Connection-Oriented and Connectionless Remote Entanglement Distribution Strategies in Quantum Networks

Zhonghui Li, Kaiping Xue, Jian Li, Nenghai Yu, David S. L. Wei, and Ruidong Li

Abstract

Quantum network is a promising platform for numerous quantum applications, including distributed quantum computing, secure communication, and improved sensing. Implementing entanglement distribution between remote quantum nodes plays a vital role in realizing the quantum network's capabilities, and it requires effective remote entanglement distribution protocols. To meet this requirement, we propose two strategies, namely connection-oriented and connectionless, to achieve end-to-end entanglement distribution inspired by the designs of classical communication. For the connection-oriented strategy, an exclusive quantum connection is pre-established between the source and destination nodes. For the connectionless strategy, entanglement swapping is performed hop-by-hop tentatively. In this way, the best-effort service is provided for the source node to establish long-distance entanglement with the destination node. Analogous to classical communication, the proposed strategies have their advantages and disadvantages. Our simulation results show that the connectionless strategy is more efficient and robust than the connection-oriented strategy in terms of throughput. However, the connection-oriented strategy provides reliable end-to-end entanglement distribution but at the expense of higher overhead. Moreover, the application scenarios of these two strategies are discussed. This work paves the road for designing end-to-end entanglement distribution protocols in quantum networks.

Introduction

Recently, quantum communication has attracted increasing attention from research and industrial communities. Some small-scale quantum key distribution networks in metropolitan areas have already been implemented to provide commercial services, such as the DARPA [1] and the SECOQC [2]. With the advancement of quantum technology, connecting numerous quantum nodes to form quantum networks to achieve wide-area quantum communication is becoming closer to reality [3, 4]. Quantum network provides a foundational platform for realizing ground-breaking quantum applications, such as distributed quantum computing, unconditional secure communication, and quantum clock synchronization. Its main function is to generate and distribute entangled states between quantum nodes to support various quantum applications.

Entanglement generation is a technology allowing two quantum nodes directly linked via a quantum channel to share Einstein-Podolsky-Rosen (EPR) pairs [5, 6], that is, two quantum nodes are entangled. However, the implementation of enabling two distant nodes to share EPR pairs, also called end-to-end or remote entanglement distribution, is significantly hindered due to the channel loss and decoherence. Fortunately, quantum repeaters can facilitate end-to-end entanglement distribution by performing entanglement swapping [7], that is, a Local Operation, known as Bell State Measurement (BSM), with the assistance of Classical Communication (LOCC). Considering decoherence and imperfect quantum operations, it is crucial to design an effective protocol to enable distant nodes to share EPR pairs in quantum networks. Although some studies have achieved remarkable developments in quantum networks, developing entanglement distribution protocols remains a challenge due to the unique characteristics of quantum entanglement.

To overcome such a challenge, we explore the possibility of applying the classical communication strategies to quantum networks due to the similarities between quantum networks and classic networks. First, the development of both networks follows a similar trajectory [8]. As shown in Fig. 1, the progressive development of network devices promotes the expansion of communication distance and network scale. Both quantum communications and classical communications can realize the transformation from short-distance point-to-point communication to wide-area concurrent communications with the emergence of intermediate network devices such as repeaters and routers. Second, the basic structure of quantum networks is analogous to that of classic networks. They can both be characterized by three main components, that is, end nodes, routers, and links. Furthermore, the swapping operation performed in each intermediate node for implementing end-to-end entanglement distribution are similar to the hop-by-hop forwarding of packets in classic networks. Consequently, we apply the transmission strategies in classic networks to design entanglement distribution protocols in quantum networks.

In this article, we propose two basic strate-

Digital Object Identifier: 10.1109/MNET.107.2100483

Zhonghui Li, Kaiping Xue (corresponding author), Jian Li and Nenghai Yu are with the University of Science and Technology of China, China.; David S. L. Wei is with Fordham University; Ruidong Li is with Kanazawa University, Japan.

gies: connection-oriented and connectionless, to achieve end-to-end entanglement distribution in quantum networks. The proposed connection-oriented strategy is realized by establishing an exclusive quantum connection in advance to allow two far-apart quantum nodes to share EPR pairs. For connectionless strategy, entanglement swapping is tentatively performed hop-by-hop, that is, two quantum nodes do not need to pre-establish a dedicated quantum connection, and the best-effort service is provided for distributing EPR pairs between the source and the destination nodes. Our simulation results show that the connection-oriented strategy can provide the reliable end-to-end entanglement distribution, but it is inferior to the connectionless strategy in efficiency and robustness.

The rest of this article is organized as follows. The next section briefly reviews some background knowledge. The connection-oriented entanglement distribution strategy is presented following that. We then describe the connectionless strategy. Following that, simulations are performed to compare two strategies. We then present a discussion, and a summary of our work is concluded in the final section.

