A Connectionless Entanglement Distribution Protocol Design in Quantum Networks

Zirui Xiao, Jian Li, Kaiping Xue, Zhonghui Li, Nenghai Yu, Qibin Sun, Jun Lu

***Abstract*—Remote entanglement distribution plays a crucial role in quantum networks, which can support many essential and exciting quantum applications. As the network scale expands, it is urgent to design a general and efficient remote entanglement distribution protocol. Nowadays, connection-oriented remote entanglement distribution protocols are available to achieve reliable entanglement distribution. However, in memory-limited quantum networks, connection-oriented entanglement distribution protocols cannot utilize entanglement resources fully and increase the delay of End-to-End (E2E) entanglement connection establishment. To overcome these shortcomings of existing entanglement distribution protocols, we design a connectionless remote entanglement distribution protocol to let Source-Destination (S-D) pairs compete for entanglement resources simultaneously. In our protocol, a fair request scheduling algorithm is proposed to reduce the waiting time without entanglement connections between S-D pairs. Furthermore, a fast scheduling trigger mechanism is proposed to perform entanglement swapping timely to reduce the delay of E2E entanglement connection establishment. The simulation results show that the designed protocol has advantages in terms of resource utilization, throughput, the service completion time of S-D pairs, and the maximum waiting time, compared with the existing remote entanglement distribution protocol.**

***Index Terms*—Quantum networks, entanglement distribution, connectionless protocol.**

I. Introduction

With the rapid development of quantum technologies, it is gradually becoming practical to connect numerous quantum nodes to form quantum networks. Quantum network provides a foundational platform for realizing ground-breaking applications, such as distributed quantum computing [1], quantum key distribution [2], and quantum clock synchronization [3]. Many of these applications rely on remote entanglement distribution. Therefore, realizing entanglement distribution between remote nodes is an essential and core task for quantum networks.

To realize remote entanglement distribution, quantum repeaters are introduced between two distant nodes to generate short-distance entangled pairs (i.e., link-level entanglement or one-hop entanglement) and then connect the short-distance entangled pairs to form long-distance ones via entanglement swapping. According to the layered design and functional allocation of a quantum network stack [4], the remote entanglement distribution protocol is responsible for extending link-level entanglement to End-to-End (E2E) entanglement connections. Due to the unique properties of quantum mechanics, such as quantum decoherence and no-cloning theorem, we cannot directly apply existing protocol designs that have been widely used in classical networks to quantum networks. Therefore, it is important to design an entanglement distribution protocol for quantum networks to overcome such challenges and achieve efficient entanglement distribution.

Most of the existing studies focus on theoretical analysis and algorithm design of specific problems in remote entanglement distribution, e.g., path selection [5], [6], resource allocation [7], [8], and entanglement swapping problems [9]. A few other studies focus on the design of remote entanglement distribution protocols. They can be divided into connection-oriented and connectionless entanglement distribution protocols, respectively. For the former one, Kozlowski *et al.* [10] proposed a quantum data plane protocol. After that, Li *et al.* [11] designed a connection-oriented entanglement distribution protocol, which uses resource management to provide quality-of-service guarantee in terms of latency and entanglement distribution rate in memory-rich quantum networks. However, when resources and the size of quantum memory on each node in a quantum network are limited, the connection-oriented entanglement distribution protocol introduces significant classical communication delays to lock/release memory units for Source-Destination (S-D) pairs and cannot dynamically adjust the use of link-level entanglement. In addition, other S-D pairs without allocated memory units have to wait long to use entanglement resources, increasing their waiting time. For the latter one, as a pioneering study, Li *et al.* [12] proposed a framework for the connectionless entanglement distribution protocol. The authors provided constructive guidance for the protocol design of connectionless remote entanglement distribution in quantum networks. However, how to design signaling interaction process and dynamically adjust the use of link-level entanglement remains an open problem.

To solve above mentioned problems, we propose a connectionless entanglement distribution protocol that operates in a decentralized manner. Our protocol uses streamlined signaling interaction process to avoid excessive classical communication delays and connectionless entanglement distribution method to improve network resource utilization. We propose a fair request scheduling algorithm to guarantee fair request competition for link-level entanglement, which can prevent requests sent by individual S-D pairs from being unable to use entanglement resources for a long time. We also design a fast scheduling trigger mechanism to reduce the delay of E2E entanglement connection establishment by reducing the

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queuing delay for requests and re-transmission delay of re-transmission requests. **To the best of our knowledge, this is the first work of a comprehensive protocol design specifically for connectionless entanglement distribution method in quantum networks.**

