

A Review on Integration of Quantum-Classical Networks for Future Network Development

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Abstract— As quantum communication technologies are emerging tremendously, encouraging unparallel advancements in data communication, data transmission and data computational efficiency. However, because of the present constraints of quantum systems, including range, error rates, and integration complexity, the shift from classical to quantum networks is anticipated to be gradual. This study investigates the study of a quantum and classical network architecture, followed by integration of both which blends as the advantages of quantum and classical communication together, with challenges faced in integration. The hybrid system combines quantum communication components, like Quantum Key Distribution (QKD) and quantum repeaters, to offer improved security and secure key exchange, while utilizing classical networks for high-throughput, scalable data transfer. Here this study explains having both these systems integrated on shared infrastructure how it would increase complexity with respect to cost efficiency and scalability, solution on how to overcome this problem by incorporating Wavelength Division Multiplexing (WDM), wireless access for QKD and future scope of improvement in this research domain. Classical networks won't be instantly replaced by quantum networks. While quantum networks are being developed, a hybrid system would enable immediate real-world applications

Keywords—Quantum networks; Quantum communication; Quantum Key Distribution; wireless access; Wavelength Division Multiplexing.

I. INTRODUCTION

The foundation of digital communication is strongly claimed by classical networking systems which gives smooth transfer of data with high security, this is achieved with specific design hardware and software, and mainly by networking protocols [1]. Whereas quantum communication technologies are emerging tremendously, encouraging unparallel advancements in data communication, data transmission and data computational efficiency assuring greater secure communication in communication field. Unlike classical networking which has basic unit of information which is termed in bits that is 0s and 1s, in quantum networking its termed as quantum bits (qubits), which utilize properties like superposition and entanglement [2][3].

The integration of classical and quantum networking is a new step for future network development, communication and computing. With holding the robustness of classical networks and revolutionary features of this developing quantum networking system, hybrid networks are used to obtain unparalleled capabilities in data transmission, and data security. Classical networks won't be instantly replaced by quantum networks.

While quantum networks are being developed, a hybrid system would enable immediate real-world applications[7].

To overcome the gap and challenges with hybrid technologies future directions as to use emerging technologies such as AI and ML to overcome these challenges that is faced with hybrid technology. Ongoing advancements in technology in quantum networks will create a way for this seamless integration. The main motivation of this paper is to give an insight into classical and quantum networking and when they are bound together with utilizing very self-advantages which benefit in seamless data transfer and contribute better to communication domain.

II. LITERATURE REVIEW

The study by Crystal Paneks, Defining Networks with the OSI model, gives fundamental insight on OSI network layers, defining each layer by illustrating each individual functions. And explains the integration of TCP/IP within OSI framework. This paper provides information about classical networking and basic principle which is followed by to achieve present day data communication.[1]

The Study by J. K. S et al. on Quantum Network for Quantum Communication says the integration of quantum networks to present day classical networks. This paper highlights the challenges faced with the integration of quantum and modern networks, such as efficient data communication with less robust infrastructure that is resource allocation and scalability. This paper also gives future directions as to use emerging technologies such as AI and ML to overcome these challenges that is faced with hybrid technology.[2]

M Belghachi's paper, Quantum Emerging Research area, challenges, and opportunities, gives a comprehensive overview of the emerging field of quantum network how it is going to create a revolution in data communication by providing high security and scalability. This study gives a fundamental understanding of quantum networks and their mechanisms including quantum entanglement, integration of quantum networks to classical infrastructures, quantum key distribution. Main challenges that is listed out in this paper is scalability, secure data communication in large scale network and error correction. Also gives an insight into what best can be done to improve these to ensure solutions to the above-mentioned problems.[4]

The Study by M.H Krishna et al. on, Exploring Quantum Key Distribution for secure communication: A Comprehensive survey

Provides a deeper view on quantum key distribution and secure communication. This paper explains various networking protocols including BB84 and report its strengths and challenges w.r.t practical implementation. With this it also mentions the key challenges of quantum key distribution which includes scale efficiency photon loss and noise. And to address these challenges they have proposed potential solutions to improve the robustness of the system to achieve the scale. Here author also states major insights to the advancement of the quantum networks that helps in real world communication networks.[5]

According to the paper by L,Fan et al. Quantum-Classical computing for future network optimization discusses the advantages of integrating these two technologies to address faster communication gap that is found is modern communication by leveraging the strengths of quantum computing in solving complex problems such as scale and resource allocation and provide optimized framework for future enhancements in networking field.[6]