Background

The transmission strategies of data packets in classic networks can be classified into two categories: connection-oriented and connectionless. For the connection-oriented transmission scheme, two communicating parties first establish a connection (or a dedicated virtual tunnel) before transmitting data packets. The connection is released to free network resources after communication. However, the connectionless strategy does not require an end-to-end connection to be established in advance. With such a strategy, a source node sends packets to the next hop, and the classic network is only responsible for transmitting packets from the source along with the intermediate nodes to the destination node. The connection-oriented strategy can realize reliable transmission of data packets but at the expense of low transmission efficiency. The connectionless strategy adopts a best-effort manner to transmit information with higher efficiency. These two strategies can play to their strengths in different application scenarios. For example, the connection-oriented strategy is more suitable for scenarios where data integrity is more important than real-time, for example, file transfer. In contrast, the connectionless strategy benefits the applications requiring high transmission speed and low delay, for example, online video and voice-over-IP service.

Distributing EPR pairs between distant quantum nodes is the main function of quantum networks since entanglement between quantum nodes is the cornerstone of most quantum applications. Generally, end-to-end entanglement distribution mainly includes three quantum operations, that is, entanglement generation, entanglement purification, and entanglement swapping, as shown in Fig. 2.

Entanglement generation aims to distribute EPR pairs between adjacent nodes directly connected by a short-haul quantum channel. Considering the channel loss and decoherence, however, it is hard to successfully distribute EPR pairs to a pair of adjacent nodes. The success rate of entanglement generation decreases exponentially with the length of the quantum channel, that is, $p \sim e^{-\alpha l}$, where α is a constant and l is the length of the quantum channel. Generally, establishing entanglement between adjacent quantum nodes generally requires several attempts at entanglement generation. Consequently, the duration of successfully distributing an EPR pair between adjacent nodes negatively affects the end-to-end entanglement distribution rate. After the entanglement generation, each EPR pair can be directly used or stored in quantum memory [9]. Besides, multiple EPR pairs can be shared by each pair of adjacent nodes with the aid of quantum memory.

Decoherence decays entanglement fidelity, which significantly hinders the implementation of remote entanglement distribution. To overcome this obstacle, entanglement purification, which is an efficient technique to increase fidelity, needs to be performed. However, the fidelity is improved at the expense of a reduced number of entanglement resources, that is, the purification operation consumes the shared EPR pairs between adjacent nodes. Moreover, entangle-

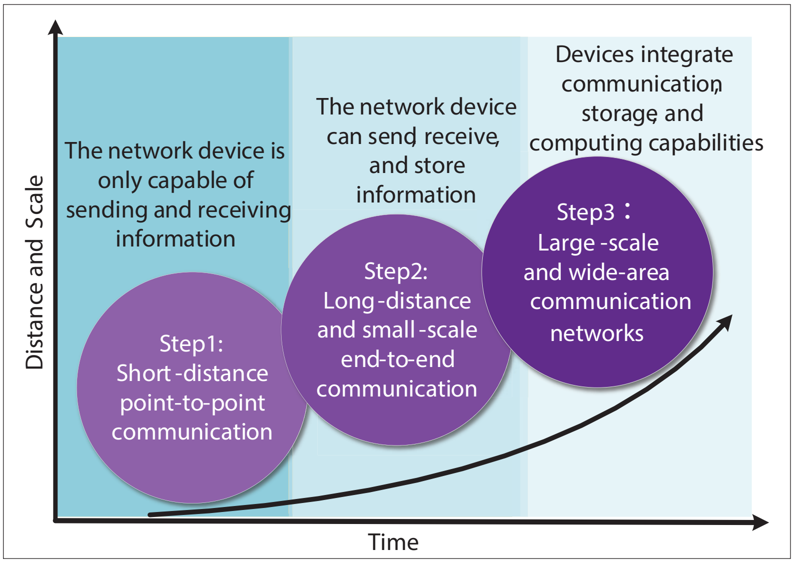

FIGURE 1. The different stages of a communication network.

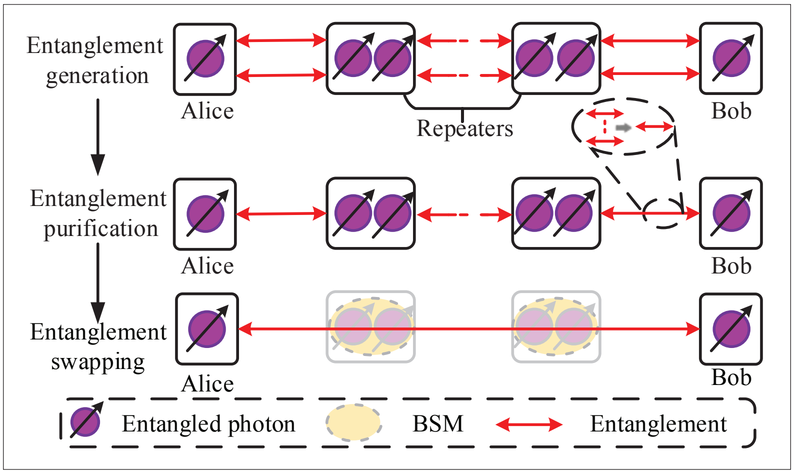

FIGURE 2. End-to-end entanglement distribution between two far-apart quantum nodes.