Our contributions in this article are as following:

- We design a connectionless entanglement distribution protocol that uses streamlined signaling interaction process and modular design to implement remote entanglement distribution. Our protocol can reduce the delay of E2E entanglement connection establishment, improve network resource utilization, and avoid long waiting time without entanglement connections between S-D pairs.
- We propose a fair request scheduling algorithm and a fast scheduling trigger mechanism for our protocol to address a critical problem, i.e., multiple requests competition problem. The proposed algorithm and mechanism can let requests sent by S-D pairs compete fairly for link-level entanglement and spend less time establishing E2E entanglement connections between S-D pairs.
- We conduct extensive simulations in SimQN [13], a discrete-event-based quantum network simulation platform, to evaluate the effectiveness of our proposed protocol. Compared with the existing protocols, our protocol shows the significant superiority in terms of throughput, delay, and resource utilization.

The rest of this article is organized as follows. Firstly, we briefly review the background knowledge on establishing entanglement connections, compare connection-oriented and connectionless entanglement distribution methods, and present the design goals of our protocol. Then, we describe the details of our connectionless entanglement distribution protocol. After that, we perform simulations to demonstrate the effectiveness of the proposed protocol and discuss the simulation results. Finally, we conclude our work in the final section.

II. Background

In this section, we first present key techniques for implementing entanglement connection establishment, i.e., entanglement generation technique and entanglement swapping technique. After that, we use an example to compare connection-oriented and connectionless entanglement distribution methods and motivate the design of our connectionless entanglement distribution protocol. At the end of this section, we present the design goals of our protocol.

A. Entanglement Connection Establishment

As shown in Fig. 1, our protocol first uses entanglement generation techniques to create entanglement links between two adjacent nodes. After that, it uses entanglement swapping techniques to stitch these links together to establish entanglement connections between S-D pairs.

Entanglement generation aims to distribute entangled pairs between adjacent nodes directly connected by quantum channels (i.e., to create link-level entanglement). Due to channel loss and quantum decoherence, the success rate of entanglement generation decreases exponentially with the length of quantum channels when using optical fibers for the transmission of quantum bits, that is, $p_{out} \sim e^{-\alpha l}$, where α is a constant and l is the length of quantum channels, as shown in Fig. 1. Our protocol can use heralded entanglement generation [14] to judge whether link-level entanglement is successfully generated. Usually, multiple attempts are required to generate link-level entanglement successfully. After entanglement generation, each entangled pair must be stored in quantum memory to reduce the effects of decoherence.

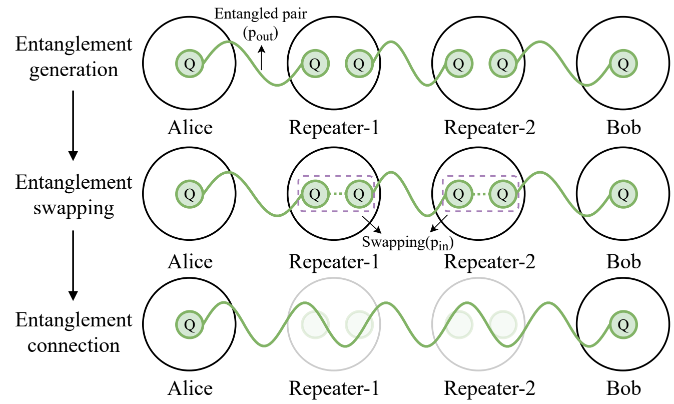

Fig. 1. End-to-end entanglement distribution between two remote quantum nodes.

It is not feasible to transmit entangled pairs directly over long distances by using one quantum channel due to transmission loss and decoherence. Therefore, entanglement swapping plays an important role in implementing remote entanglement distribution. We typically deploy quantum repeaters between distant nodes and connect a series of link-level entanglement by performing entanglement swapping at intermediate nodes to obtain E2E entanglement connections [15]. However, entanglement swapping is probabilistically successful, and entangled pairs cannot be reused after being measured. We use p_{in} to denote the success probability of entanglement swapping, as shown in Fig. 1. Meanwhile, the success of entanglement swapping can be detected by quantum measurement. In this article, we consider the hop-by-hop entanglement swapping method to establish E2E entanglement connections. When entanglement swapping is successful, intermediate nodes must transmit the results of the joint measurements to the next-hop node for Pauli frame corrections to complete the entanglement swapping.