The study by P. Sharma et al. on quantum key distribution secured optical networks, this is a survey paper on integration of quantum key distribution with optical fiber network, to ensure secure data communication. The key points the paper conveys is, quantum networking components QKD protocols, repeaters, and nodes. And address the key challenges faced with existing quantum-classical coexistence in optical networks. This paper serves the valuable resource for researchers who is interested in exploring quantum communication and optical network security. [8] The study by S. Bahrani et al. Paper says, the possibilities of combining classical communication systems with quantum communication systems. The classical networks dominate the current infrastructure but the recent developments in quantum technologies, particularly Quantum Key Distribution (QKD) has opened doors for enhancing securing through quantum mechanics principles. Having both these systems integrated on shared infrastructure would be cost-effective and scalable.[10]

The study by Qiang Zhang, et al says, Quantum Communication is evolving as a new tech for securing data transfer by leveraging the principles of quantum mechanics. The recent developments in Quantum Key Distribution (QKD) can be leveraged for better securing the network. QKD enables secure exchange of cryptographic keys based on the no-cloning theorem. This technology has been in market since a decade now, China Beijing-Shanghai QKD link, the UK quantum communication network are some examples of such networks. Such advancements have increased the possibilities of integrating classical and quantum communication systems and their utility and scalability.[11]

III. CLASSICAL NETWORKING

First, Classical networking system is termed as foundation for the modern communication system for transmission of data from source to destination by establishing protocols with physical medium. This networking system uses traditional networking models which are open system interconnection or transport control protocol/internet protocol to route the data and send to desired destination with less time securely. Traditional networks primarily operate on optical signals to carry data which serves a wide range of applications. Networking components used for transmission of data are routers, switches, cables which use software protocol for the process of transmission. In recent years routers and switches are widely used as a networking node, for data to get routed to reach the destination. Networking protocols such as transmission control protocol/internet protocol, ethernet, Wi-Fi are used to manage task of addressing the IP address, manage traffic engineering, and help in error detection.

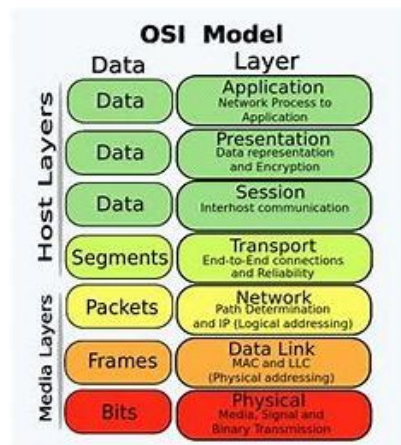


Fig 1. OSI Model: The 7 layers of OSI Model

Even though this system is used widely in the present world this too face limitations with latency and security as data is money in this generation high security data transfer with high speed is demanded. In classical networking data transfer operates in structured way. This process starts with data encapsulation as it will now be referred to, the data is fragmented into smaller pieces, called packets, and each fragmented data packet comes with headers and trailers that includes important information such as the sender and receiver address, and error-detecting data. The data then travels through the OSI which is shown in above Fig (1) or TCP/IP model networking architecture layers. The data came from user actions such as sending an email or loading a website at the application layer. The transport layer receives it and ensures reliability by segmenting the packet for error detection and acknowledgment through protocols such as TCP (Transmission Control Protocol) or UDP (User Datagram Protocol).[1]