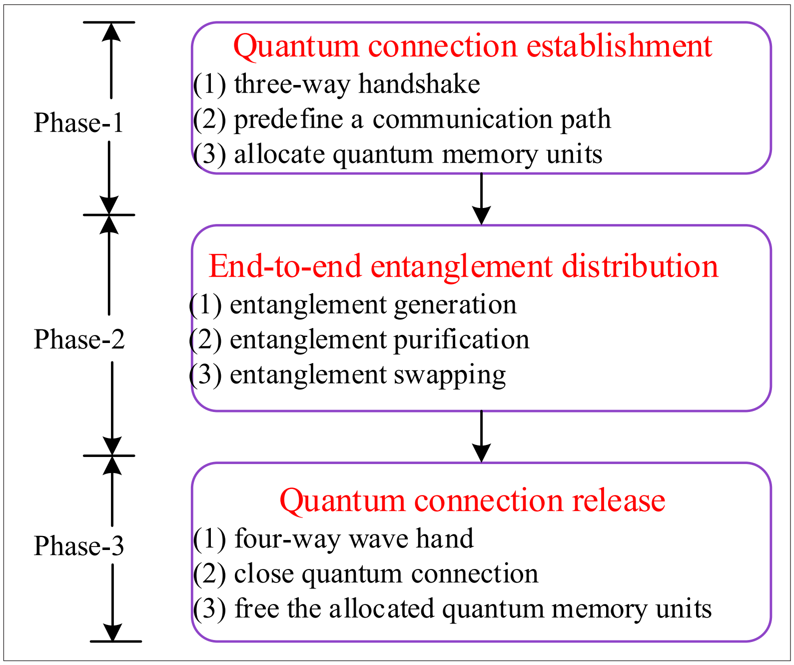

FIGURE 3. The process of connection-oriented entanglement distribution in quantum networks.

ment purification is imperfect, and its success rate is determined by the fidelity of the EPR pairs being measured. Hence, considering that the purification operation is imperfect and consumes the shared EPR pairs which are regarded as the important resource for end-to-end entanglement distribution, entanglement purification will significantly affect the performance of end-to-end entanglement distribution.

Entanglement swapping plays a vital role in implementing remote entanglement distribution. By the mean of LOCC, two non-entangled quantum nodes can share EPR pairs. Hence, we can deploy multiple quantum repeaters between two far-apart quantum nodes and perform entanglement swapping along the repeater chain to realize end-to-end entanglement distribution. In this way, multiple short-haul quantum links can be coupled to allow EPR pairs to be shared between the remote Source and Destination (S-D) nodes. Most notably, entanglement swapping is also an imperfect quantum operation, and EPR pairs cannot be reused after being measured. Consequently, a higher success rate of entanglement swapping facilitates the improvement of the end-to-end entanglement distribution rate.

Quantum memory is an important enabling technology for both connection-oriented and connectionless entanglement distribution strategies in quantum networks. With advances in quantum physics and device development, quantum memory shows attractive advantages in terms of long lifetime, high fidelity, high multi-mode capability, and so on. Under laboratory conditions, the storage fidelity of quantum memory can reach 99.3 ± 0.2 percent [10], and the single-photon can be stored for more than one hour [11]. Although the coherence time of quantum memory is still very short in practical application scenarios, it can be expected to be greatly extended in the near future. Besides, a quantum memory can be designed as the combination of multiple independently accessible memory units (or cells) [12]. Based on this design, a unique identification label consisting of information such as identity and address can be assigned for each quantum memory unit to distinguish different EPR pairs stored in quantum memory. Hence, the EPR pairs that need to be measured can be easily retrieved by the unique label. Furthermore, by storing the pre-shared EPR pairs before entanglement swapping, quantum memory can mitigate the negative impact of the latency caused by entanglement generation on the end-to-end entanglement distribution rate. Hence, it is feasible and beneficial to apply quantum memory in quantum networks for end-to-end entanglement distribution.

Connection-Oriented Entanglement Distribution

Connection-oriented entanglement distribution strategy is similar to connection-oriented classical communication. In this way, a quantum connection between each distant S-D pair needs to be established first. To realize the reliable end-to-end entanglement distribution, each quantum node on the selected path reserves dedicated quantum memory units to establish an exclusive quantum connection. As shown in Fig. 3, the process of connection-oriented entanglement distribution between the S-D pair Alice and Bob includes three phases.