B. Connection-oriented and Connectionless Entanglement Distribution Methods

There are two different methods for entanglement distribution: connection-oriented and connectionless. The connection-oriented entanglement distribution method [10], [11] must establish/release virtual circuits to lock/release memory units between S-D pairs based on a resource allocation algorithm, followed by entanglement generation attempts on the already allocated memory. The entangled pairs generated on the link and stored in the already allocated memory units can only be used by requests sent by specific S-D pairs. As shown in Fig.

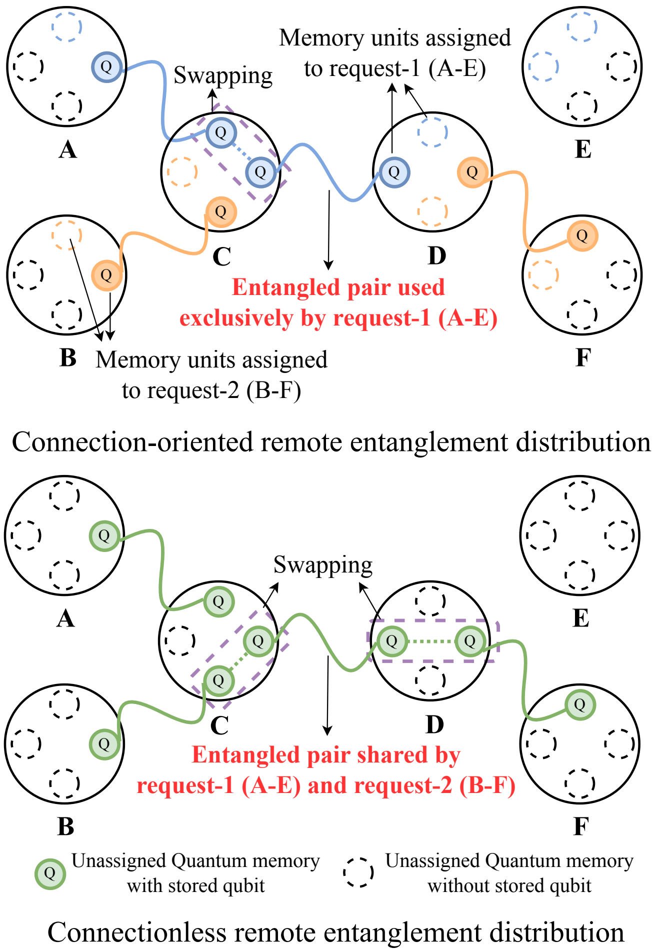

Fig. 2. A typical example of the connection-oriented entanglement distribution method (top) and the connectionless entanglement distribution method (bottom). The significant difference between the connection-oriented entanglement distribution method and the connectionless entanglement distribution method is whether or not the memory resources on a node are locked (i.e., whether or not the entanglement resources stored on the memories are dedicated).

2, the generated entangled pairs stored in the blue memory units can only be used by S-D pairs A-E, and the generated entangled pairs stored in the orange memory units can only be used by S-D pairs B-F. Therefore, the entanglement resource generated between C and D cannot be used by request-2. The connection-oriented entanglement distribution method cannot dynamically adjust the use of link-level entanglement. In this way, the connection-oriented entanglement distribution method cannot establish entanglement connections between A and E or B and F. It causes the waste of entanglement resources. Furthermore, other S-D pairs that do not establish virtual circuits have to wait long to use entanglement resources, increasing their waiting time.

In contrast, the connectionless entanglement distribution method [12] lets the source nodes of S-D pairs send requests to compete for the use of link-level entanglement. It uses the designed request scheduling algorithm to determine the order of each request on nodes using link-level entanglement and dynamically adjusts the use of link-level entanglement. In this way, as shown in Fig. 2, with a well-designed request scheduling algorithm, the entanglement resource generated between C and D can be used by request-2. The connectionless entanglement distribution method can establish an E2E entanglement connection between B and F. This example shows that the connectionless entanglement distribution method can use streamlined signaling process. This example also shows that the design of the request scheduling algorithm is important. It can help the connectionless entanglement distribution method dynamically adjust the use of link-level entanglement. As a result, it has advantages in terms of delay and network resource utilization.

C. Design Goal

As shown in Fig. 2, in the scenario where node memory units are limited and link-level entanglement generation is prone to failure, we find that the connectionless entanglement distribution method can establish more entanglement connections than the connection-oriented entanglement distribution method in this scenario. At the same time, the connectionless entanglement distribution method can avoid the tedious signaling interaction process of establishing/releasing "virtual circuits" and avoid waiting for the release of "virtual circuits" established by other S-D pairs before using the resources generated on links, so it can start establishing entanglement connections between S-D pairs more quickly. This article aims to design an efficient and easy-to-deploy connectionless entanglement distribution protocol for memory-limited quantum networks. Specifically, this protocol should allow each S-D pair to share link-level entanglement, thus avoiding introducing additional classical communication delays to lock/release memory units for each S-D pair. Meanwhile, this protocol should be able to dynamically adjust the use of link-level entanglement (thus, performing dynamic resource allocation) and reduce the waiting time before entanglement connections are established between S-D pairs.

