence, if two remote parties Alice and Bob each holds one qubit of an entangled pair, they can communicate quantum information instantly and securely. This forms the basis of many quantum applications, such as quantum key distribution (QKD), remote teleportation and superdense coding. QKD is a specifically promising application, which enables truly secure and unbreakable key exchange that is not possible with classical cryptographic systems. In this work, we focus on unicast quantum communications via 2-qubit Bell pairs. Quantum multicast or broadcast can be realized with M-partite ($M > 2$) Greenberger-Horne-Zeilinger (GHZ) states [1], which we leave to our future studies.

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Quantum Internet and Entanglement Distribution

Just like the Internet provides the playground for all networked applications, the Quantum Internet is to support all applications that require communication of quantum information. With networked quantum repeaters, it can serve remote applications such as QKD and distributed quantum computing that span across significantly larger geographical areas than what can be covered by single-hop or small-scale quantum networks. Its core functionality is to distributed entanglements between sources and destinations.

Quantum Internet Components

Physical components of the Quantum Internet include quantum nodes, quantum links, and classical links. A quantum node is a quantum computer that is capable of generating and/or maintaining entanglements. While nodes can have varying functionality and capability, each node hosts at least two types of basic devices: quantum memories for storing entangled qubits, and quantum measurement circuits for performing networking functionalities and quality evaluation.

Both quantum and classical links are needed to interconnect quantum nodes. Both links can be wired or wireless, and can be implemented differently between different pairs of nodes. For quantum links, promising candidates include short-range optical fiber or satellite relays [2]. Importantly, the quantum and classical links do not need to conform to the same topology, though it is sometimes beneficial for them to reuse the physical medium such as existing optical fiber to reduce deployment cost. More generally, design of the Quantum Internet is largely informed by the classical communication infrastructure that it relies on. For instance, timely establishment of entanglements requires predictable and low-latency classical communications for both control and data plane information exchange.

In addition to the physical components, several logical components have been introduced. A *quantum network stack* represents a set of classical and quantum programs that are designed to

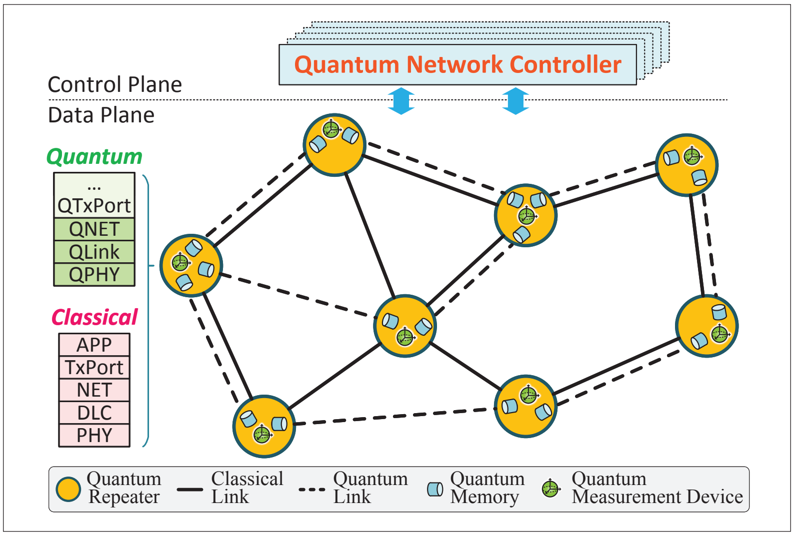

FIGURE 1. Quantum Internet physical and logical components.

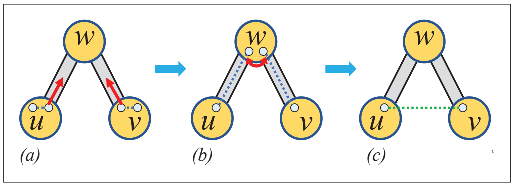

FIGURE 2. Basic quantum network operations: a) Entanglement generation; b) Entanglement swapping; c) Entanglement established.

provide entanglement distribution and/or quantum communication functionalities to upper-level applications. Although no standard layering exists, most researchers have identified the physical-, link- and network-layer functionalities in a quantum network stack, similar to their counterparts in classical networks [2]. Some have also looked into transport-layer design such as flow and congestion control [3]. Among these, network-layer design, such as entanglement routing or distribution, is one of the key focuses due to its significant impact on performance (e.g., throughput and quality of entanglement distribution) of quantum networks. A quantum network can be distributed, where quantum repeaters self-coordinate to make networking decisions; or centralized, in which case a central *quantum network controller* oversees the operation of the quantum network. The controller runs classical algorithms to manage the whole or a portion of the Quantum Internet, and coordinates with distributed quantum nodes through classical communications. It spans from the much successful software-defined networking (SDN) paradigm in classical networks, and is rather necessary given the complexity of designing quantum network protocols due to coordination between quantum and classical components.