Phase-1: Quantum Connection Establishment

Different from connection-oriented classical communication, the first phase of connection-oriented entanglement distribution attempts to build an exclusive quantum connection between Alice and Bob, that is, each node on the selected path assigns dedicated quantum memory units. This phase is mainly realized with the assistance of classical communication. We can use a three-way handshake to establish the dedicated quantum connection via classic networks. First, Alice sends the connection establishment request to Bob, and a communication path is selected according to the routing algorithm. Then a request acknowledgment responded by Bob is forwarded among the selected path to Alice. The acknowledgment will notify each quantum node on the selected path to allocate quantum memory units for this S-D pair. To achieve reliable end-to-end entanglement distribution, the allocated memory units will be tagged with a label to indicate that they are occupied and cannot be seized by other requests. Last, when Alice receives an acknowledgment from Bob, Alice sends a connection establishment acknowledgment to inform Bob that the exclusive quantum connection is established for end-to-end entanglement distribution.

Phase-2: End-to-End Entanglement Distribution

This phase consists of three vital quantum operations: entanglement generation, entanglement purification, and entanglement swapping. The function of entanglement generation is to enable adjacent quantum nodes to share EPR pairs stored in the allocated quantum memory units. Considering that distributing an EPR pair between adjacent nodes brings non-negligible latency and entanglement fidelity decays with storage time, entanglement generation between adjacent nodes is performed in parallel instead of hop-by-hop from the source to the destination node to reduce the latency of the end-to-end entanglement distribution. Most notably, although two quantum nodes share an EPR pair, there is no competition for the shared EPR pairs between two entangled nodes for BSM operations. In other words, each node on the selected path can perform BSM operation individually, and the destination node can manipulate entangled states locally based on the results of all the nodes' measurements to achieve end-to-end entanglement distribution. Hence, we adopt a parallel design to perform entanglement swapping and entanglement purification to improve the performance of end-to-end entanglement distribution. Finally, Alice and Bob are entangled. Note that EPR pairs cannot be reused after BSM. Therefore, three quantum operations are performed repeatedly to allow EPR pairs to be shared by Alice and Bob.

Phase-3: Quantum Connection Release

This phase releases the quantum connection of the S-D pair to free the allocated memory units. For the connection-oriented strategy, the quantum connection between Alice and Bob continuously occupies the allocated quantum memory units to offer reliable end-to-end entanglement distribution. To improve the performance of quantum networks, we need to unfetter the occupied memory units in time to serve other S-D pairs. We propose a four-way handshake protocol to release the quantum connection in this phase. First, Alice sends a classical notification to Bob that the communication is finished. When Bob receives the notification, it sends back a release acknowledgment to Alice. Then Bob closes the quantum connection and sends an announcement to notify each node on the selected path to free the allocated memory units. Finally, Alice responds with an acknowledgment to Bob.

The connection-oriented strategy provides reliable end-to-end entanglement distribution by establishing an exclusive quantum connection. There are some challenges to implementing this strategy. First, it is worth noting that remote entanglement distribution is governed by quantum mechanics, where both the distribution rate and entanglement fidelity affect quantum networks' performance [13]. The connection-oriented strategy requires an efficient routing algorithm to facilitate remote entanglement distribution. Besides, the imperfect entanglement swapping will increase the latency of remote entanglement distribution, which negatively affects the fidelity of EPR pairs shared by each remote S-D pair. Therefore, redundant EPR pairs should be distributed as compensation for the imperfect entanglement swapping and further used for purification to improve entanglement fidelity. Furthermore, the sequence of entanglement swapping and purification is also worth discussing since it affects the fidelity of end-to-end entanglement pairs and the number of the shared EPR pairs consumed for end-to-end entanglement distribution.

Connectionless Entanglement Distribution

For the connection-oriented strategy, end-to-end entanglement distribution is realized by allocating quantum memory units to establish an exclusive quantum connection. However, the occupied memory units will block other end-to-end entanglement distribution requests due to the limited memory units in each quantum node. Hence, the connection-oriented strategy is not friendly for concurrent entanglement distribution between multiple S-D pairs. Here, the EPR pairs shared by each pair of adjacent quantum nodes can be considered a network resource to serve S-D pairs on demand with the assistance of quantum memory. Based on this consideration, we further propose a connectionless entanglement distribution strategy.

The specific connectionless strategy can be introduced as follows. To realize end-to-end entanglement distribution, entanglement swapping is tentatively performed hop-by-hop, and Alice is only responsible for doing its best to attempt to share EPR pairs with Bob. In other words, an exclusive quantum connection between Alice and Bob does not need to be built. The structure of the connectionless strategy is shown in Fig. 4. It consists of two core parts, that is, entanglement generation and end-to-end entanglement distribution. These two parts work independently at the link layer and the network layer [14]. Considering concurrent entanglement distribution and the fact that purification operation reduces the number of shared EPR pairs between adjacent nodes, maintaining sufficient entanglement resources between adjacent nodes to serve multiple requests is required for the connectionless strategy. Here, the event-based trigger mode can be adopted in the link layer [9] to guarantee that adjacent nodes always be entangled. Explicitly, the released quantum memory units trigger entanglement generation after each BSM operation. In this way, the other S-D pairs' requests can be satisfied in a timely manner by directly using the complemented EPR pairs rather than waiting for the successful entanglement generation. The second part, end-to-end entanglement distribution, is realized by entanglement purification and entanglement swapping. Entanglement purification is only performed when a swap operation is required. And entanglement swapping is tentatively executed hop-by-hop from the source to the destination node.