III. Protocol Design and Implementation

A. Overview

In this section, we propose a connectionless entanglement distribution protocol, which provides remote entanglement distribution through modular design and decentralized operations. It consists of a memory management module, an entanglement tracking module, and a request scheduling module, each of which has its own functionality and design goals. First, the memory management module is designed to prevent nodes from having no free memory unit to store entangled pairs generated with neighboring nodes during the runtime of our protocol. Second, the entanglement tracking module is designed to help the source nodes of S-D pairs track the state and storage location of entangled pairs during hop-by-hop entanglement swapping. Third, the request scheduling module, which contains a fair request scheduling algorithm and a fast scheduling trigger mechanism, is designed to perform request scheduling to address the critical problem, i.e., multiple requests competition problem. Through the collaboration of these well-designed modules, our protocol can

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establish E2E entanglement connections between S-D pairs in a decentralized manner, as shown in Fig. 3.

Next, we will introduce the main modules and signaling interaction process in detail in our protocol.

B. Module Design

Memory management module. The memory management module is designed to prevent nodes from having no free memory unit to store entangled pairs generated with neighboring nodes during the runtime of our protocol. In the connectionless entanglement distribution method, the source nodes of S-D pairs can send requests simultaneously to compete for entanglement resources so that intermediate nodes may receive many requests. The intermediate nodes need to perform entanglement swapping to extend the entanglement distance and "transit" the received requests. If no memory management module exists on nodes, requests may occupy all the quantum memory units of nodes in the network, that is, the memory units of nodes are all occupied by multi-hop entangled pairs. Then, the node has no free memory unit to store the generated link-level entanglement. Therefore, no link-level entanglement resource is available for the stored multi-hop entanglement at the node to perform entanglement swapping. This situation can increase the delay of E2E entanglement connection establishment. Therefore, we design the memory management module by refining the use of memory units so that requests from different directions use different memory units. Through using the memory management module, our protocol can set aside a portion of free memory units for each request to store the generated link-level entanglement resources.

Entanglement tracking module. Our protocol must track entangled pairs and entanglement swapping involved in establishing each E2E entanglement connection for the following reasons: First, our protocol is based on the connectionless entanglement distribution method, where E2E entanglement connections are established by hop-by-hop entanglement swapping. The source nodes of S-D pairs need to know with which node it has currently established multi-hop entanglement and also need to know in which memory unit entangled pairs are stored. Second, after entanglement swapping, the node performing entanglement swapping needs to inform the source node of requests and successor nodes about the result of entanglement swapping. Therefore, the entanglement tracking module is designed to help the source nodes of S-D pairs track the state and storage location of entangled pairs during hop-by-hop entanglement swapping.

When the source nodes of S-D pairs send requests, when intermediate nodes perform entanglement swapping (successfully or unsuccessfully), and when the destination nodes of S-D pairs receive requests, our protocol needs to use the following signaling interaction process to help the two nodes involved in entanglement keep track of the state of entangled pairs. In our signaling format design, *pre* and *suc* represent the predecessor and successor nodes involved in entanglement swapping, respectively. In addition, *result* indicates the classical information obtained from successful entanglement swapping. We also use *src/suc/dst_storage_idx* to represent the storage location of entangled pairs on the corresponding node. Compared with other protocols, our protocol uses more streamlined classical signaling interaction process to track the state of entangled pairs.