Figure 1 illustrates the different components and their relations in the Quantum Internet.

Entanglement Distribution

Several primitive operations are at the core of entanglement distribution in the Quantum Internet.

Single-Hop Entanglement Distribution: Consider a pair of nodes who would like to communicate quantumly. In the simplest case, if there is a direct quantum link between the two nodes, then one can generate multiple entanglements, keep one qubit in each entangled pair, and send the other qubit to the remote party via the quantum link. The two nodes can then use these entanglements to communicate any time later.

This simple process is however non-trivial in practice. First, entangled qubits may decohere soon after generation, affecting how long they can be used for communication. Second, noise can lead to both generation failures, and low-quality entanglements being distributed that could lead to communication error. As these deficits pertain to the underlying quantum mechanics, they have been modeled as intrinsic properties of the quantum nodes and links. For instance, *decoherence time* describes how long a qubit stored at a node can stay coherent, and is expected to increase with advances in quantum hardware though still being limited in near future; *success probability* describes the probability that an entanglement is successfully generated and distributed along a physical link; *fidelity* describes the probability that an entanglement is in the desired entangled state versus some other random state. These properties depend on the type, implementation and environment of the quantum operations involved, including the physical distance of a link. In practice, one can use a single-photon detector to receive laser beams consisting of millions of photons to measure the success probability and fidelity.

Multi-Hop (Remote) Entanglement Distribution: Now consider nodes that do not share a quantum link. Entanglements may still be established between them via entanglement swapping. Assume the two nodes are both connected to an intermediary node. Two entanglements can first be distributed along the links between both nodes and the intermediary respectively. Then, the intermediary performs a swapping operation on the two local qubits, consuming them and yet entangling the two remote qubits owned by the other nodes, as shown in Fig. 2. The most popular method for entanglement swapping involves the intermediary performing Bell state measurements (BSMs) on the two local qubits, and then reporting the results to the two remote nodes via classical communications. Depending on the measurement results, the two remote qubits are then in one of the four Bell states and thus entangled despite never interacting with each other. Generally, this process can be performed by all nodes along an *entanglement path* to establish an end-to-end entanglement between two remote nodes.

Entanglement swapping is also subject to noise during measurements. Thus swapping may lower both the success probability and the fidelity of entanglement establishment. Both values decrease exponentially with the length of an entanglement path.

Entanglement Purification: Entanglement purification tackles the exponentially degrading fidelity of entanglements generated along long paths. Bennett *et al.* [4] presented the first purification protocol which, by *consuming* two entanglements both with fidelity of more than 1/2, can produce an entanglement with a higher fidelity than both consumed entanglements. This process can be applied recursively on multiple entanglements,

Topology model	Parameters and default values	Naming in figures	Notes
Waxman	$\alpha = 0.2$, $\beta = 0.8$	waxman_α_β	Distance-aware; generate links probabilistically based on distances
Threshold	max distance d = 1500 km	threshold_d	Distance-aware; generate all links with distance bounded by d
Delaunay graph	n/a	delauney	Location/distance-aware; the dual graph of Voronoi cells of all nodes
Repeater chain (RC) tree	n/a	rc_tree	Distance-aware; min-distance spanning tree on the complete graph with all nodes
Ring lattice	number of neighbors $k = 4$	ring_lattice_k	Distance-aware; ring formed by approximate Traveling Salesman on complete graph
Erdős-Rényi graph	probability $p = 0.2$	erdos_renyi_p	Distance-agnostic; randomly connect each node pair with probability p
Barabasi-Albert scale-free graph	number of neighbors $k = 4$	barabasi_albert_k	Distance-agnostic; new node connects to existing ones with probability \propto degrees

TABLE 1. List of evaluated topologies with default generation parameters.

until the generated entanglement reaches a pre-defined fidelity threshold. The cost is a much reduced number of entanglements between end nodes. The fidelity improvement versus the number of consumed entanglements differs by the purification protocol and the error model adopted, while being ultimately governed by the law of physics as specified by the von Neumann entropy. Further, purification may also reduce the fidelity of the generated entanglement if one of the source entanglements has fidelity lower than 1/2 [4]. In practice, this requirement is even higher due to noise in the purification process itself.