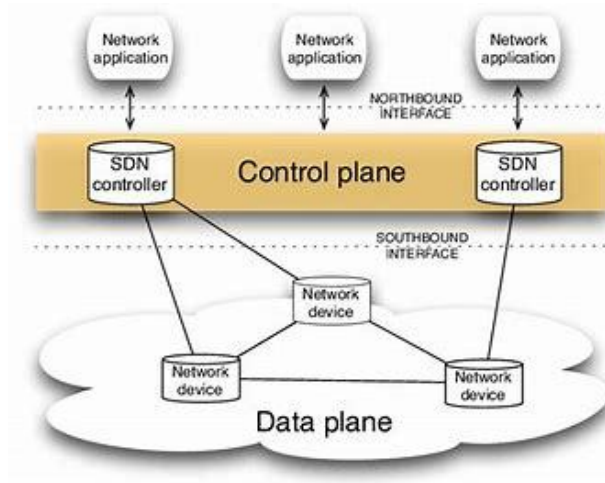


Fig 2. Architecture of classical routing system

Data is then given logical IP addresses and routed to the destination via the most efficient path at the network layer. Next comes data link layer followed by physical layer, here data link layer prepares data by adding Media access control address for the transmitted data frame this serves as layer 2 in networking OSI model, physical layer converts this framed data packets to electrical signals then are transferred via optical or cable depending on the transmission medium. These data packets is traversed across networking devices such as switches and routers which forward the data packets to the destined network or desired destination. At destination process is reversed, physical/electrical signals are again converted back as data, then here headers are removed as data moves from layer to layer, original information is reassembled and delivered at destination application. In this process to ensure data integrity error detection mechanisms are introduced which promises reliable and efficient communication. This type of seamless data transfer from source to destination can be seen in this classical networking system.

In networking there are 2 main components which work together and manage the operation of forwarding the traffic within the network. They are control plane and data plane. Above Fig (2) describes the architecture of network device and the operation of these two main integral components. Here out of this control plan is very much responsible for decision making which includes traversing and getting the best possible route for the data packet to travel to the destination[9]. This also maintains routing and forwarding tables. Control plane operates using protocols like OSPF, BGP, ISIS, which helps in exchanging routing information between two networks and form a network topology. Control plane is termed as brain of the network, as it handles all valuable operations such as handling policies, making routing decision also perform network management tasks.

Another important component is the data plane which is responsible for using information provided by the control plane and forwarding the data packets to the destination in real time with a high efficiency rate. This data plane also handles tasks like encapsulation decapsulation and apply routing policies. Data plane relay on high-speed hardware to ensure high efficiency and high-speed data transfer across network topology. Together with control and data plane we can achieve seamless operation of data communication in a network topology.

IV. QUANTUM NETWORKING

Here in this section introduction to quantum networks, its key concepts and technologies and emerging research areas challenges are discussed,

Quantum network is the future of communication domain. Its functionality makes it play a dominant role in the communication industry by enabling principles such as quantum key distribution (QKD), quantum sensing, and quantum computing.

In previous section (I) we have discussed on classical methods in network communication, here in this section we will discuss highlights of quantum networking and then followed by describing fundamental differences between quantum networking and classical networking.[2] Main principles that hold quantum communication high are QKD, superposition, and entanglement [6]. Unlike classical networking which has basic unit of information which is termed in bits that is 0s and 1s, in quantum networking its termed as quantum bits (qubits), which utilize properties like superposition and entanglement. Important components of quantum networks include QKD, quantum repeaters, quantum routing:

QKD: This is a method for secure communication which allows 2 nodes to give a shared random secret key, this is to ensure we have secure communication. Which is used for encryption and decryption of data, this is based on principles of quantum mechanics.

Quantum key distribution is methodology which uses quantum mechanics for secure communication, as mentioned above its used for encryption and decryption of data. Most prominent QKD protocol and BB84 uses polarization of photons to encode keys. Once its securely shared its used for encrypting data which promises secure communication which is most fundamental property of network communication.

Quantum repeaters: unlike we have advance routers and switches in classical networking system here its termed as quantum repeaters, this is an advanced device used in quantum communication which extends the range by overcoming photon loss and decoherence in long distance transmissions, this is the key factor which will be used to build large scale quantum networks.

Quantum routing: This technique is motivated as a classical routing system as we need to send our data securely with low latency over a long distance ensuring efficient and reliable transmission between networks.

Fig (3) is basic architecture of quantum networks[3]; this is a complex and multi-layered that needs integration of various components and technologies. The design is critical for the development of practical quantum communication systems. This is designed to traverse the quantum information between multiple nodes/end users. There are many key components of quantum network architecture which includes,

- Quantum nodes: these are basic building blocks of this quantum network, with quantum processor in each node, which is used to generate measure and manipulate the quantum information.
- Quantum channels: these are the physical channels used to transmit quantum information between nodes, these can be connected via different physical medium such as microwave cavities, fiber optics.
- Quantum repeaters: unlike we have advance routers and switches in classical networking system here its termed as quantum repeaters, this is an advanced device used in quantum communication which extends the range by overcoming photon loss and decoherence in long distance transmissions, upon breaking long distance quantum communication link into short segment this is the key factor which will be used to build large scale quantum networks.
- Quantum control system: this is used to communicate and manage different components in quantum networks, such as quantum channels, processors and memories.