Similar to connectionless communication in classic networks, the connectionless strategy cannot achieve reliable end-to-end entanglement distribution. For each S-D pair, the source node only

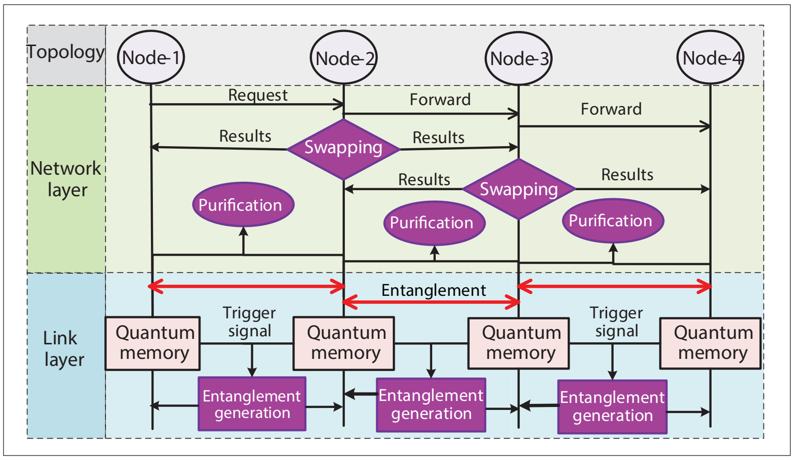

FIGURE 4. The structure of connectionless entanglement distribution in quantum networks.

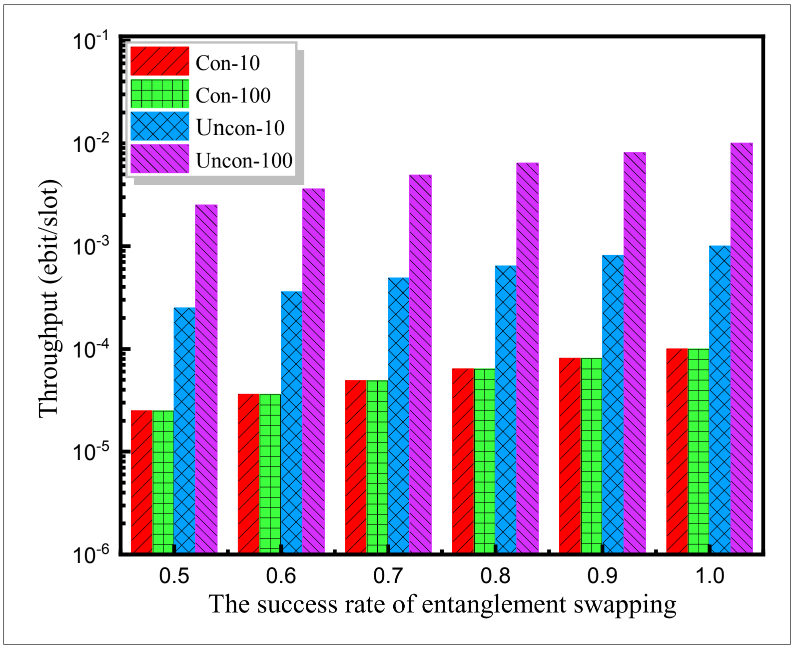

FIGURE 5. The throughput of two strategies under different memory size and different success rate of entanglement swapping in quantum nodes.

needs to initiate an end-to-end entanglement distribution request. Then an entangled relationship is tentatively extended in a hop-by-hop manner under the control of a routing algorithm. When an intermediate quantum node receives the request, the processing of this request has two results. For the first situation, that is, there are sufficient EPR pairs that can be used for entanglement swapping, the quantum node will allocate EPR pairs for this request. Then entanglement purification and entanglement swapping are performed successively to extend the distance of entanglement generation. After the swap operation, the node will forward the request to the next hop. Otherwise, the quantum node discards the request and responds with feedback through the classic networks to indicate that the path is blocked. Then, the previous-hop needs to attempt to perform entanglement swapping with other adjacent quantum nodes. Considering decoherence, we can introduce a timer to judge if the path is reachable. If no EPR pairs are shared by the S-D pair after a certain time, the source node considers that the end-to-end entanglement distribution is unsuccessful. Then the source node attempts to be entangled with the destination node again. For the connectionless strategy, multiple EPR pairs shared by each S-D pair are distributed independently, that is, they are distributed by performing entanglement swapping among different quantum repeater chains. Hence, the connectionless strategy outperforms the connection-oriented strategy in the end-to-end entanglement distribution rate.