Recent research has focused on designing entanglement distribution protocols (with or without purification) due to their significant impact on the Quantum Internet performance. Nevertheless, just like how the Internet structure has fundamentally impacted the design of Internet protocols (IP, TCP, BGP/OSPF, etc.), we believe the structure of the Quantum Internet will also profoundly impact quantum network protocol design, perhaps even more than in the Internet due to the exponentially degrading success probability and fidelity with increasing path lengths and/or physical distances of links. In light of this, the next sections outline our initial study of topology design for the Quantum Internet.

Comparative Study of Quantum Internet Topologies

The primary goal of the Quantum Internet is to *deliver long-lasting, high-fidelity entanglements between source-destination pairs with high throughput*. Recent advance in quantum memories has demonstrated storage of entangled qubits for as long as one hour [5], which is well enough for most quantum applications. We thus focus on two primary metrics for evaluating Quantum Internet topologies:

Entanglement Distribution Rate (EDR): EDR measures the rate of entanglement distribution between any pair of source and destination. We use the average EDR (AEDR) between an arbitrary selection of source-destination pairs as one metric.

End-to-End Fidelity: End-to-end fidelity measures the fidelity of entanglements generated between a source-destination pair, following a specific entanglement distribution scheme. We use the average end-to-end fidelity (AFDL) between an arbitrary selection of source-destination pairs as one metric.

For sake of topology evaluation, metrics should generally be defined independently of specific entanglement distribution schemes. However, there lacks an optimal algorithm to compute arbitrary AEDR-AFDL trade-offs. Hence, we adopt an optimal protocol to compute the AEDR metric, while measuring the AFDL with respect to the AEDR-optimal protocol specifically, as detailed in the next subsection.

Evaluation Methodology

We consider network topologies that may arise in real-world scenarios. The most widely demonstrated topologies for quantum networking are repeater chains (RCs) [6], homogeneous lattice (LT) [7] and the star topology [8]. For instance, an experimental star-topology quantum network testbed has been built at the University of Arizona [8]. Since attributes such as success probabilities are distance-dependent, some have adopted distance-based topologies, such as a distance-threshold graph [6], or more generally the Waxman random graph model [9]. Recently, impact of general topologies such as Erdős-Rényi graphs and scale-free graphs have been studied [10], though the focus has primarily been on the end-to-end capacity of *one specific source-destination pair*. Our study compares topologies for serving multi-commodity traffic in the multi-tenent Quantum Internet. The categories of topologies and their default parameters are shown in Table 1.

To measure the EDR of a topology, we utilize the optimal remote entanglement distribution (ORED) protocol proposed by Dai *et al*. [6]. Specifically, the ORED protocol formulates a linear program to derive the maximum EDR achievable between a pair of nodes. We extend the formulation to compute the maximum total EDR between multiple source-destination pairs. Then, to obtain end-to-end fidelity, we decompose the ORED solution into entanglement paths used by each source-destination pair, and then compute the average fidelity of all paths weighted by their EDRs. We do not consider entanglement purification, which has complicated impacts on the EDR and end-to-end fidelity that pertains to the specific error model, purification protocol, and even order of purification performed along an entanglement path [11]. We discuss purification-aware topology design as important future work below.

To compare different topologies, we simulate an area of $4{,}654 \times 2{,}660$ km^2 (approximately the

