Modeling for Performance Evaluation of Quantum Network

Shahad Hussein and Alharith Abdullah

July 16, 2022

Modeling for Performance Evaluation of Quantum Network

Shahad A. Hussien[1], Alharith A. Abdullah[1]*
College of Information Technology
University of Babylon
Babil, Iraq

alharith@itnet.uobabylon.edu.iq

Abstract. Quantum networks are emerging sciences and are anticipated to be the core networking technologies in the future. Due to the difficulty of implementing quantum networks in a real way, because quantum devices are not widely available, they only exist within their laboratories. In addition, they are costly and also need special environments that are not easy to obtain in other than laboratories. In this paper, the authors build a simulator using the language of Python programming to simulate quantum networks in terms of quantum devices, such as repeaters, final nodes and channels, where the behavior of these elements within the network is simulated for the purpose of sending quantum information represented by quantum bits, and therefore the work will be within the principle of the graph and finally facilitate experiments on networks Quantum devices without the need for real physical devices. The most remarkable result that emerged from the simulated data generated and detected is that the modeling process provides guidance for quantum networks design, characterization of their protocols, and their behavior. As a result of this study, one could simulate a quantum network repeater and end node as well as a quantum link (entanglement link) and implement some of the quantum protocols like Quantum Key Distribution (QKD), Teleportation and quantum protocol. In the end, it is concluded the possibility of simulating the behavior of the quantum network, its devices, and protocols, as well as implementing it and developing the quantum applications, an integrated study about the quantum internet and its routing in it. In addition, we were able to develop a quantum repeater protocol in order to enable end-to-end entanglement.

Keywords: Quantum Network, Quantum Internet, Entanglement Probability, Quantum simulation, Qubits

1 Introduction

Quantum networks are the networks through which devices are interconnected, where these devices communicate through quantum communications by exploiting quantum mechanics, where the success of quantum information technologies lies at the heart of quantum networks [1]. Also, it provides great capabilities unparalleled in classical networks, and therefore, these capabilities are used in the formation of penetrations on classical networks [2].

The nature of the work and behavior of quantum networks in transferring and sharing information is not an easy process that can be imagined. It depends on the principle of quantum entanglement between quantum bits that exist within quantum memories [3]. At the same time, the delivery of this information within the best path to the recipient is based on the principle of entanglement swapping according to the criteria adopted by the routing protocol used in a quantum router (currently adopted quantum repeater), which details will be clarified in the following sections.

On the other hand, imagining quantum networks does not stop there. It also extends to the architecture of the quantum Internet, as it specializes in what is contained in quantum networks [3]. Accordingly, the development of quantum networks makes the implementation of the quantum internet in the near future. Due to this, there is a need to test everything related to quantum networks, such as testing protocols and the nature of the work of devices and evaluating their performance before implementing them in a real way to avoid problems that may appear at that time, and this can be done at the laboratory. Still, because quantum devices are not widely available, need special environments, and are very expensive, it is challenging to apply quantum networks to real devices for the purpose of testing. Therefore, the trend is toward building a simulator for quantum networks [4].

As for quantum networks, such simulators (classical network simulators) are not compatible with them. Through this, it can be said that there are no basic simulators for working with quantum networks, but with that, some sources have shown the existence of some simulators for quantum networks built using programming languages like QuNetSim [4]. NetSquid is often closer to the SQUANCH than the SimulaQron in terms of behavior, as it stimulates the physical property of quantum devices like noise in the link, but it is not available to everyone yet [5]. In comparison, SQUANCH is similar to the SimulaQron in terms of performing tasks, except that it adds the possibility of simulation within the physical layer, which allows simulating the processing of quantum information. In addition, it allows the user to add the error model within the physical layer [6]. Besides, SimulaQron simulates software that runs within the application layer on quantum devices, and thus, it simulates quantum internet programs [7]. Some of which are open source while the others are not. Therefore, this research aims to build a simulator for quantum networks, where it is easy for developers to develop quantum applications and protocols and their ease of implementation on network devices, in addition to developing a quantum repeater protocol and allocating it to each of the nodes specialized in implementing this protocol based on the cumulative pre-entanglement possibilities. The use of this entanglement is over long distances to carry out the transmission of quantum information in the process of teleportation.