In addition to the challenge of designing routing algorithms, there are two problems that we need to solve for the connectionless strategy. The first problem is the request scheduling in each quantum node. The request scheduling design determines the order in which entanglement swapping is performed for each request. This order will affect the node's processing of the request due to the consumption of the shared EPR pairs, thus affecting the end-to-end entanglement distribution rate. The other problem is the allocation of the shared EPR pairs. The solution to this problem determines which EPR pairs are used for entanglement swapping and purification operation. Note that each attempt of entanglement generation is independent, that is, the fidelity of different EPR pairs between adjacent nodes are not the same. Considering that the success rate of entanglement purification and the output fidelity of entanglement purification is directly related to the input EPR pairs' fidelity, the allocation of the shared EPR pairs significantly affects the fidelity of the entanglement between each S-D pair.

Performance Analysis

We take a comprehensive performance comparison between connection-oriented and connectionless strategies in terms of throughput, robustness, and concurrency with a different success rate of entanglement swapping and quantum memory size via simulations. The throughput is defined as the number of the shared EPR pairs between each S-D pair in a time slot. We use the robustness to study the effect of the success rate of entanglement swapping on successfully allowing S-D pairs to share an EPR pair. Besides, the concurrency indicates that how many end-to-end entanglement distribution requests can be satisfied simultaneously. Here, the simulation parameters in the procedure of entanglement distribution are set according to Ref. [9], for example, the time spent for entanglement swapping is about 0.1ms. In our simulations, both entanglement distribution strategies adopt the shortest path routing algorithm to implement end-to-end entanglement distribution in a randomly generated network topology.

Efficiency of End-to-End Entanglement Distribution

Connectionless strategy (Uncon-10 and Uncon-100) has better performance on throughput than connection-oriented strategy (Con-10 and Con-100). As shown in Fig. 5, we compare the throughput of these two strategies under two conditions where the sizes of quantum memory in each node are 10 and 100, that is, the number of EPR pairs shared by adjacent nodes is 10 and 100, respectively. Since the connection-oriented strategy is achieved by reserving quantum memory units, the throughput will not be affected by the size of the memory. For the connectionless strategy, each quantum node can directly choose the idle EPR pairs to perform entanglement swapping instead of repeated entanglement generation attempts. Consequently, the connectionless strategy outperforms the connection-oriented scheme in throughput, and this advantage becomes more significant as the size of quantum memory increases.

Robustness

When the number of EPR pairs shared by adjacent nodes is equal to one and two, respectively, we compare the delay of the two strategies for one teleportation process in the case of one node failure. Connectionless strategy is more robust than connection-oriented strategy. As shown in Fig. 6a, no matter how many EPR pairs are shared by adjacent nodes, connectionless strategy (Uncon-1 and Uncon-2) takes less time than the connection-oriented strategy (Con-1 and Con-2). For the

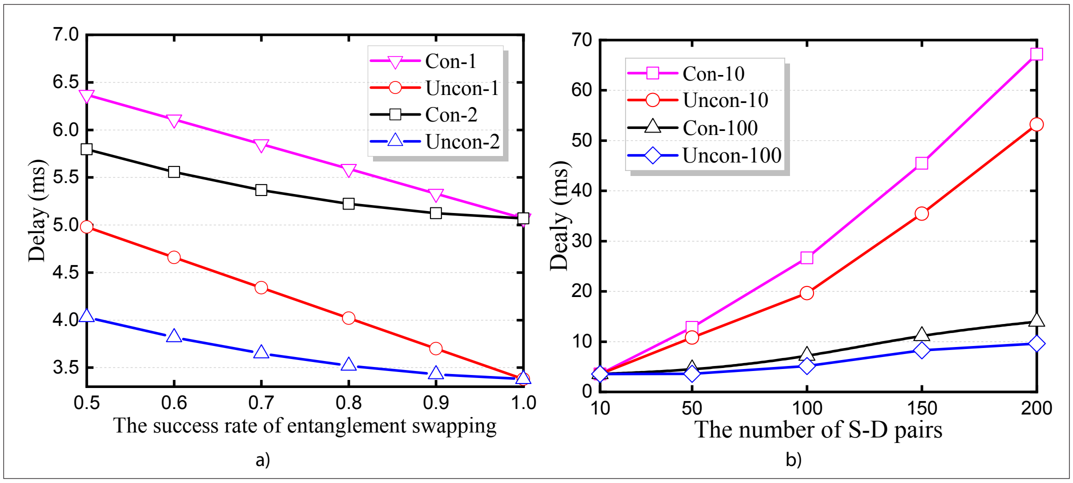

FIGURE 6. The performance comparison between the two strategies in terms of robustness and concurrency: a) robustness; b) concurrency.

connection-oriented strategy, the network system needs to re-establish a new quantum connection by allocating dedicated memory units on another path. Besides, connection-oriented strategy is more susceptible to the failure of entanglement swapping than the connectionless strategy since the fact that entanglement swapping can be performed by employing the unallocated EPR pairs in connectionless strategy instead of re-executing entanglement generation attempts until it succeeds.