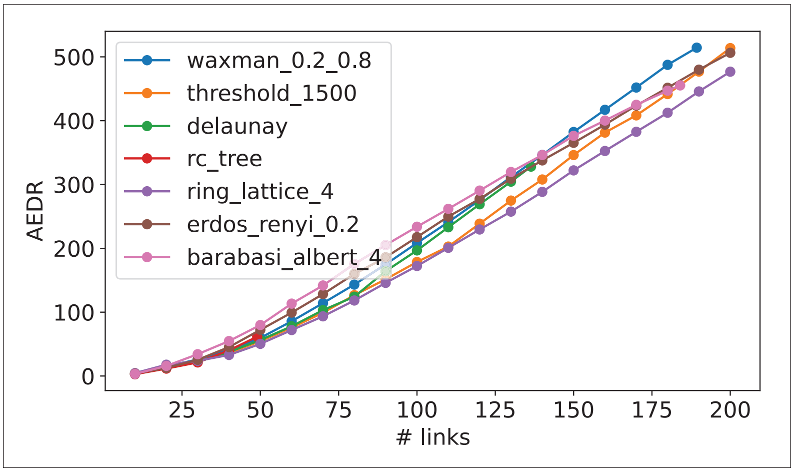

FIGURE 3. Average entanglement distribution rate (AEDR) versus number of links in tested topologies.

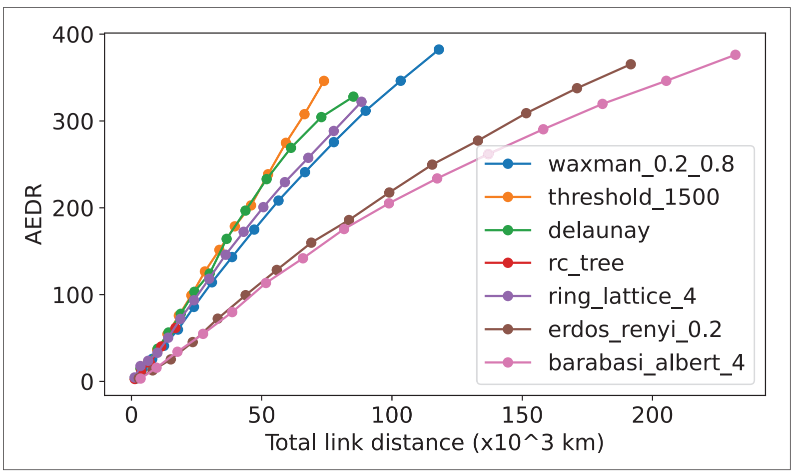

FIGURE 4. Average entanglement distribution rate (AEDR) versus total distance of links in tested topologies.

size of the US). We randomly place 50 nodes in the area, and generate topologies with different models; we then generate 50 random source-destination pairs. For each topology, we incrementally build it through a sequence of graph augmentation starting from an empty graph, and then adding the 10 links that have the shortest physical distances in the topology in each augmentation step, until all links have been added. We assume all links have a uniform capacity of 10, and a random fidelity uniformly in [0.7, 0.95]. Following [9], success probability of a link *uv* is puv = $e^{-0.0002 \cdot d_{uv}}$, where d_{uv} is the physical distance between the nodes; the success probability of BSM is uniformly 0.9. We then compute the performance metrics for selected source-destination pairs on each augmented topology. Final results are averaged over multiple randomized runs under each setting.

Preliminary Results

AEDR: Figure 3 shows the AEDR achieved by different topologies versus the number of links added based on their distances. Among top players, Barabasi-Albert scale-free topologies have higher AEDR than any other topology when the number of links is small. This is likely because scale-free topologies have shorter paths *in terms of hop count* than other graphs as most nodes are connected to a few central nodes with large degrees, and based on how the graphs are augmented only short-distance links are added initially. However, more links are added, Waxman topologies become dominant. This is because when more links are added, Barabasi-Albert starts to add links over longer distances, leading to degraded entanglement success probability despite the added connectivity. Meanwhile, the Waxman model still adds shorter-distance links with larger probability, and hence the average success probability of links is higher.

The effect of distance is more visible in Fig. 4. Here we use the total distance of all connected links as a cost metric, representing roughly the amount of work to build a topology with a given set of links. In Fig. 4, distance-aware topologies can achieve a much higher AEDR-to-distance ratio than distance-agnostic topologies. One can observe that the threshold model, which connects all links with distances bounded by a parameter, can achieve the highest cost efficiency since it connects the shortest links (links with the highest success probabilities) between nodes. Delaunay graphs also achieve good cost efficiency but has an upper bound on the number of links, as it only connects nodes who are neighbors in the Voronoi diagram given node locations. Overall, distance-aware topologies can achieve good AEDR by connecting links with shorter distances, while distance-agnostic topologies suffer from increased distances of links, which increase the cost while decreasing AEDR due to low success probabilities. Graphs such as RC tree and Delaunay have limited scalability in terms of number of links; their AEDRs are consequently bounded.