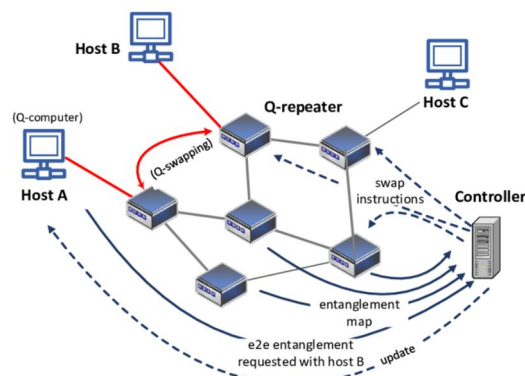


Fig 3. Quantum Network Architecture

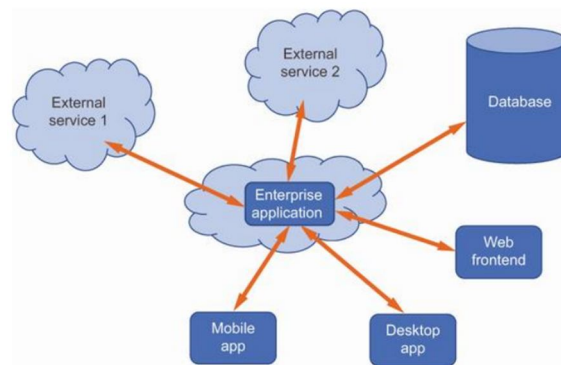


Fig 4. Various Application of quantum networks

The above Fig (4) shows various applications of quantum networks. With the above application quantum network gives secure communication which is achieved by enabling unbreakable encryption using quantum cryptography also quantum sensing which allows researchers to achieve great heights such as navigation healthcare and environmental monitoring[3].

With the above eye-catching applications of quantum communication, we also need to focus on the main challenges that is faced in achieving most reliable and efficient communication through quantum communication, they are scalability: building larger scale network as we have not developed advance devices and components error detection and fault tolerance quantum system, so lack of resources is the major drawback in present scenario.

Quantum states are highly sensitive to environmental disturbance this can lead to major loss in data communication as data is money and losing a data will not give efficient outcomes.

Creating a hybrid system by Integration of quantum network with classical networks is also a challenge.

V. HYBRID NETWORKING APPROACH

For this last drawback there is a scope in research, as quantum networking is the future of communication industry adopting a part of already existing classical networking to increase robustness of quantum networking will surely be a game changer, some researchers have explored this novel approach by integrating quantum and classical networking.

This hybrid approach can be a combination of robust infrastructure and scalability in traditional method of communication plus unbreakable security of quantum communication. With the current usage of high-speed data transmission communication system, the demand for securing it has become the need of the hour. This has led to the possibilities of combining classical communication systems with quantum communication systems. The classical networks dominate the current infrastructure but the recent developments in quantum technologies, particularly Quantum Key Distribution (QKD) has opened doors for enhancing securing through quantum mechanics principles. Having both these systems integrated on shared infrastructure would be cost-effective and scalable.

We are looking into the possibilities, challenges and solutions for seamless integration of these systems and their future in communication networks.

A. Quantum Communication and its significance that can be adopted for hybrid method[4][11]:

Quantum Communication is evolving as a new tech for securing data transfer by leveraging the principles of quantum mechanics. The recent developments in Quantum Key Distribution (QKD) can be leveraged for better securing the network. QKD enables secure exchange of cryptographic keys based on the no-cloning theorem. This technology has been in market since a decade now, China Beijing-Shanghai QKD link, the UK quantum communication network are some examples of such networks. Such advancements have increased the possibilities of integrating classical and quantum communication systems and their utility and scalability.

Challenges in Integration [11]:

Though the Coexistence of these two systems is essential for future of communication, there exists unique challenges.

- The primary issue with quantum communication is the weakness of quantum signals (single photons) when compared to the strong pulses which are used in classical communication. A minor crosstalk noise from classical system can significantly weaken the quantum signal.
- Effective utilization of optical fibers in the existing infrastructure is crucial for cost-effectiveness and scalability but the Raman scattering and four-wave mixing in optical fibers create noise which affects the quantum signals.
- Allocation of resources in the existing infrastructure to both the systems is a complex task.