Concurrency

We compare the delay in concurrent end-to-end entanglement distribution when the number of EPR pairs shared by two adjacent nodes is equal to 10 and 100, respectively (Fig. 6b). The simulation results show that the connectionless strategy (Con-10 and Con-100) is more friendly to concurrent entanglement distribution between multiple S-D pairs than the connection-oriented strategy (Uncon-10 and Uncon-100), and this advantage increases as the number of quantum memory units increase. The reason is that the connection-oriented strategy is implemented by establishing exclusive quantum connections for S-D pairs, which results in the continuous occupation of entanglement resources on the predefined path and introduces extra delay.

Discussion

The connection-oriented strategy generally provides a more reliable end-to-end entanglement distribution by establishing an exclusive quantum connection. However, this strategy leads to low entanglement distribution efficiency, especially for concurrent entanglement distribution between multiple S-D pairs. Hence, the connection-oriented strategy can play a better role in the application scenarios where end-to-end entanglement distribution needs to be reliably achieved with low real-time requirements, for example, file transfers and E-mail. The connectionless strategy achieves more efficient but less reliable end-to-end entanglement distribution. Thus, the main application scenarios for connectionless strategies are those applications that require the high end-to-end entanglement distribution rate, such as video chat and quantum internet of things based on entanglement.

There are some challenges in the implementation of both two strategies. For the connection-oriented strategy, considering the imperfection of entanglement swapping, we need to design a routing algorithm with a high success rate of end-to-end entanglement distribution to select a quantum repeater chain. Considering decoherence, redundant memory units need to be allocated for each S-D pair to store EPR pairs used for purification operation. Hence, how to achieve this function in a quantum network with limited storage capacity is also an issue. An efficient routing algorithm is also required for the connectionless entanglement distribution strategy to reduce the number of entanglement swapping operations. Besides, we need to solve resource allocation and request scheduling problems to implement concurrent entanglement distribution between multiple S-D pairs. To be noted, both the two strategies rely on classical communication, the great benefits of Software Defined Networking (SDN) [15] can also be leveraged in these two strategies to efficiently realize end-to-end entanglement distribution through the centralized designs.

Conclusion

To start timely guidance regarding the protocol design of end-to-end entanglement distribution, we presented two basic strategies, that is, connection-oriented strategy and connectionless one, in large-scale quantum networks. The connection-oriented entanglement distribution strategy is implemented by allocating exclusive quantum memory units on the selected path for each S-D pair to establish a quantum connection. In contrast, in the connectionless strategy, EPR pairs shared by a pair of distant quantum nodes are distributed by tentatively performing entanglement swapping hop-by-hop from the source to the destination node. Analogous to classical communication, the connection-oriented strategy provides a reliable end-to-end entanglement distribution service. However, this scheme performs worse than the connectionless strategy regarding transmission efficiency and robustness. Although our work provides constructive guidance for the protocol design of remote entanglement distribution in quantum networks, some challenges still hinder the implementation of these two strategies, for example, routing algorithms, resource allocation, connection establishment, connection release, and so on. These challenges will gradually be overcome, and we are confident that quantum networks will provide a wide range of promising services with the continuous progress of quantum information technology.

Acknowledgment

This work is supported in part by Anhui Initiative in Quantum Information Technologies under grant No. AHY150300 and Youth Innovation Promotion Association of Chinese Academy of Sciences (CAS) under Grant No. Y202093.

References

[1] C. Elliott *et al.*, "Current Status of the DARPA Quantum Network," *Quantum Information and Computation III*, vol. 5815. ISOP, 2005, pp. 138–49.

[2] M. Peev *et al.*, "The SECOQC Quantum Key Distribution Network in Vienna," *New J. Physics*, vol. 11, no. 7, 2009, p. 075001.

[3] H. J. Kimble, "The Quantum Internet," *Nature*, vol. 453, no. 7198, 2008, pp. 1023–30.

[4] S. Wehner, D. Elkouss, and R. Hanson, "Quantum Internet: A Vision for the Road Ahead," *Science*, vol. 362, no. 6412, 2018.

[5] H. Bernien *et al.*, "Heralded Entanglement Between Solid-State Qubits Separated by Three Metres," *Nature*, vol. 497, no. 7447, 2013, pp. 86–90.

[6] Y. Yu *et al.*, "Entanglement of Two Quantum Memories via Fibres Over Dozens of Kilometres," *Nature*, vol. 578, no. 7794, 2020, pp. 240–45.