The present research is divided as follows: Section (2) of the research reviews some Quantum Network considerations, while the proposed Quantum Network Platform Design is revealed in Section (3), and Section (4) shows the result and discussion of the research, finally, the conclusions are revealed Section (5).

2 Consideration of Quantum Network

There are many considerations that are specific to quantum networks, such as no-cloning, quantum measurement, quantum entanglement, and others. This section will summarize the most important principles that the present research deals with.

2.1 Qubits and Entanglement

A single quantum bit carries two possibilities for the information it transmits [1]. Therefore, Entanglement indicates that two quantum particles (qubits) are in a common state. Also, these two particles, regardless of the distance between them, one of them is completely affected by the other immediately [8]. Through this, one of the qubits of the entanglement pair can be directly fixed once the other qubit of this quantum state is measured according to quantum mechanics. It represents the core of quantum internet; besides, quantum entanglement is a unique concept, and it is impossible to find anything like it in the classical physics upon which the current classical networks depend [2].

2.2 Quantum Entanglement Swapping

Entanglement Swapping is a recent phenomenon considered a fundamental key to the realization of quantum networks, especially the transmission and routing of quantum data [3][9]. Through which Einstein-Podolsky-Rosen (EPR) pairs can be shared over long distances [10], so quantum networks based on repeaters can overcome the problem of loss during the quantum information transmission process [11] due to the absence of the possibility of signal amplification within these repeaters due to quantum mechanics [3][11]. Fig. 1. (a). represents a short link (short distance entanglement) between the qubits of quantum memories of the quantum repeater and the end nodes. While (B) represents forming the long-distance entanglement after swapping on repeater [8][3], as shown in Fig.1.

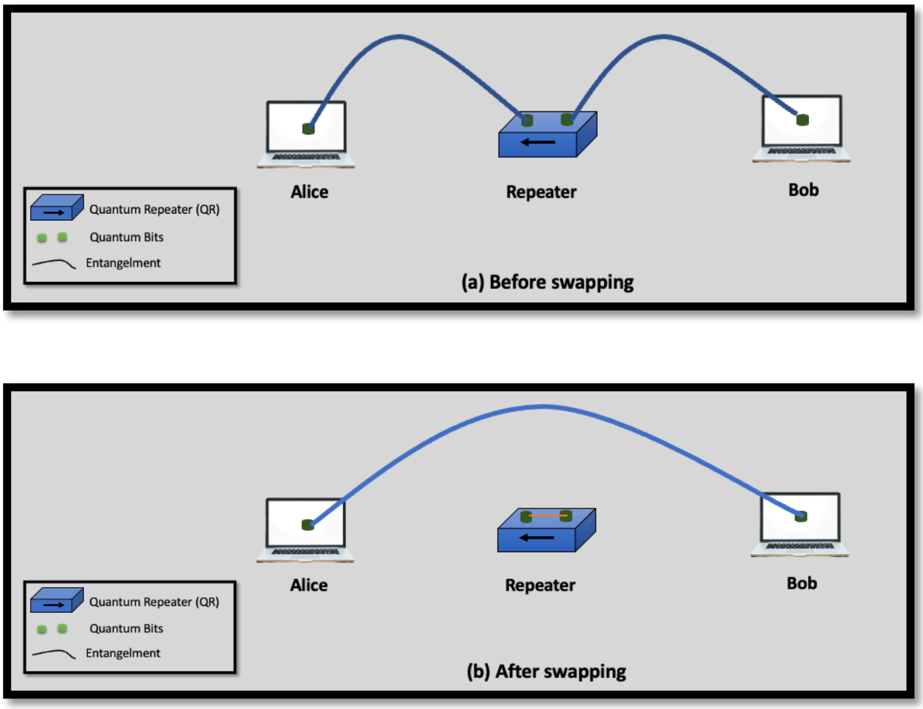

Fig. 1. Build a Long-Distance Entanglement by Entanglement Swapping Alice represents the sender, and Bob represents the receiver

2.3 Quantum repeater

The heart of the quantum internet is the repeater node. This node makes it possible to establish long-term communication between the sender and the receiver [3].