– When there is an unoccupied link-level entanglement between the source nodes and next-hop nodes of S-D pairs, the source nodes of S-D pairs use signaling *Success* = {request_idx, src, dst, suc, src_storage_idx, suc_storage_idx, result} to send the request with the sequence number *request_idx* to next-hop nodes and informs next-hop nodes that the request with the sequence number *request_idx* has occupied link-level entanglement generated on *suc_storage_idx* memory unit.
– When intermediate nodes fail to perform entanglement swapping, intermediate nodes use signaling *Fail* = {request_idx, pre, suc, pre_storage_idx, suc_storage_idx} to inform node *pre* and node *suc* to release the memory units with index numbers *pre_storage_idx* and *suc_storage_idx* on the node, respectively.
– When intermediate nodes perform entanglement swapping successfully, intermediate nodes use signaling *Success* to forward the request with sequence number *request_idx* to node *suc*.
– When nodes receive signaling *Success*, it means that nodes have received the request with sequence number *request_idx*. Our protocol has successfully established entanglement between the current node (i.e., node *suc*) and node *src*, and entangled pairs are stored in memory unit *suc_storage_idx* of node *suc* and memory unit *src_storage_idx* of node *src*, respectively.
– When the receiving node of *Success* is node *dst*. Node *dst* will send signaling *Finish* = {request_idx, src, dst, src_storage_idx, dst_storage_idx, result} to node *src*. Based on the information in signaling *Finish*, node *src* can know that the request with sequence number *request_idx* has successfully established an entanglement connection between node *src* and node *dst*, and the storage location of entangled pairs on node *src* (i.e., *src_storage_idx*).

Request scheduling module. The request scheduling module is designed to perform request scheduling, which contains a fair request scheduling algorithm and a fast scheduling trigger mechanism. The fair request scheduling algorithm determines the order of each request on nodes using link-level entanglement. The fast scheduling trigger mechanism determines when to execute the designed fair request scheduling algorithm. Our protocol uses the proposed fair request scheduling algorithm to avoid multiple requests using the same entanglement resource simultaneously and dynamically adjust the use of link-level entanglement. Meanwhile, our protocol uses the designed fast scheduling trigger mechanism to reduce the delay of E2E entanglement connection establishment.

In our protocol, nodes record the usage information of the entanglement resources on links, i.e., nodes can know which S-D pair uses the link-level entanglement. The workflow of the fair request scheduling algorithm is as follows: 1) Nodes select the request sent by the S-D pair that uses the least resources

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(e.g., Alice-Bob) from the queue for scheduling at the current node based on the information recorded by the node. Our request scheduling algorithm prioritizes the requests sent by Alice for scheduling. 2) Since Alice may send more than one request to establish an entanglement connection (since Alice may wish to establish multiple entanglement connections with Bob), nodes may receive more than one request from Alice. In this case, nodes allow the request with the highest fidelity among the requests sent by Alice to use the one entanglement resource generated on the link first. 3) Nodes then update the information about the usage of the entanglement resource on the link. Our protocol repeats the above processes until all entanglement resources on links are used up, or there is no request waiting to be scheduled on nodes. Therefore, the fair request scheduling algorithm can help our protocol dynamically adjust the use of link-level entanglement. Compared to connection-oriented entanglement distribution protocols, it can also guarantee requests sent by S-D pairs compete fairly for link-level entanglement and avoid long periods when no entanglement connections are established between specific S-D pairs.

In addition to the fair request scheduling algorithm, our protocol uses the fast scheduling trigger mechanism to decide when to execute the designed fair request scheduling algorithm. The fair request scheduling algorithm is executed in two cases to use generated resources as soon as possible to minimize the queuing delay of requests: 1) When link-level entanglement is generated and memory management is complete, nodes want to forward requests queued in nodes to next-hop nodes as soon as possible. 2) When a new request arrives, the receiving node wants the new request to use pre-generated entanglement resources immediately. Moreover, once the source nodes of S-D pairs receive signaling *Fail*, the source nodes will immediately try to send a new request without waiting for all requests sent by that node to be processed. It can reduce the waiting time for re-attempting entanglement connection establishment. Our protocol uses the fast scheduling trigger mechanism to reduce the queuing delay of requests on nodes and the waiting time for re-attempting entanglement connection establishment, thus reducing the delay of E2E entanglement connection establishment.

C. Example of Protocol Workflow

We use Fig. 3 to illustrate the implementation of our protocol with a concrete example. As shown in Fig. 3, Node-1 receives two requests (request-1 and request-2), both of which want to establish entanglement connections between the source (Node-1) and destination (Node-4) nodes of requests to serve upper-layer applications. The protocol workflow is as follows.

1. Node-1 triggers request scheduling after completing memory management, and the fair request scheduling algorithm lets request-1 use entanglement generated between Node-1 and Node-2 first. Node-1 uses classical signaling *Success* = {request_idx, source_node, destination_node, receive_node, src_loc_idx, rec_loc_idx, result} to send request-1 to Node-2 and informs Node-2 that entanglement generated between Node-1 and Node-2 has been used by request-1.