B. Solutions for Coexistence

Addressing the challenges is crucial, below are a few solutions proposed.[11]

- Wavelength Division Multiplexing (WDM): It allocates different wavelength channels for QKD and classical data within the same fiber.
- Mitigate noise: Quantum signal can further be isolated by Narrow-band filtering and time-gating. Also by reducing the launch power of classical signals the noise can be mitigated.
- Wireless Access for QKD: it extends QKD to passive optical networks and therefore balances noise reduction and user flexibility.
- Orthogonal Frequency Division Multiplexing: it helps in more efficient use of spectral resources and better isolation between classical and QKD signals by enhancing time-frequency filtering.

VI. FUTURE DIRECTION

The future of hybrid communication involves:

- Innovations: in the field of advanced filtering techniques and photon detectors to improve performance.
- Dynamic Network Management: Dynamic techniques in wavelength allocation and resource management need to be developed for addressing the challenges in the hybrid model.
- Integrate with emerging technologies: Adoption of the new tech like AI and ML and integrate them into the hybrid model for effectiveness and scalability and to address the challenges.

VII. CONCLUSION

Classical networking has been in use for data communication for the past 2 decades, it has advanced standardized protocols and robust infrastructure devices which serve as backbone of this classical networking system. This architecture has served globally in data communication and providing internet for day-to-day applications.

Quantum networking on the other side is the next revolution in communication networking domain. With the quantum principle and mechanics this can create a unparallel achievement in data security through various quantum technologies such as quantum key distribution and serving as the base foundation for quantum computing carving the path for next-generation internet, also with the promising fundamental quantum mechanics introducing innovative communication method like quantum teleportation. These are the emerging technologies in this field of quantum computing and communication, still there is a scope of improvement and innovation in this field.

Integration of traditional or classical networks with quantum represents the next generation invention in communication systems. Combination of reliability and scalability of classical networks and quantum networks, hybrid system has its own limitation but to look up on the bright side it unlocks the new insights in secure way of communication, with low latency. This integration of classical networks with quantum opens new possibilities creating advance milestones ensuring secure efficient and reliable communication.

Also, future of hybrid communication focus on enhancing the performance of dynamic network by managing the resource allocation since we require robust infrastructure for larger scale nodes, integrating this with emerging technologies like AI and ML will further help to address existing challenges and improve scalability. This paper concludes as when we say next booming technology this does not straight away diminish the use of classical networking system, while quantum networks are developing, a hybrid system would enable immediate real-world applications.