While quantum repeaters are subject to quantum laws like the theory of non-cloning [12], their work is limited to quantum information and through which control messages can be exchanged between nodes by linking repeaters with other repeaters and quantum processors through the classical internet [3][12].

In the end, since all types of networks are not free from loss resulting in the channel that connects the network as a result of the surrounding physical conditions and others, the presence of repeaters is necessary, as it is installed at distances commensurate with the amount of loss existing in the channel to improve the performance of the network, whether quantum was it classic [4]. The next section will explain more details about how quantum repeaters work.

2.4 Network Stack

Computer networks are complex, whether they are classical or quantum networks. The OSI model is followed to break the complexity found in classical networks. Then, the TCP/IP model is used, where the network becomes operating in several layers, each layer in the model plays a role and serves. The next layer, and therefore each layer, receives information messages (packets) from the previous layer. The necessary information is added to the message packet and passed to a higher layer than it at one end of the network, while the other end reverses the operations carried out by the first end. Thus, it obtains the basic information sent from the sender to the recipient [1]. In addition to that, each layer of the model has its own set of protocols, and the data has a specific name in each layer. Also, every physical device works according to a certain layer in the network. For example, the data in the network layer is called packets, referred to as a segment at the transport layer, and while the physical switch device operates at the data link layer, the physical router device operates at the network layer, and so on.

Quantum networks are not conceptually different from classical networks, as they also have their difficulty. Thus, quantum network concepts, such as entanglement, session communication techniques and error scaling, lead us to a layered architecture of their but remain lab-scale. Due to the radical quantum field limitations, it does not constitute a complete network architecture because it is still under experiment [5].

While classical network software and hardware work in the TCP/IP model, quantum network software and hardware operate within a model almost similar to what is used in current networks, which is called the layer model (as shown in Fig. 2.). It consists of four layers arranged from top to bottom: application layer, transport layer, network layer, and network access layer. Each has its tasks, and perhaps some of them are similar to what is found in the classic networking model [13], as follows:

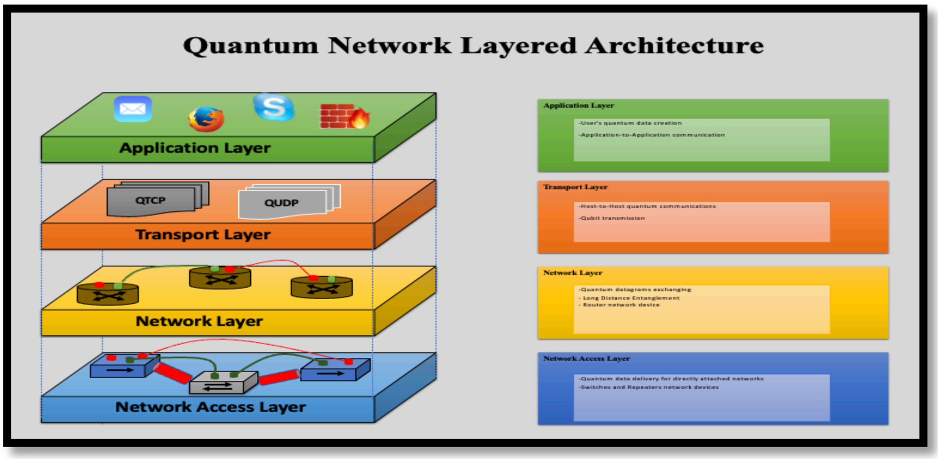

Fig. 2. layered model of Quantum Network Architecture

3 Quantum Network Platform Design

This section deals with the proposal of the current study to implement the GUI Model through which the work of the quantum network is simulated in terms of graphic design, interfaces and devices control, and the proposed quantum repeater protocol work mechanism.