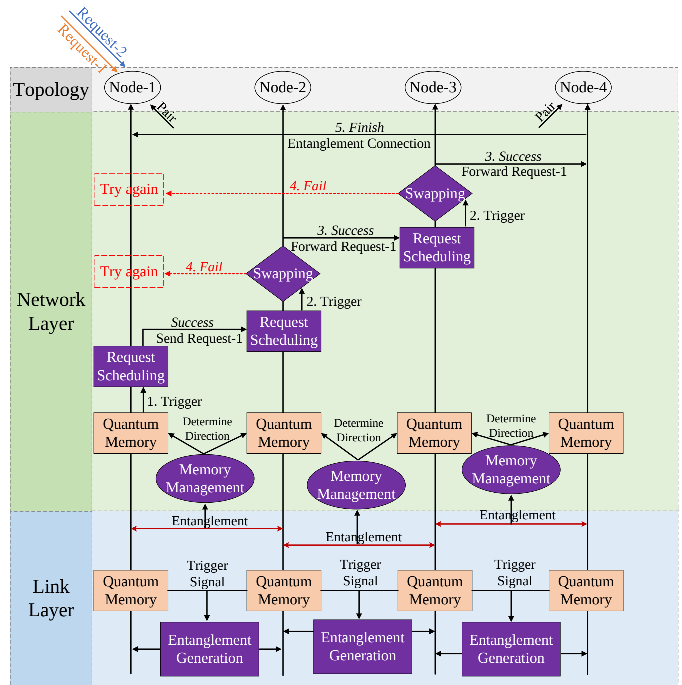

Fig. 3. Example sequence of our designed connectionless entanglement distribution protocol.

2. When Node-2 receives request-1 (i.e., Node-2 receives signaling *Success* which contains request-1), it immediately triggers request scheduling, and the fair request scheduling algorithm lets request-1 use pre-generated entanglement between Node-2 and Node-3 for entanglement swapping.
3. If entanglement swapping is performed successfully, Node-2 uses classical signaling *Success* to send request-1 to Node-3 and informs Node-3 that request-1 has established a two-hop entanglement between the source node of request-1 (Node-1) and Node-3. Node-3 will perform the same operation as Node-2.
4. If entanglement swapping is performed unsuccessfully, Node-2 uses classical signaling *Fail* = {request_idx, source_idx, receive_idx, src_loc_idx, rec_loc_idx} to inform the successor node (Node-3) and the source node of request-1 (Node-1) that the entanglement resource at the corresponding location has been used and triggers the source node of request-1 (Node-1) to send a new request.
5. When the destination of request-1 (Node-4) successfully receives request-1, it must use classical signaling *Finish* = {request_idx, source_node, destination_node, src_loc_idx, des_loc_idx, result} to inform the source node of request-1 (Node-1) that an entanglement connection has been established between the source and destination nodes of request-1.
6. Node-1 and Node-4 deliver the successfully established entanglement connection to upper-layer application.

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IV. Simulation

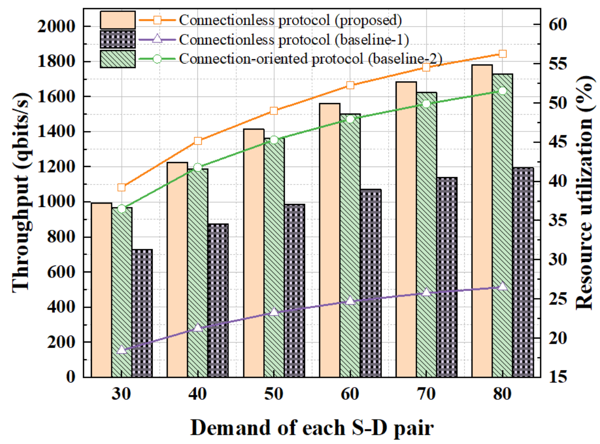
In this section, we evaluate the performance of our connectionless entanglement distribution protocol through extensive simulations using a discrete-event-based network simulation platform for quantum networks, SimQN [13]. Specifically, we evaluate the performance of the proposed protocol compared with existing entanglement distribution protocols under the different demand of S-D pairs scenarios and different entanglement swapping success probability scenarios, respectively.