REFERENCES

- [1] Crystal Panek, "Defining Networks with the OSI Model," in *Networking Fundamentals*, Wiley, 2020, pp.43-73, doi: 10.1002/9781119650768.ch2. keywords: {Protocols;Computational modeling;Data models;Physical layer;TCP/IP;Measurementunits;Internet},<https://doi.org/10.1002/9781119650768.ch2>
- [2] J. K. S and S. G. C., "Quantum Network for Quantum Communication," 2023 7th International Conference on Computation System and Information Technology for Sustainable Solutions (CSITSS), Bangalore, India,2023,pp.1-5, <https://doi.org/10.1109/CSITSS60515.2023.10334148>
- [3] S. K. Sood and Pooja, "Quantum Computing Review: A Decade of Research," in *IEEE Transactions on Engineering Management*, vol. 71, pp. 6662-6676, 2024, <https://doi.org/10.1109/TEM.2023.3284689>
- [4] Belghachi, Mohammed. (2023). Quantum Networks: Emerging Research Areas, Challenges, and Opportunities. 10.1364/opticaopen.22662175. <http://dx.doi.org/10.1364/opticaopen.22662175>
- [5] M. H. Krishna, A. Juttiga, M. Shobharani, D. Deepa, C. Anilkumar and A. Sarabu, "Exploring Quantum Key Distribution for Secure Communication: A Comprehensive Survey," 2023 International Conference on Energy, Materials and Communication Engineering (ICEMCE), Madurai, India, 2023, pp. 1-5, <https://doi.org/10.1109/ICEMCE57940.2023.10434018>
- [6] L. Fan and Z. Han, "Hybrid Quantum-Classical Computing for Future Network Optimization," in *IEEE Network*, vol. 36, no. 5, pp. 72-76, September/October 2022, <https://doi.org/10.1109/MNET.001.2200150>
- [7] G. Ramachandran, "Control-Plane Observability Through Data-Plane Performance," 2024 16th International Conference on Communication Systems & NETworkS (COMSNETS), Bengaluru, India, 2024, pp. 889-896, doi: 10.1109/COMSNETS59351.2024.10426959. keywords: {Wide area networks;Protocols;Toy manufacturing industry;Optical variables measurement;Routing;Behavioral sciences;Streams;Wide area networks;Traffic Engineering;Data-plane;Control-plane;Active Measurements;Latency},<https://doi.org/10.1109/COMSNETS59351.2024.10426959>
- [8] P. Sharma, A. Agrawal, V. Bhatia, S. Prakash and A. K. Mishra, "Quantum Key Distribution Secured Optical Networks: A Survey," in *IEEE Open Journal of the Communications Society*, vol. 2, pp. 2049-2083, 2021, doi: 10.1109/OJCOMS.2021.3106659. Keywords: {Optical fiber networks;Security;Protocols;Repeaters;Quantum networks;Photonics;Optical pulses;Quantum-classical coexistence;quantum key distribution;lightpath attacks;optical networks;routing;wavelength and time-slot allocation;trusted repeater nodes}, <https://doi.org/10.1109/OJCOMS.2021.3106659>
- [9] A. S. Cacciapuoti, M. Caleffi, R. Van Meter and L. Hanzo, "When Entanglement Meets Classical Communications: Quantum Teleportation for the Quantum Internet," in *IEEE Transactions on Communications*, vol. 68, no. 6, pp. 3808-3833, June 2020, doi: 10.1109/TCOMM.2020.2978071, <https://doi.org/10.1109/TCOMM.2020.2978071>
- [10] S. Bahrani, O. Elmaghrabi, G. C. Lorenzo, M. Ghalaii and M. Razavi, "Quantum and classical communications on shared infrastructure," 2019 21st International Conference on Transparent Optical Networks (ICTON), Angers, France, 2019, pp. 1-2, doi: 10.1109/ICTON.2019.8840309. keywords: {Crosstalk;Wireless communication;Optical fiber communication;Optimized production technology;Wavelength division multiplexing;Optical crosstalk;Quantum key distribution;wireless quantum access networks;quantum-classical communications networks}, <http://dx.doi.org/10.1109/ICTON.2019.8840309>
- [11] Qiang Zhang, Feihu Xu, Yu-Ao Chen, Cheng-Zhi Peng, and Jian-Wei Pan, "Large scale quantum key distribution: challenges and solutions [Invited]," *Opt. Express* 26, 24260-24273 (2018), <https://doi.org/10.1364/oe.26.024260>
- [12] P. Botsinis et al., "Quantum Search Algorithms for Wireless Communications," in *IEEE Communications Surveys & Tutorials*, vol. 21, no. 2, pp. 1209-1242, Secondquarter 2019, doi: 10.1109/COMST.2018.2882385. <https://doi.org/10.1109/COMST.2018.2882385>
- [13] Xu, Yuehan & Wang, Tao & Li, Lang & Zhao, Huanxi & Huang, Peng & Zeng, Guihua. (2023). Simultaneous continuous-variable quantum key distribution and classical optical communication over a shared infrastructure. *Applied Physics Letters*. 123. 10.1063/5.0164931, <http://dx.doi.org/10.1063/5.0164931>
- [14] Zhang Q, Xu F, Chen YA, Peng CZ, Pan JW. Large scale quantum key distribution: challenges and solutions [Invited]. *Opt Express*. 2018 Sep 3;26(18):24260-24273. doi: 10.1364/OE.26.024260. PMID: 30184911.
- [15] A. S. Cacciapuoti, M. Caleffi, F. Tafuri, F. S. Cataliotti, S. Gherardini and G. Bianchi, "Quantum Internet: Networking Challenges in Distributed Quantum Computing," in *IEEE Network*, vol. 34, no. 1, pp. 137-143, January/February 2020, doi: 10.1109/MNET.001.1900092. <https://doi.org/10.1109/MNET.001.1900092>
- [16] Zhao, Yangming & Qiao, Chunming. (2023). Distributed Transport Protocols for Quantum Data Networks. *IEEE/ACM Transactions on Networking*. PP. 1-16. 10.1109/TNET.2023.3262547. <https://doi.org/10.1109/TNET.2023.3262547>