AFDL: In Fig. 5, we show the AFDL of topologies versus the number of links. Many topologies have zero AEDR when there are few links, and hence their AFDL values are undefined and hence not shown. The AFDL values of most topologies first experience a dip with increasing number of links, but then starts to increase or stays the same afterwards. This is because when there are few links, not all source-destination pairs are connected, and the connected ones generally have short entanglement paths. When more links are added, more pairs are connected with longer paths, resulting in a drop in AFDL due to the fidelity loss over longer paths. After all source-destination pairs are connected, adding more links increases path diversity, and more entanglements can be established over additional shorter paths that are previously occupied or not available. Hence the AFDL again increases.

Among topologies, RC tree achieves the lowest AFDL, as most nodes are connected via the only path that is significantly longer than in other graphs. Threshold and ring lattice generally achieve higher AFDL when building the topologies incrementally. This is because these two models connect nodes more "locally" than other models, that is, they will first build connections between clusters of nodes that are physically closer to each other, before adding links between nodes that are farther away. Meanwhile, other models add links across the board, resulting in longer paths and hence lower AFDL. This is most obvious in Erd\H{o}s-Rényi graphs, which adds links globally with an independent probability, and in Delaunay graphs, which limits the number of links between any cluster of physically close nodes due to its triangulation property. Naturally they result in the lowest AFDL in most cases. Waxman and Barabasi-Albert models add links with probabilities correlated to how "local" each candidate link is, and hence result in higher AFDL than Erdős-Rény and Delaunay but lower AFDL than threshold and ring lattice. In Waxman, the locality effect is pertained to how physically close a pair of nodes is, while in Barabasi-Albert the effect is related to the degree of each node during initial connection and subsequent link adding. Since fidelity is not distance-dependent in our study, we omit the figure showing AFDL versus total distance of links, which has similar trends as Fig. 5.

Summarizing the results, under the assumed channel model, we observe that the popular repeater chain/tree topology is not suitable for the Quantum Internet due to both the low AEDR and the low AFDL as well as limited scalability, calling for study and evaluation using more realistic quantum network topologies. Distance-aware models such as Waxman, threshold or ring lattice generally achieve both higher AEDR and higher AFDL than distance-agnostic models when the link building costs are proportional to physical distances. The threshold model and the Waxman model achieve high AEDR when fully built, while also delivering reasonable AFDL. Hence they may be suitable for protocol evaluations with quantum network simulations. Meanwhile, we point out that these early findings are not conclusive as the graph generation parameters' impacts are not comprehensively evaluated. This, combined with other limitations elaborated below, calls for extensive future research to fully understand the principles and trade-offs in quantum network topology design.

Limitations and Future Work

Here, we discuss several limitations of our study and propose future research directions.

EDR-Fidelity Trade-Off

The selection of entanglement paths can affect end-to-end fidelity of established entanglements. The ORED and path decomposition algorithms we use do not consider end-to-end fidelity, and hence the measured AFDL values may not represent the optimal AFDL that can be obtained on these topologies. Both fidelity-aware ORED and fidelity-optimal path decomposition are non-trivial and most likely NP-hard. Advances in these problems would allow characterization of the EDR-fidelity trade-off in a network, which is core to Quantum Internet design.

Purification-Awareness

The end-to-end fidelity in our study only depends on the entanglement path taken and is irrelevant to the success probability or the EDR. Purification introduces possible flexible EDR-fidelity trade-off, by consuming low-fidelity entanglements to generate high-fidelity ones. Its effectiveness (i.e., fidelity improvement) and success probability are both closely related to the fidelity of the consumed entanglements. For instance, under the protocol of Pan *et al.* [12], purifying two entanglements with fidelity $F_1, F_2 > 1/2$ results in an entanglement with fidelity