[7] K. Azuma and G. Kato, "Aggregating Quantum Repeaters for the Quantum Internet," *Physical Review A*, vol. 96, no. 3, 2017, p. 032332.

[8] M. Caleffi *et al.*, "The Rise of the Quantum Internet," *Computer*, vol. 53, no. 6, 2020, pp. 67–72.

[9] A. Dahlberg *et al.*, "A Link Layer Protocol for Quantum Networks," *Proc. Annual Conf. ACM Special Interest Group on Data Communication on the Applications, Technologies, Architectures, and Protocols for Computer Communication (SIGCOMM)*, ACM, 2019, p. 159–73.

[10] C. Liu *et al.*, "On-Demand Quantum Storage of Photonic Qubits in an On-Chip Waveguide," *Physical Review Letters*, vol. 125, no. 26, 2020, p. 260504.

[11] Y.-Z. Ma *et al.*, "Elimination of Noise in Optically Rephased Photon Echoes," *Nature Commun.*, vol. 12, no. 1, 2021, pp. 1–7.

[12] Y. Pu *et al.*, "Experimental Realization of a Multiplexed Quantum Memory With 225 Individually Accessible Memory Cells," *Nature Commun.*, vol. 8, no. 1, 2017, pp. 1–6.

[13] R. Horodecki *et al.*, "Quantum Entanglement," *Reviews of Modern Physics*, vol. 81, no. 2, 2009, p. 865.

[14] W. Kozlowski, A. Dahlberg, and S. Wehner, "Designing a Quantum Network Protocol," *Proc. 16th Int'l. Conf. Emerging Networking EXperiments and Technologies (CoNEXT)*, ACM, 2020, pp. 1–16.

[15] K. Benzekki *et al.*, "Software-Defined Networking (SDN): A Survey," *Security and Communication Networks*, vol. 9, no. 18, 2016, pp. 5803–33.

Biographies

Zhonghui Li (leestone@mail.ustc.edu.cn) received his bachelor's degree from the School of Information and Software Engineering, University of Electronic Science and Technology of China, in 2018. He is currently working toward the Ph.D degree from the School of Cyber Science and Technology, University of Science and Technology of China. His research interests include quantum networking and network security.

Kaiping Xue [M'09, SM'15] (kpxue@ustc.edu.cn) received his bachelor's degree from the Department of Information Security, University of Science and Technology of China (USTC), in 2003 and received his Ph.D. degree from the Department of Electronic Engineering and Information Science (EEIS), USTC, in 2007. Currently, he is a Professor in the School of Cyber Science and Technology, USTC. His research interests include future Internet architecture design, transmission optimization, network security, and quantum networking. He is an Fellow of the IET. He is the corresponding author of this article.

Jian Li [M'20] (lijian9@ustc.edu.cn) received his bachelor's degree from the Department of Electronics and Information Engineering, Anhui University, in 2015, and received his Ph.D degree from the Department of Electronic Engineering and Information Science (EEIS), University of Science and Technology of China (USTC), in 2020. He is currently a Post-Doctoral fellow with the School of Cyber Science and Technology, USTC. His research interests include future Internet architecture design, satellite-terrestrial integrated networks, and quantum networking.

Nenghai Yu (ynh@ustc.edu.cn) received his bachelor's degree from the Nanjing University of Posts and Telecommunications, Nanjing, China, in 1987, the M.E. degree from Tsinghua University, Beijing, China, in 1992, and his Ph.D. degree from the Department of Electronic Engineering and Information Science (EEIS), University of Science and Technology of China (USTC), Hefei, China, in 2004. Currently, he is a Professor in the School of Cyber Science and Technology, USTC. He is the Executive Dean of the School of Cyber Science and Technology, USTC, and the Director of the Information Processing Center, USTC. His research interests include multimedia security and quantum networking.

David S. L. Wei [SM'07] (wei@cis.fordham.edu) received his Ph.D. degree in Computer and Information Science from the University of Pennsylvania in 1991. From May 1993 to August 1997 he was on the Faculty of Computer Science and Engineering at the University of Aizu, Japan (as an Associate Professor and then a Professor). He is currently a Professor of Computer and Information Science Department at Fordham University. His research interests include cloud computing, big data, internet of things, cognitive radio networks, and quantum networking.

Ruidong Li [SM'07] (lrd@se.kanazawa-u.ac.jp) received his bachelor's degree in engineering from Zhejiang University, China, in 2001, and received his Ph.D degree from the University of Tsukuba in 2008. Currently, he is an associate professor in College of Science and Engineering, Kanazawa University, Japan. Before joining Kanazawa University, he was an a senior researcher with the Network System Research Institute, National Institute of Information and Communications Technology (NICT). His research interests include big data networking, blockchain, information-centric network, internet of things, network security, wireless networks, and quantum Internet.