3.1 GUI Modeling

The proposed simulation model consists of sections, where the following Fig. 3 represents the way to organize our simulator into four sections: A: the network preview frame, B: the tools frame, C: the protocols frame, and D: the processing follow-up frame.

Where this interface was designed on the PyCharm platform from JetBrains software company by using the Tkinter library of graphic interface design in the programming language Python. Therefore, this library provides many tools that help build interactive interfaces, such as the button, the dropdown list, and others. Still, on the other hand, the Networkx library was used mainly to provide the requirements for building the network based on this on the principle of graph theory. This library is considered one of the best and most widely used libraries in existence libraries. Moreover, this library can provide many functions that facilitate building networks and dealing with them, such as adding nodes, linking between nodes, and analyzing the network.

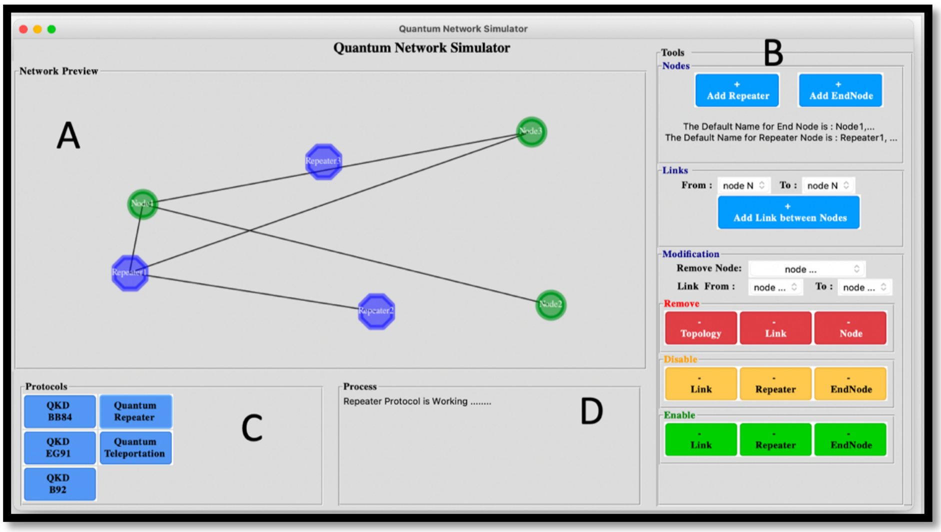

Fig. 3. GUI of Quantum Network Simulation

The Network Preview Frame

. This window includes the presentation of network design, where the contents of the network are explained in an easy-to-understand manner, and these components can be distinguished. In addition to that, the network devices that are added from the tool window can be identified, as well as distinguishing whether the devices or channels are activated or not. This framework includes a graphic illustration of what is being done within this network.

The Tools Frame

. This frame includes all the tools necessary to deal with quantum networks and is divided into a group of subframes. Each of which provides for specific tools, where the first subframe offers the ability to add quantum devices (End nodes and quantum repeaters Nodes) and the links between nodes. While the deletion sub-frame includes the possibility to delete any previously added component. Besides, the tools for enabling and disabling devices and links give the capability to delete the entire network topology.

The Protocols Frame

. This frame contains the most important protocols in quantum networks, such as the quantum key distribution protocols, the quantum teleportation protocol, and the proposed quantum repeater protocol, which will be discussed in the next section. Later, the authors will add more quantum protocols that help in performing the work of the network, such as routing tangle.