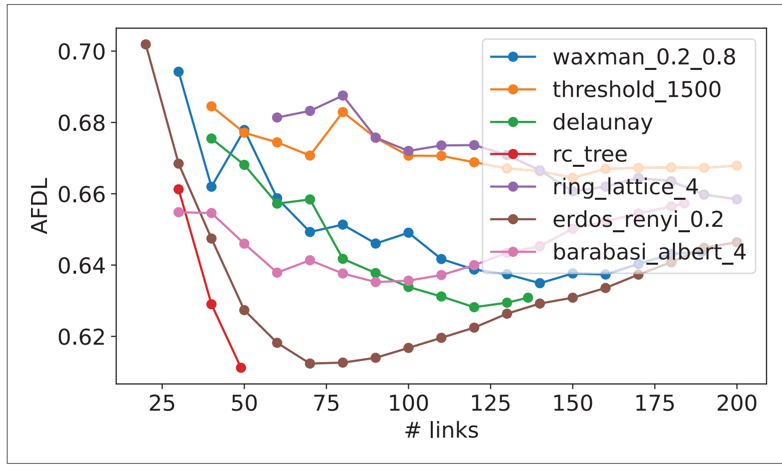

FIGURE 5. Average fidelity (AFDL) versus number of links in tested topologies.

$$F' = \frac{F_1F_2}{F_1F_2 + (1 - F_1)(1 - F_2)},$$

with a success probability of $F_1F_2 + (1 - F_1)(1 - F_2)$. Hence, with a factor

$$\frac{F_1F_2 + (1 - F_1)(1 - F_2)}{2}$$

of expected EDR reduction, one can obtain a stream of entanglements with fidelity $F' > F_1, F_2$, out of two streams of entanglements of fidelity F_1, F_2 respectively.

The non-linearity of fidelity and success probability makes designing an optimal purification protocol a challenging open problem. The design space includes when should purification be applied, and the order of purification between entanglements generated along different paths. Characterizing the EDR-fidelity trade-off with purification is also an important open problem.

Network Augmentation

Our study provides a naive way to progressively build a network, by incrementally adding links in the order of distances (costs) based on a pre-defined topology. However, our method assumes fixed source-destination pairs, and augments the graph in a heuristic manner. Optimal network augmentation would ideally provide high EDR and high fidelity between a varying set of source-destination pairs, and consider the different EDR demands and fidelity requirements of the source-destination pairs. Capacity augmentation has been studied in the early days of the Internet and is continuously an important problem in scenarios such as data centers, wireless sensor networks and vehicular networks. However, studying the quantum version of this problem requires better understanding of fundamental aspects of quantum networking, including network building and maintenance costs, attributes such as success probability and fidelity, and the fundamental EDR-fidelity trade-off of a given network.

Quantum-Optical Network Co-Design

Future Quantum Internet will likely operate alongside the classical Internet in existing optical fibers [13]. In classical optical networks, topology design has been extensively studied, where it has often been referred to as "virtual/logical topology design."

The Quantum Internet is not built in one day. Existing research has focused on either the underlying physical layer mechanics, or designing systems and protocols upon an hypothetically existing infrastructure.

Such problems focus on choosing what set of "lightpaths" (optically continuous multi-fiber-hop circuits) to establish on a given fiber topology, subject to constraints like wavelength multiplexing, maximum lightpath span and impairment awareness. Amongst these works, some consider short-lived lightpaths each set up and torn down of the rest ("optical burst switching"), and to integrate consideration of sub-wavelength traffic routing on the topology formed by lightpaths ("traffic grooming") [14, 15]. Moreover, other works study how a priori knowledge of traffic can inform topology design thereby allowing custom and non-regular topology graphs to be developed for any given fiber plant and traffic demand combination. All these techniques in classical optical networks are worthwhile to be re-visited for designing the Quantum Internet. Furthermore, when quantum and classical networks operate over the same optical infrastructure, their co-existence can have further implications in terms of traffic demands, resource allocation and performance isolation, which warrant further investigation.

Summary

The Quantum Internet is not built in one day. Existing research has focused on either the underlying physical layer mechanics, or designing systems and protocols upon a hypothetically existing infrastructure. This article intends to bring about perspectives on what type of network infrastructure is suitable for the Quantum Internet, and how should it be continuously built as the classical Internet was. Through preliminary study, we analyzed the entanglement distribution rate and end-to-end fidelity of popular quantum network topologies, utilizing an optimal remote entanglement distribution algorithm with heuristic path decomposition. We also showed the performance implication of incrementally building these topologies based on a heuristic graph augmentation rule. We pointed out limitations of current approaches (including our preliminary study) and called for further research into the fundamental principles and trade-off of quantum topology design. We hope these will motivate more efforts in relevant fields.

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