A. Simulation Setup

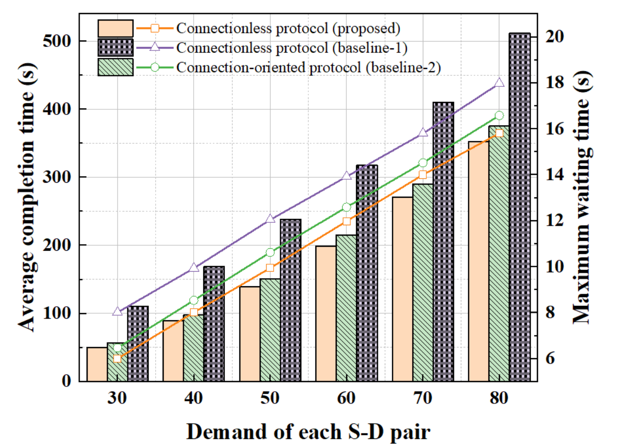
Default parameters. The simulation involves randomly generated network topology, randomly selected S-D pairs, randomly selected number of requests sent by the S-D pairs, and control parameters for quantum memory and entanglement generation rate. We randomly generated a network topology with 100 nodes, 200 quantum links, and 30 S-D pairs. Each node allocates 100 quantum memory units for each quantum channel. We generally set the entanglement generation probability $p_{out} = 0.8$ and the entanglement swapping success probability $p_{in} = 0.8$. The entanglement generation rate is 50 per second (i.e., link-level entanglement generation is attempted every 20 ms). The transmission delay of classic packets is 10 ms. We adopt the shortest path routing algorithm to find a suitable path for S-D pairs in the randomly generated network topology. For a given set of parameters, simulations are run 100 trials and the averaged results are shown.

Comparison schemes. We compare our designed connectionless entanglement distribution protocol with two entanglement distribution protocols. One is the existing connection-oriented entanglement distribution protocol [11], the other is the baseline for connectionless entanglement distribution protocol (using a threshold/time trigger mechanism that triggers request scheduling after reaching a specific threshold or after a particular time elapses). We use baseline-1 to denote the baseline for connectionless entanglement distribution protocol and baseline-2 to denote the connection-oriented entanglement distribution protocol, respectively.

Performance metrics. We compare the performance of different schemes with respect to four metrics: resource utilization, throughput, average service completion time, and maximum waiting time in the network. Resource utilization is defined as the ratio of the entanglement resources used to the resources generated on the path. Throughput represents the number of successfully established E2E entanglement connections in the network over a period of time. The demand of S-D pairs (i.e., the number of entanglement connections each S-D pair wants to establish) may differ. We refer to the time it takes for an S-D pair to enter the network until it has established the required number of entanglement connections as the service completion time of the S-D pair. We define the mean of the service completion time of all S-D pairs in the network as the average service completion time. In addition, we define the largest service completion time among all S-D pairs as the maximum waiting time.



(a) Throughput (left, column graph) vs. Resource utilization (right, line graph)



(b) Average completion time (left, column graph) vs. Maximum waiting time (right, line graph)

Fig. 4. Performance comparison for different demands of each S-D pair in terms of throughput, resource utilization, average completion time, and maximum waiting time.

B. Simulation Results

Effect of the demand of each S-D pair. To investigate how the concurrency, i.e., the demand of each S-D pair [1], impacts the performance of our designed connectionless protocol, we increase the demand of each S-D pair from 30 to 80, and repeat the simulations. Simulation results are shown in Fig. 4. The proposed protocol has advantages in resource utilization, throughput, average service completion time, and maximum waiting time in the network compared to baseline-1 and baseline-2. From Fig. 4a, we can observe that the resource utilization and throughput achieved by all protocols increase when the demand of each S-D pair increases. Because the source nodes of S-D pairs send more requests to use entanglement resources. The proposed protocol has higher resource utilization and throughput. It uses the connectionless entanglement distribution method and fair request scheduling algorithm to adjust resource allocation, thus avoiding wasting resources. The baseline-1 has the lowest resource utilization

[1]The number of end-to-end entanglement connections we need to establish between the source and destination of this S-D pair. When the "demand of S-D pair" is satisfied, the S-D pair will exit from the quantum network.

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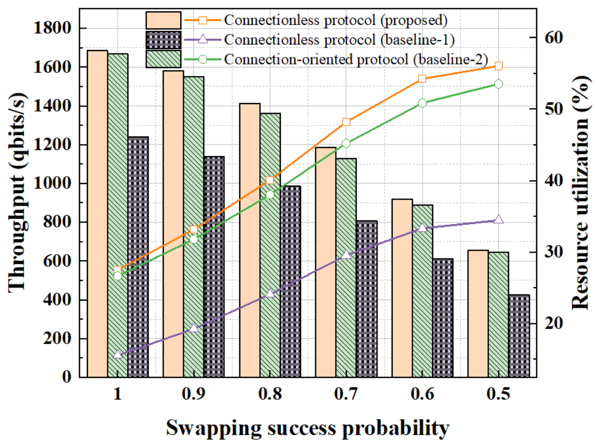
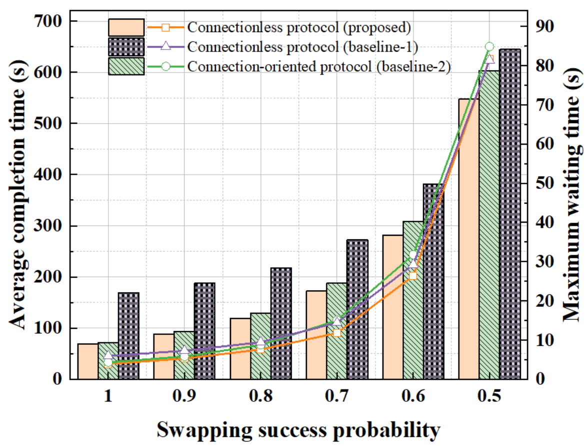