The Processing Follow-Up Frame

The processing framework enables the follow-up of some of the processing that takes place during the network design process. For example, displaying the number of devices in the network or deleting a specific device or link and the details that take place during the implementation of a protocol.

3.2 Protocols Modeling

The quantum repeater is considered the heart of quantum networks, as it is responsible for connecting devices with each other. In addition, the quantum repeater overcomes the challenge of long distances connections in quantum networks [11]. The developed quantum repeater protocol that will increase the end-to-end entanglement probability between connected ends, where the probability of end-to-end entanglement success depends on the pre-entanglements cumulatively. Fig. 4. represents the workflow diagram of the proposed protocol.

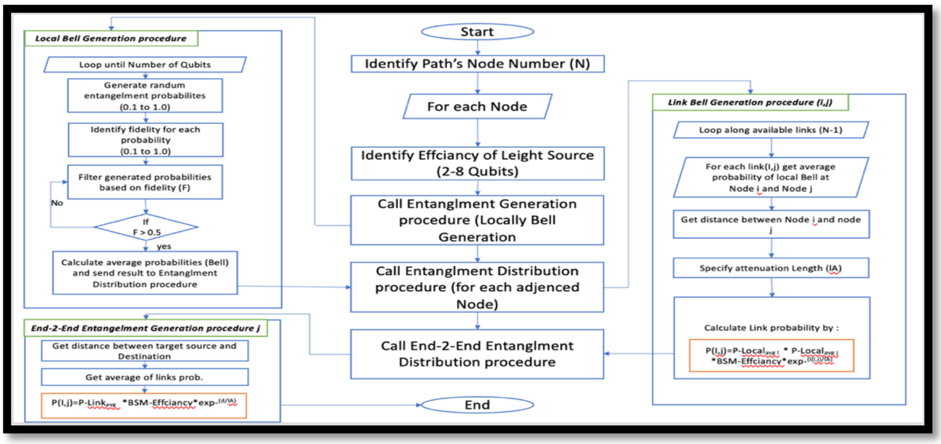

Fig. 4. Quantum Repeater Protocol workflow

Since the principle of operation of the quantum repeater depends on the property of entanglement, it is assumed that the light source generates entangled qubits on each node with a probability (P-Local), as shown in Fig. 5. The number of qubits generated within the nodes ranges from 2 to 8 [15]. However, the maximum number of entangled qubits generated is 8 qubits [14], where we chose the maximally entangled qubits based on high fidelity for each probability [4].

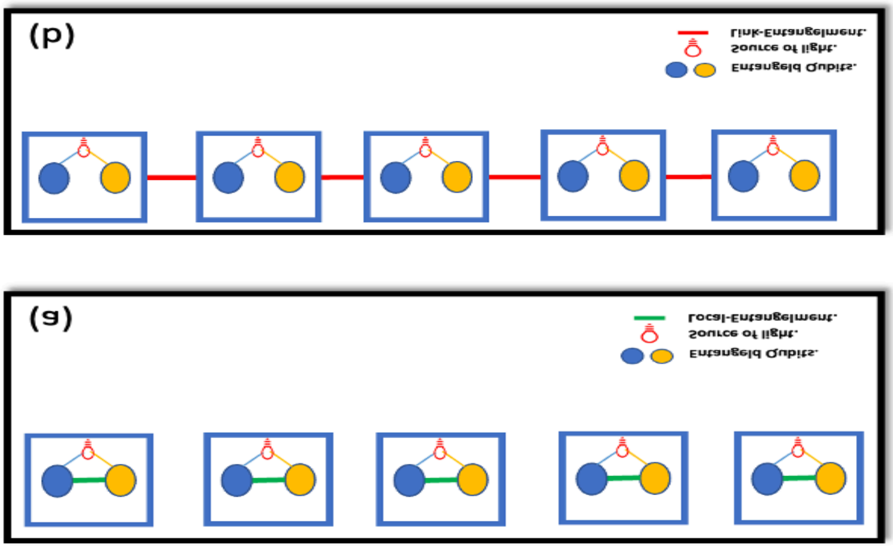

Fig. 5. Entanglement Generation (a) Within Quantum Repeater (b) between Quantum Repeater