(a) Throughput (left, column graph) vs. Resource utilization (right, line graph)



(b) Average completion time (left, column graph) vs. Maximum waiting time (right, line graph)

Fig. 5. Performance comparison for different entanglement swapping success probability in terms of throughput, resource utilization, average completion time, and maximum waiting time.

and throughput since it does not use the fast scheduling trigger mechanism, leaving many generated resources unused in the network. As shown in Fig. 4b, the average service completion time and maximum waiting time increase with the demand of each S-D pair. Because we need to establish more entanglement connections between each S-D pair. The proposed protocol uses the fast scheduling trigger mechanism and streamlined signaling interaction to reduce the delay of E2E entanglement connection establishment. Thus it has the lowerest average service completion time. In addition, it uses the fair request scheduling algorithm to establish entanglement connections between S-D pairs simultaneously and independently, thus having the lowest maximum waiting time.

Effect of the entanglement swapping success probability. To investigate how the entanglement swapping success probability impacts the performance of different protocols, we pick a value from the set $1.0, 0.9, 0.8, 0.7, 0.6, 0.5$ to be this probability and repeat simulations. Simulation results are shown in Fig. 5. Since the proposed protocol is not designed for a specific scenario, it is applicable to various scenarios so that we can observe similar observations as in Fig. 4. However, when the entanglement swapping success probability is low, the proposed protocol and baseline-2 have similar performance since with a low entanglement swapping success probability, very few entanglement connections can be established between S-D pairs. From Fig. 4a, lower entanglement swapping success probability leads to lower throughput. The resource utilization achieved by all protocols increases when the entanglement swapping success probability decreases since there are many re-transmission requests in the network, increasing the consumption of entanglement resources. The proposed protocol uses the fast scheduling trigger mechanism to enable the source nodes of S-D pairs to re-transmit the request immediately after entanglement swapping failure so that the re-transmitted request can quickly use entanglement resources, thus having the highest resource utilization and throughput. As shown in Fig. 5b, the average service completion time and maximum waiting time increase as the entanglement swapping success probability decreases. Because re-transmission requests increase the delay of E2E entanglement connection establishment. Similar to the reasons in Fig. 4b, the fast scheduling trigger mechanism and the fair request scheduling algorithm allow the proposed protocol to have the lowest average service completion time and maximum waiting time.

V. Conclusion

In this article, we studied the connectionless entanglement distribution protocol design to implement remote entanglement distribution for various quantum applications. First, we analyzed connection-oriented and connectionless entanglement distribution methods and indicated that the connectionless entanglement distribution method has advantages in memory-limited quantum networks. After that, we designed a connectionless remote entanglement distribution protocol. To avoid introducing additional classical communication delays to lock/release memory units for each S-D pair, our protocol allows S-D pairs to share link-level entanglement. In our protocol, a fair request scheduling algorithm is designed to dynamically adjust the use of link-level entanglement and reduce the waiting time without entanglement connections between S-D pairs. Furthermore, a request scheduling trigger mechanism is designed to reduce the delay of E2E entanglement connection establishment by reducing the queuing delay for requests and re-transmission delay of re-transmission requests.

Through the extensive simulations on SimQN, we verified the effectiveness of the proposed protocol. Our protocol has advantages in resource utilization, throughput, the service completion time of S-D pairs, and the maximum waiting time. Although this article provides a concrete connectionless remote entanglement distribution protocol for quantum networks, some challenges still hinder the performance of our proposed protocol, e.g., the success probability of entanglement swapping, the coherence time of quantum memory, and so on. It is foreseen that as quantum information technology continues to advance, these challenges will be gradually overcome, and our protocol can perform better. In the future, we plan to consider incorporating purification into our protocol to further improve the quality of entanglement connections.

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