Then, according to equation (1), the authors calculate the probability of entanglement distribution (P-Link) between adjacent nodes (see **Error! Reference source not found.** b). Where, the probability of entanglement between nodes (Pi, j) depends on the two local probabilities that were previously generated for both neighboring nodes, in addition to the length of the optical link connecting the two nodes (l (i, j)). However, the probability decreases exponentially with the increase in the length of the optical link [16] [5], and the probability is also affected by the efficiency of quantum devices, such as Bell-state Measurement (BSM) and others.

$$\text{P-Link}(i,j)=\text{P-Local}_{avg\ I} * \text{P-Local}_{avg\ j} * \text{BSM-Efficiency}*\exp\text{-}^{(l(I,j)/lA)} \quad (1)$$

Where the BSM-Efficiency will concede constant, and lA represents fiber optical length attenuation. After completing the calculation of the p-link between adjected nodes along the path between source and destination, one can calculate the end-to-end entanglement probability (P-E2E) according to equation (2), which is also affected by distance (di, j) between target source and destination. BSM-Efficiency that performs entanglement swapping [17], and probability of Link entanglement (P-link), as

$$\text{P-E2E}\ (i,j)=\text{P-Local}_{avg} * \text{BSM-Efficiency}*\exp\text{-}^{(d(I,j))} \quad (2)$$

Thus, we can choose a path with a high end-to-end probability of exchanging quantum information using teleportation.

4 Results and discussion

The proposed quantum network simulator is generally conducted in several stages. First, a quantum network is modeled using a set of basic network components: quantum repeater devices and end-user devices and the physical links are represented by optical links. Then, the quantum protocols in the network are programmed and assigned to the devices, such as the quantum repeater protocol, which is assigned to work on the quantum repeater device. Finally, this network is implemented and turned on. Table (1) is a comparison between previous simulations and this work in simulating a quantum network.

The simulator works on simulating a large part of the physical layer. In addition to the network and application layers of the quantum layered model, quantum bits have been generated within the quantum repeater device with random possibilities to take all the possibilities. Besides, the quantum repeater can work with in terms of the presence of entanglement between the qubits inside it according to the source light used (laser). Then, the selection of maximally entangled qubits within each repeater creates a distribution of entanglement among the memories of quantum qubits. However, the authors have depended on the highest fidelity between the generated entangled qubits. On the other hand, after applying equations 1 and 2, the researchers have obtained a long-distance entanglement between distant quantum devices, which is then used to transfer quantum information between sending and receiving devices.

Table 1. General comparison of quantum network simulators

SimulaQron (2018) [7]	SQUANCH (2018) [6]	NetSquid (2021) [5]	Our Qu-Net-simulator (2022)
• Possibility of simulation within the Application layer • The simulation is open source. • Programmed in python • Don't have GUI. • Available for everyone	• Possibility of simulation within the Application and physical layer • The simulation is open source. • Programmed in python • Don't have GUI. • Available for everyone	• Possibility of simulation within the Application and physical layer • The simulation is open source. • Programmed in python • Don't have GUI. • Doesn't available for everyone yet	• Possibility of simulation within the Application, network and physical layer • The simulation is open source. • Programmed in python • Has GUI. • Doesn't available for everyone yet

5 Conclusion

In conclusion, the current work presents the most important basics that lie in quantum networks, especially in the quantum internet. In addition to building a quantum network simulator in terms of devices and protocols that work within different layers of the layered model of the quantum internet, it provides the possibility of developing applications for quantum networks. The proposed quantum network simulator is under development, and new features, protocols and tools will be added over time. Besides, as long as the quantum internet is still at the lab level, i.e., under test, the simulator will remain in a state of constant updating, as it has been built and implemented using software libraries belonging to Python, and it is possible to update and add to them as needed in future.

References

1. Pirker, A., & Dür, W. : A quantum network stack and protocols for reliable entanglement-based networks. *New Journal of Physics*, *21*(3), 033003(2019).
2. Cacciapuoti, A. S., Caleffi, M., Tafuri, F., Cataliotti, F. S., Gherardini, S., & Bianchi, G. : Quantum internet: networking challenges in distributed quantum computing. *IEEE Network*, *34*(1), 137-143(2019).
3. Basset, F. B., Rota, M. B., Schimpf, C., Tedeschi, D., Zeuner, K. D., Da Silva, S. C., ... & Trotta, R.: Entanglement swapping with photons generated on demand by a quantum dot. *Physical Review Letters*, *123*(16), 160501(2019).
4. DiAdamo, S., Nötzel, J., Zanger, B., & Beşe, M. M.: Qunetsim: A software framework for quantum networks. *IEEE Transactions on Quantum Engineering*, *2*, 1-12 (2021).
5. Coopmans, T., Knegjens, R., Dahlberg, A., Maier, D., Nijsten, L., de Oliveira Filho, J., ... & Wehner, S.: Netsquid, a network simulator for quantum information using discrete events. *Communications Physics*, *4*(1), 1-15 (2021).
6. Bartlett, B.: A distributed simulation framework for quantum networks and channels. *arXiv preprint arXiv:1808.07047* (2018).
7. Dahlberg, A., & Wehner, S.: SimulaQron—a simulator for developing quantum internet software. *Quantum Science and Technology*, *4*(1), 015001(2018).
8. Caleffi, M., Cacciapuoti, A. S., & Bianchi, G.: Quantum Internet: From communication to distributed computing!. In *Proceedings of the 5th ACM International Conference on Nanoscale Computing and Communication* (pp. 1-4)(2018).
9. Behera, B. K., Seth, S., Das, A., & Panigrahi, P. K.: Demonstration of entanglement purification and swapping protocol to design quantum repeater in IBM quantum computer. *Quantum Information Processing*, *18*(4), 1-13 (2019).
10. Ma, L., Slattery, O., & Tang, X.: Optical quantum memory and its applications in quantum communication systems. *J. Res. Natl. Inst. Stan*, *125*, 125002 (2020).
11. Shirichian, M., & Tofighi, S.: Protocol for routing entanglement in the quantum ring network. In *2018 9th International Symposium on Telecommunications (IST)* (pp. 658-663). IEEE (2018).

12. Kozlowski, W., Dahlberg, A., & Wehner, S.: Designing a quantum network protocol. In *Proceedings of the 16th International Conference on emerging Networking EXperiments and Technologies* (pp. 1-16) (2020).

13. Yu, N., Lai, C. Y., & Zhou, L.: Protocols for packet quantum network intercommunication. *IEEE Transactions on Quantum Engineering*, *2*, 1-9 (2021).

14. Shi, S., & Qian, C.: Concurrent entanglement routing for quantum networks: Model and designs. In *Proceedings of the Annual conference of the ACM Special Interest Group on Data Communication on the applications, technologies, architectures, and protocols for computer communication* (pp. 62-75) (2020, July).

15. Dahlberg, A., Skrzypczyk, M., Coopmans, T., Wubben, L., Rozpędek, F., Pompili, M., ... & Wehner, S.: A link layer protocol for quantum networks. In *Proceedings of the ACM Special Interest Group on Data Communication* (pp. 159-173) (2019).

16. Shi, S., & Qian, C.: Modeling and designing routing protocols in quantum networks. *arXiv preprint arXiv:1909.09329* (2019).

17. Pant, M., Krovi, H., Towsley, D., Tassiulas, L., Jiang, L., Basu, P., ... & Guha, S.: Routing entanglement in the quantum internet. *npj Quantum Information*, *5*(1), 1-9 (2019).